Enhanced process control during selective electron beam melting through advanced machine technology

Christopher Arnold, Fuad Osmanlic, Christoph Pobel, Max Wormser, Carolin Körner

Selective electron beam melting (SEBM) is a promising approach in the fields of additive manufacturing of metals. It opens the possibility to produce complex geometries and to process a wide range of metallic alloys for various applications. To achieve a high level of quality for every component, the process parameters should be adapted to the characteristics of the required geometry. Currently available machine technology is not yet qualified for this kind of adjustment. To overcome the limitations, an advanced machine technology is introduced, which delivers new possibilities for process monitoring and control.

Keywords – additive manufacturing, backscatter electron detector, molten layer defects, selective electron beam melting, Ti-6Al-4V powder.

Introduction

Selective electron beam melting (SEBM) is an additive manufacturing process that is based on layer-wise and selective consolidation of metal powder. It offers the possibility to produce complex shapes and to process sophisticated metal alloys. The barrier for industrial breakthrough of additive manufacturing technologies is currently seen in a lack of repeatability and process control [1]. To overcome these limitations, many process parameters and their respective influence on the process have to be considered.

SEBM is an additive powder-bed fusion process. A rake system within a vacuum chamber is used to apply a defined powder layer. As a first step, the powder layer is slightly sintered by heating it up with a fast and defocused electron beam. The resulting particle connectivity provides sufficient electrical conductivity and mechanical stability for the next step in which a focused electron beam selectively melts the current cross-section of the desired geometry. Afterwards the next powder layer is applied and the cycle repeated until the final solid part is obtained.

In SEBM, there are two kind of approaches on process monitoring. First, there is the application of light optical systems, especially infrared thermography (IRT), which offers the possibility to generate images and to evaluate the thermal distribution along the build area [2 – 5]. Main drawback of this approach is the susceptibility of light optical systems to metallization caused by melt pool evaporation, which has to be counteracted by additional protection systems [2, 5].

The second approach besides light optics is electrons optics (ELO). It has been shown that backscatter electrons can be used to acquire layer-wise images during the SEBM-process and afterwards reconstruct a 3D-density map of the sample [6]. While this has been shown for the production of simple cuboid samples with varying beam power, this approach is in the following about to be extended to complex geometries with varying scan length.

Experimental

The additive manufacturing process was performed using an in-house development EBM system which combines the vacuum chamber, including powder management and build tank, of an Arcam EBM S12 and an electron beam welding gun by *pro-beam AG & CO. KgaA* (Planegg, Germany). The gun operates with an acceleration voltage of 60 kV while the tungsten filament delivers a beam power up to 6 kW. The system has incorporated a backscatter electron detector which provides the possibility of recording electron optical images.

The manufactured component was a bracket made of Ti-6Al-4V, which was built on request of an external partner. It is meant to be inserted in an application which is critical in terms of weight. To reduce the required mass of the component a topology optimization was applied by the external partner. Considering the complex shape of the component and the small lot size which was requested, the bracket was an ideal part to be produced by additive manufacturing and to evaluate the capability of ELO-imaging. The geometry of the bracket, which has size of about 55 × 10 × 38 mm³, is depicted in Fig. 1.

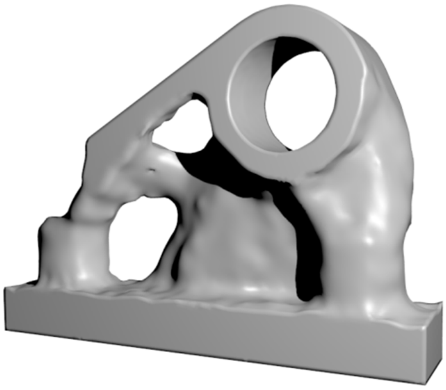

Fig. 1. Computer model of the bracket to be built by selective electron beam melting.

The process parameters for Ti-6Al-4V were chosen according to previous investigations [7]. The preheating was set to operate the process at a target temperature of 1023 K (750 °C). Furthermore a controlled vacuum of $2e^{-3}$ mbar of Helium atmosphere was applied. The cross-section was melted using a standard hatch pattern whereby the scan direction of adjacent hatch lines was alternated by 180°, often referred to as a snake-like manner. The line spacing was constant at 100 µm while contour melting was not applied. The hatch direction was rotated by 90° after each layer. The layer thickness was constant at 50 µm. Feedstock was gas-atomized Ti-6Al-4V powder supplied by Tekna Advanced Materials Inc. (Sherbrooke, Canada) with a particle size distribution between 45 and 105 µm.

The backscatter electron detector had been used during the whole process to capture post-hatching electron optical images of the sample surface. The pixel resolution was set to 75 µm/pixel while the beam diameter was around 300 µm. To receive a suitable backscatter signal, the exposure time was set to 0.4 µs/pixel and the beam current to 3 mA.

To visualize the defect distribution and the defect geometry, a virtual longitudinal cross-section of the sample was calculated from the layer-wise captured ELO-images. The ELO-images were stacked upon each other in chronological order to reconstruct a 3D density map of the sample. To achieve a correct ration between x/y and z-coordinate, pixel resolution and layer-thickness had to be taken into account. The 3D reconstruction was afterwards virtually cut in longitudinal direction (y = const.) to get the desired cross-section in x-z-direction.

Results

Fig. 2 shows the ELO-image of the component cross-section in an exemplary height of ca. 20 mm. Most of the molten surface is smooth and dense. Nevertheless, there is a distinctive pore in the narrow part of the component. At the upper edge of the melt

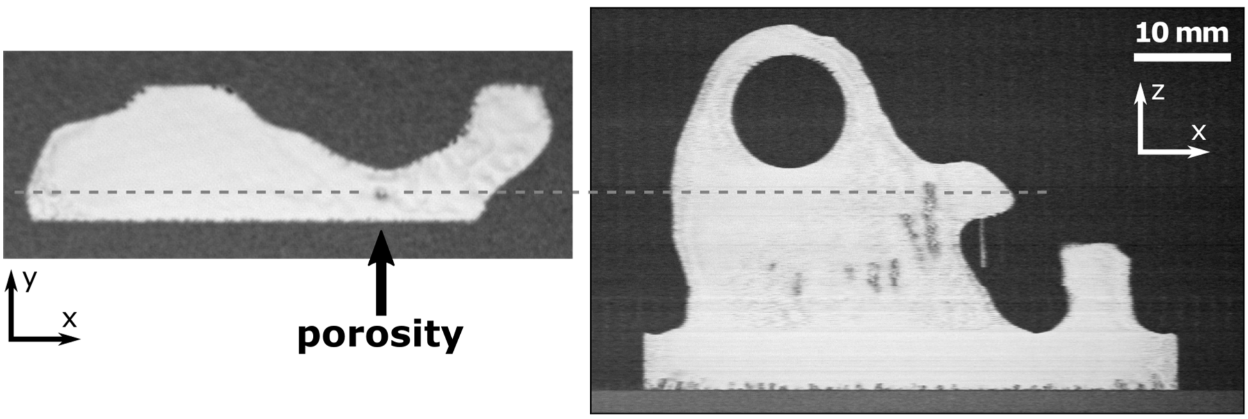

Fig. 2. Left: Electron optical (ELO) image acquired by backscatter electron detection. Depicted is the component cross-section at a height of ca. 20 mm. While most of the surface is smooth and dense, there is a single pore in the narrow part of the component. Right: Longitudinal cross-section through the 3D reconstruction of the component. It can be seen that the porosity seen in the 2D-ELO-image spreads across multiple layers.

surface, there are some small dark regions which look like pores or an increase in surface roughness.

The right side of Fig. 2 shows a corresponding longitudinal cross-section through the 3D reconstruction of all ELO images. The y-coordinate for cutting the object is chosen in a way that the distinctive porosity which can be seen on the left side of Fig. 2 lies inside the cross-section (marked by the dashed line). It can be seen that the geometry of the bracket is depicted correctly by the 3D reconstruction. The pore observed in the layer-wise ELO-image is expanded to a channel-like porosity, which spreads across multiple layers. Inside the component there are even more channel-like pores in different regions and with different sizes. Especially in the bottom part of the component, the porosity is strongly increased.

The production of complex geometries by selective electron beam melting is prone to generation of defects. As seen on the left side of Fig. 2 there is a single defect in a narrow part of the component. There is a high probability that this defect will decrease the mechanical stability of the component, especially with respect to dynamic loading. The reason behind the defect generation is the occurrence of strongly different scan lengths and the usage of beam parameters which are not adjusted accordingly. In the example above, the scan length differs strongly between the x- and y-direction. This leads to inhomogeneous thermal conditions which have a negative impact on the consolidation behavior of the material. A second effect can be observed at the upper edge of the melt surface. There are small dark regions which increase the roughness of the edge between melt surface and surrounding powder. This can be explained by the overhang of the component in this section of the layer. The consolidation of material and the formation of a smooth molten layer is hampered by the powder layer, which shows a different surface tension and different thermal properties compared to the compact material. While this effect is only small in the discussed example, it is very critical for strong overhangs, e.g. when building a T-beam structure.

Information about the three-dimensional structure of the defects may be obtained by stacking the acquired ELO-images layer-wise upon each other. As shown by previous investigation [6], there is a strong relationship between surface defects recorded by ELO-imaging and the volume defects of the final component. By considering the right side of Fig. 2 it can therefore be assumed that the distinctive pore, which was observed in the ELO-image, is part of a big channel-like porosity. The formation of these pores is discussed in detail by Bauereiß et al. [8]. The longitudinal cross-section also cuts other pores inside the component. Especially, there is a strong porosity in the bottom part of the component. This is due to the transition from the support structure, which is arranged between base-plate and component, to the first layers of the component. These first layers are manly build upon sintered powder which is not homogenous but shows a statistic distribution. Like the overhang-phenomena mentioned before, this leads to an increased probability of pore formation. If the energy input is high enough, these pores are filled in subsequent layers. Nevertheless, there is a remaining amount of porosity in the first layers of the component.

To overcome the problems resulting from non-constant scan-length and overhangs, the local energy input has to be chosen by taking into account the geometry of the component. This can be achieved either by empirical adaption of the parameters or even better by development of a suitable model which considers the three-dimensional geometry, the moving heat source and the different thermal properties of material and powder-bed. Furthermore, full beam-control is required to implement advanced scan strategies into the process.

Conclusions

Electron optical imaging by backscatter electron detection is a suitable approach for process monitoring in selective electron beam melting. It is capable of visualizing defects in the molten layers without further requirements concerning sample preparation. By delivering fast and detailed information about the condition of every molten layer, it strongly contributes to the understanding of defect generation mechanisms. It is a suitable tool for process monitoring which helps to evaluate the quality of the resulting component. In future, it will be a fast and reliable method to evaluate the success of advanced melt strategies which take into account the geometry of the component.

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Christopher Arnold *- Chair of Materials Science and Engineering for Metals, University of Erlangen-Nuremberg, Martensstr. 5, D-91058 Erlangen, Germany;*

Tel.: +49 9131 8527513;

Fax: +49 9131 8527515;

E-mail: christopher.arnold@fau.de

Fuad Osmanlic *- Joint Institute of Advanced Materials and Processes, University of Erlangen-Nuremberg;*

E-mail: fuad.osmanlic@fau.de

Christoph Pobel *- Joint Institute of Advanced Materials and Processes, University of Erlangen-Nuremberg;*

E-mail: christoph.pobel@fau.de

Max Wormser *- Joint Institute of Advanced Materials and Processes, University of Erlangen-Nuremberg;*

E-mail: max.wormser@fau.de

Prof. Dr.-Ing. habil. Carolin Körner *- Chair of Materials Science and Engineering for Metals, University of Erlangen-Nuremberg;*

E-mail: carolin.koerner@fau.de