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Process development of 99.95% pure copper processed via selective electron beam melting and its mechanical and physical properties[☆]

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ABSTRACT

Additive manufacturing by selective electron beam melting (SEBM) was used to fabricate pure copper specimens. A process window at process temperature of 530 °C, gives the required beam powers and deflection speeds for manufacturing dense specimens (> 99.5%). The microstructure of SEBM specimens was analyzed by using optical and scanning electron microscopy (SEM). Electrical conductivity, thermal conductivity, hardness, and mechanical performance were investigated by using eddy current, laser flash analysis, Vickers hardness and tensile tests, respectively. It was found that the variation of beam power and scan speed results in different microstructures from columnar to nearly equiaxed grain. The electrical conductivity of SEBM-processed specimens was above 58 MS/m (> 100 IACS) while their hardness was around 55 HV0.05 and 46 HV5 without any dependency on processing parameters within the process window. The tensile tests revealed how vertical cracks affect the mechanical strength under tensile loading condition. The results of this study not only show a reliable process window but also introduce the links between processing parameters, defect formations, conductivity and mechanical strength of pure copper specimens manufactured by SEBM.

1. Introduction

Pure copper exhibits outstanding electrical and thermal conductivity along with a good corrosion resistance and antibacterial performance [1,2]. The combination of these properties makes copper an excellent material for a broad field of applications such as electronic systems, automotive industry and construction industry [3]. The processing routes of copper components are diverse since they can be cast, wrought, welded and machined. However, there is still a lack of a processing route to manufacture engineering components made of copper with complex geometries. Additive manufacturing (AM) of pure copper by means of powder-bed fusion is state of the art. This technique not only eliminates the need for tooling (i.e., molds) but also enables it to manufacture more optimized and complex components than metal casting. From an industrial point of view, AM allows low volume production of customized metal components and diminishes the capital investment and transportation costs since the production line can be located closer to the consumer. In addition, traditional metallurgical processing of bulk melt/solidification products involving thermo-mechanical treatments could be facilitated in the AM of similar products by tailoring and optimizing processing parameters [4,5].

AM of metallic materials by powder-bed fusion employs either electron beam (selective electron beam melting - SEBM) or laser (selective laser melting - SLM) as a source of energy for melting of powders. AM of pure copper by SEBM could be the most practical and efficient technique. The reason for this is that pure copper powders reflect laser wave lengths (1000–1100 nm), used in commercially available SLM machines, which results in a low absorption degree of under 2% and thus, ineffective heating and melting of powders [6]. On the other hand, AM of pure copper by using electron beam shows much better absorption rates of about 80% which is sufficient for effective melting of powders and manufacturing dense parts [7,8]. In addition, AM by SEBM is conducted under high vacuum conditions which can prevent oxidation of metallic powders with high affinity to oxidation such as copper and titanium [9].

The authors of this paper [8] along with other researchers [10–12] have already reported successful SEBM of pure copper components which indicated a high electrical conductivity up to 95% IACS [13] and 97% IACS [12]. But still the claimed 100% IACS could not be reached. Despite such good results, mechanical properties of SEBM-processed

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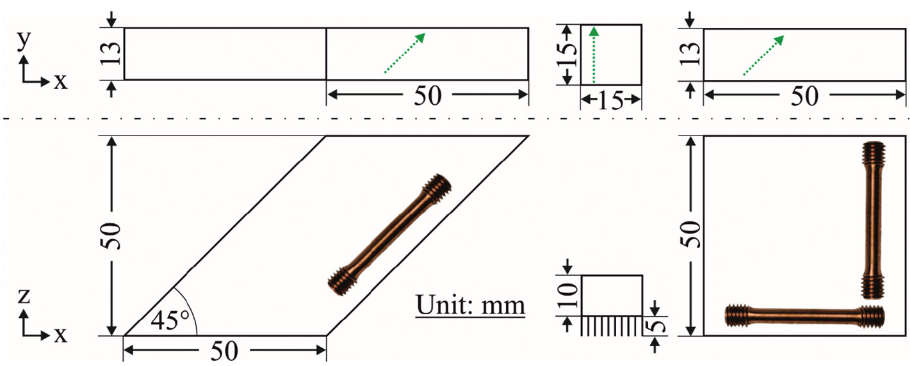

Fig. 1. Technical drawing of the manufactured samples. *Z*-axis corresponds to build direction. Green arrows depict the scan strategy. The tensile samples show exemplary the three different tested directions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Powder batch as specified by ICP-OES and oxygen measurement.

Element	Cu	Al	Ba	Ca	Cd	Co	Cr	Fe	Ga	K	Li	Mg	Mn
Mass fraction [ppm]	Bal.	< 2	< 1	< 1	< 1	< 1	< 1	< 2	< 2	< 1	< 1	< 1	< 1
Element	Mo	Na	Ni	O	P	In	Pb	Se	Si	Sn	W	Zr	
Mass fraction [ppm]	< 1	< 1	< 1	188	< 5	< 2	< 2	< 5	6	< 2	< 5	< 1	

Table 2
Measured particle size distribution and powder characteristics as flow rate, apparent density and tap density.

Particle size distribution	µm	$D_{V(10)} = 55.4$	$D_{N(10)} = 47.3$
	µm	$D_{V(50)} = 78.1$	$D_{N(50)} = 63.8$
	µm	$D_{V(90)} = 110$	$D_{N(90)} = 89.9$
Flow rate	s/50 g	21.72 ± 0.16	
Apparent density	g/cm^3	4.79 ± 0.01	
Tap density	g/cm^3	5.47 ± 0.03	

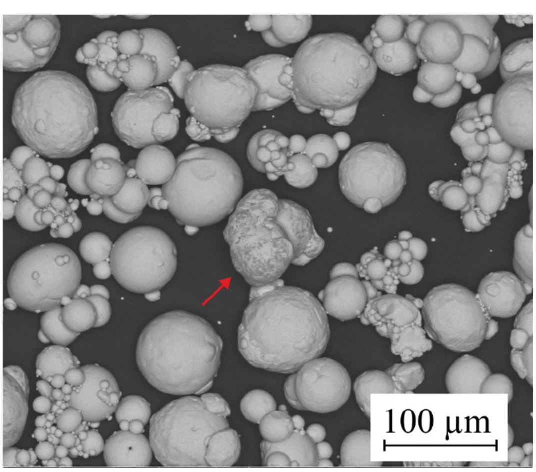

Fig. 2. Copper powder in delivery condition. SEM image recorded by a BSE detector. Round particles with satellites are displayed and some particles show a darker surface that can be referred to copper oxide (red arrow). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

pure copper have not been properly investigated up to now. Frigola et al. [12] reported a partial result of the tensile test, the yield strength of 76 MPa for SEBM-processed pure copper specimens without investigating the link between the microstructure, sample orientation and mechanical properties. The current study presents a stable process window for development of pure copper components by utilizing SEBM technique. The major emphasis has been placed on understanding the interrelation between processing parameters, microstructure evolution and physical and mechanical properties of SEBM-processed pure copper specimens.

2. Materials and Methods

Pure copper specimens were manufactured by selective electron beam melting in an Arcam A2 device [14]. During the SEBM process, the powder bed temperature was set at 530 °C while the scan speed was varied in the range of 0.25 to 10 m/s and the beam power was varied in the range of 175 to 2000 W. For the tensile test specimens, the parameter set of 0.5 m/s and 450 W was chosen because it is located in the center of the process window for dense samples and also the external optical appearance indicates a good parameter set in terms of accuracy. This is important if complex geometries with different scan lengths need to be realized. For all specimens the automatic mode for the electron beam is disabled. With the automatic mode, while melting, various functions would control the electron beam speed and power to improve the overall build quality of complex geometries by adjusting the beam to locally varying conditions (Negative surfaces, long or short scan lengths or local overheating). The whole process takes place at a low partial pressure of He ($2 \cdot 10^{-3}$ mbar). The manufacturing of one layer consists of 4 steps: applying a new powder layer, preheating the powder surface, selective melting and lowering the process table with a certain distance. The heating-up and the preheating are crucial for the SEBM. It stabilizes the process and avoids powder blow-ups. A more detailed and comprehensive description can be found in [15,16]. In the melting step, the beam selectively melts the powder bed surface with a meandering scan strategy (Snake) in which the hatch direction was rotated by 90° after deposition of each layer. The line offset between neighboring lines was 0.1 mm and the layer thickness was 50 µm. SEBM-processed specimens were manufactured on pure copper plates with the size of 150 × 120 × 15 mm^3 (Material: CW008A). The specimens were manufactured with three different geometries and dimensions, as shown in Fig. 1. The hatch direction for each type of specimens is shown with green arrows. Optical microscope (Carl Zeiss – Axio Imager M1 m) and SEM (FEI - Quanta 450) were employed to investigate the microstructure of specimens. In order to perform microstructure analysis as well as porosity and crack density measurements, the cuboid samples were halved along build direction and subsequently,