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SELECTIVE LASER MELTING OF COPPER ALLOY

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Abstract. Additive Manufacturing (AM) of copper and its alloys is a promising way to produce parts with complex geometries without tooling. One of the AM processes is Selective Laser Melting (SLM) technology that uses a laser beam to fuse powder layers to obtain a final part. Laser processing of copper is considered to be a challenging task due to its high thermal conductivity and poor laser absorptivity. In the present work, Cu-Cr-Zr-Ti alloy powder has been utilized in the SLM process to produce bulk samples. SLM process parameters (laser power, scanning speed, hatch distance) have been optimized to achieve almost fully-dense samples with a relative density of about 99.2% and a smooth surface. The obtained bulk samples were used to evaluate the microstructure of the as processes Cu-Cr-Zr-Ti alloy, which consisted of elongated grains with the size of 30–250 µm. A test part built using the optimized SLM parameters was 3D-scanned to evaluate the dimension accuracy, which resulted in the average deviation of +88 µm / -81 µm from the CAD-model.
Keywords: Selective Laser Melting, Copper Alloy, Powder Metallurgy

1. Introduction

Additive manufacturing (AM) or laser additive technologies are one of the most rapidly developing manufacturing processes. They combine usage of digital CAD-design for creating a computer model of a future part and making the part by automatically adding material layer-by-layer. Selective Laser Melting (SLM) is one of those technologies. SLM belongs to «Powder Bed Fusion» group, i.e. involves having a build platform or a plate, on which forming of powder layer is done [1]. Making of a part is done layerwise by forming a layer of powder material, melting of this layer by laser irradiation accordingly to CAD-file cross-section shape and joining each following layer with the previous one [1,2]. SLM technology features multiple advantages in comparison with conventional methods of manufacturing, such as possibility of creating functional complex part without tooling, increasing manufacturing speed and using of wide range of materials resulting in high flexibility of production [2]. Nowadays SLM is used in such manufacturing sectors as aerospace sector, automobile sector, electronics industry, biomedicine and other high-technology fields [3,4,5]. High cooling speeds up to 10^4 K/s, characteristic for SLM process, allow obtaining materials with fine-dispersed structure which leads to high mechanical properties of parts [6,7].

Copper and its alloys have high electrical and thermal conductivity and are the most important conducting materials in electrical engineering. Besides, high corrosion resistance, machinability and relatively low cost determine copper wide use in industry in pure state as well as in alloys [8]. Cu-Cr-Zr-Ti alloy is a precipitation strengthening alloy which is considered as a promising material for such applications as the combustion chamber liner of a rocket engine and as heat sinks of the components of the first wall and diverter of the international thermonuclear experimental reactor (ITER) [9]. Using SLM technology for

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producing complex-shaped parts from copper alloys, in particular with internal cooling channels, can increase overall performance of such parts and shorten the manufacturing cycle.

Manufacturing copper parts by SLM is difficult due to copper's low laser absorption and high thermal conductivity [10]. Therefore, high energy input is required for fully melting the powder material.

At the moment, SLM process of copper has not achieved enough attention. There are papers, which show the possibility of obtaining bulk specimens from Cu-Cr-Zr or Cu-Sn alloys [10-12] by SLM. Yet the microstructure features voids in the form of pores, cracks, and the elative density of the materials does not exceed 95%. In the work carried out by Fraunhofer Institute for Laser Technology ILT copper components with relative density of 99.9% were produced using SLM. However, it is said that laser power up to 1000 W is required in order to achieve high density [13].

In this paper, the investigation of SLM of copper alloy using lasers with both Gaussian and uniform beam profiles has been carried out. Process parameters have been varied to obtain copper alloy parts with relative density of 99.2%. Also the analysis of accuracy of parts manufactured by SLM using test model for 3D-scanning has been done.

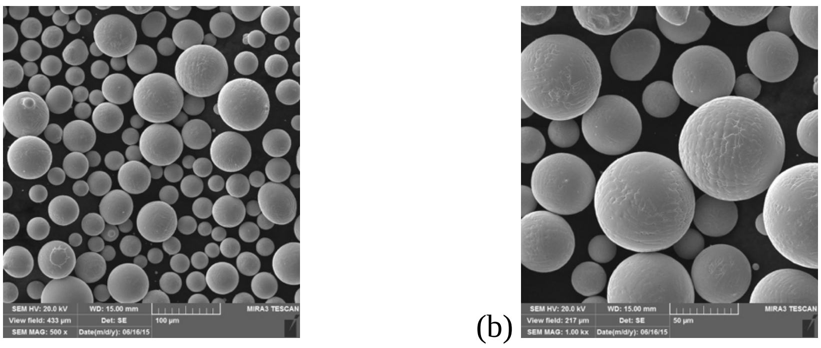
2. Materials and methods

As the initial material Cu-Cr-Zr-Ti alloy powder was used with the particles size distribution being from 16 to 79 μm. The chemical composition of the used copper alloy is presented in Table 1. The images of powder particles, obtained by Scanning Electron Microscopy (SEM), are shown in Fig. 1. Powder particles have spherical form and dendritic surface morphology.

Table 1. Chemical composition of Cu-Cr-Zr-Ti alloy

Element	Cu	Cr	Zr	Ti
Content, wt.%	balance	0.50-0.70	0.02-0.05	0.02-0.05

The study of SLM process was carried out using SLM Solution SLM 280HL system, which equipped with two ytterbium fiber lasers with power of 400 W (focus spot diameter is approximately 80 μm with Gaussian beam profile) and 1000 W (focus spot diameter is approximately 700 μm with uniform beam profile). Bulk specimens were manufactured on a stainless build plate in argon atmosphere.



(a) (b)

Fig. 1. SEM-images of Cu-Cr-Zr-Ti powder at x500 (a) and x1000 (b)

For evaluation of process parameters effect on porosity of the build samples, a set of test specimens was made with the size of each one of 10x10x15 mm^3. Porosity measurements were carried out using metallographic and Archimedes methods. In case of the metallographic method the images of microsections surfaces were obtained by optical microscope Leica DMI5000 M with x50 magnification, then the images were converted into 8-bit (Fig. 2) using

ImageJ software, then the threshold was applied to evaluate the amount of pores calculating their area.

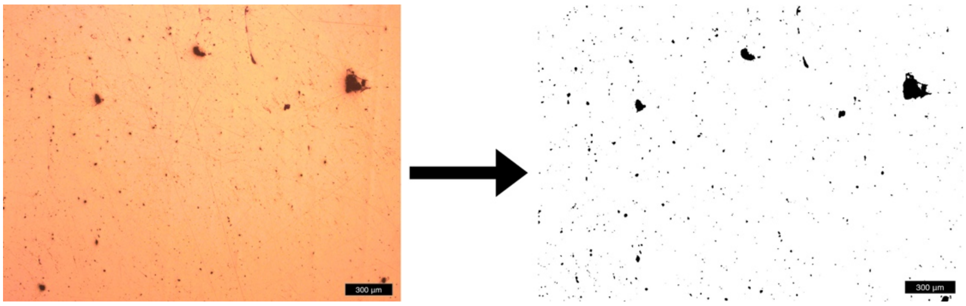


Fig. 2. Processing of the images of the specimens microsections for porosity evaluation

The microsections for microstructure studies were prepared using standard metallography methodology and $FeCl_3$ water solution as an etchant.

For study of geometrical accuracy of produced parts 3D-scanning of a test part was employed using laser 3D-scanner Optimet MiniConoScan 3000 with the scanning accuracy of 20 µm. The obtained data was compared to STL-file of the test part using Geomagic Studio.

3. Results and discussions

The following parameters were varied: laser power (P), scanning speed (V), hatch distance (h), layer thickness (t). Process parameters affect the energy input during SLM, which is the amount of energy from laser applied to metal powder volume unit per unit time. Increasing laser power leads to higher energy input, while increasing scanning speed, hatch distance, layer thickness on contrary lowers the energy input during SLM [12]. In this paper for specimens manufacturing the chess-board scanning strategy was used, wherein each layer is separated into squares, and the laser beam scans the "black" squares first, and then scans the "white" ones perpendicularly to each other. Laser power was varied from 200 to 400 W for the laser with Gaussian beam profile, from 800 to 1000 W for the laser with uniform beam profile. Scanning speed was varied from 200 to 1000 mm/s, hatch distance – from 50 to 150 µm, layer thickness was set to 30 and 50 µm.

(a) (b)

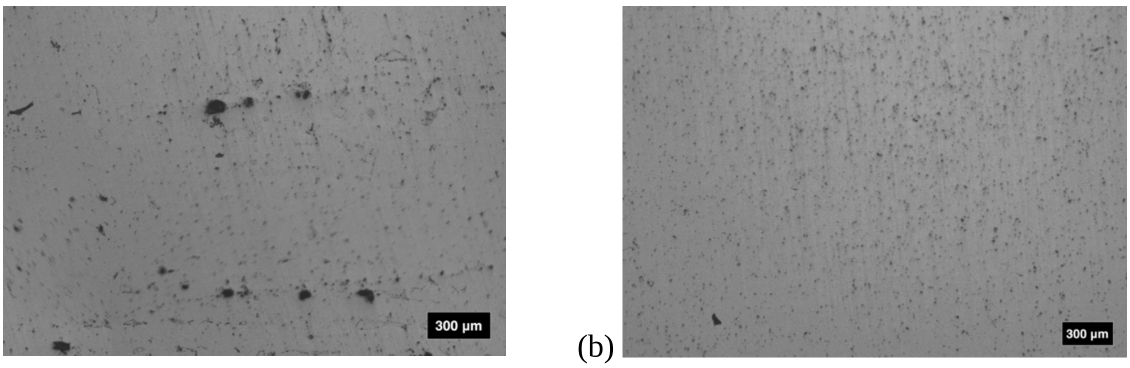


Fig. 3. Microsections of Cu-Cr-Zr-Ti alloy specimens, produced by SLM using layer thickness of 30 µm, at x50 magnification:

(a) laser power – 300 W, scanning speed – 300 mm/s, hatch distance – 150 µm;

(b) laser power – 300 W, scanning speed – 250 mm/s, hatch distance – 150 µm

The specimen produced with 30 µm layer thickness, 300 W laser power and 300 mm/s scanning speed has had the lowest relative density, which indicates insufficient energy input for fully melting of the powder material using said parameters set (Fig. 3, a). Decreasing scanning speed to 200 and 250 mm/s and increasing laser power to 350 and 400 W leads to reduction of material porosity. Applying 300 W laser power, 250 mm/s scanning speed, 150 μm hatch distance leads to the relative density of the material of 98.5%, however a large amount of fine pores with the size of 10–20 μm is present (Fig. 3, b).

Figure 4 shows the photographs of the surfaces of the Cu-Cr-Zr-Ti produced by SLM. Applying a high laser power of 800 W can be used to obtain bulk copper alloy material with high relative density, as shown above, however it negatively affects the geometry of the parts due to an intense overheating of the material and sintering of the powder along the part's surfaces (Fig. 4, c). This also results in a formation of tempering colours on the surface (Fig. 4, a). Occurrence of pores might also be associated with formation of oxides on the surface, which worsen the melt wetting and decrease the fluidity of the melt. Thermal conductivity of the stainless build plate might be insufficient for cooling the parts during SLM and the heat-dissipation takes place not intensive enough, which results in overheating of the material. Besides of that, overheating of the material might lead to partial separation of the specimens from the supports, which associated with high thermal stresses during SLM [13]. Applying 400 W laser power, the specimens' surface is clean; no sintered powder along the parts' surface is present (Fig. 4, b, d).

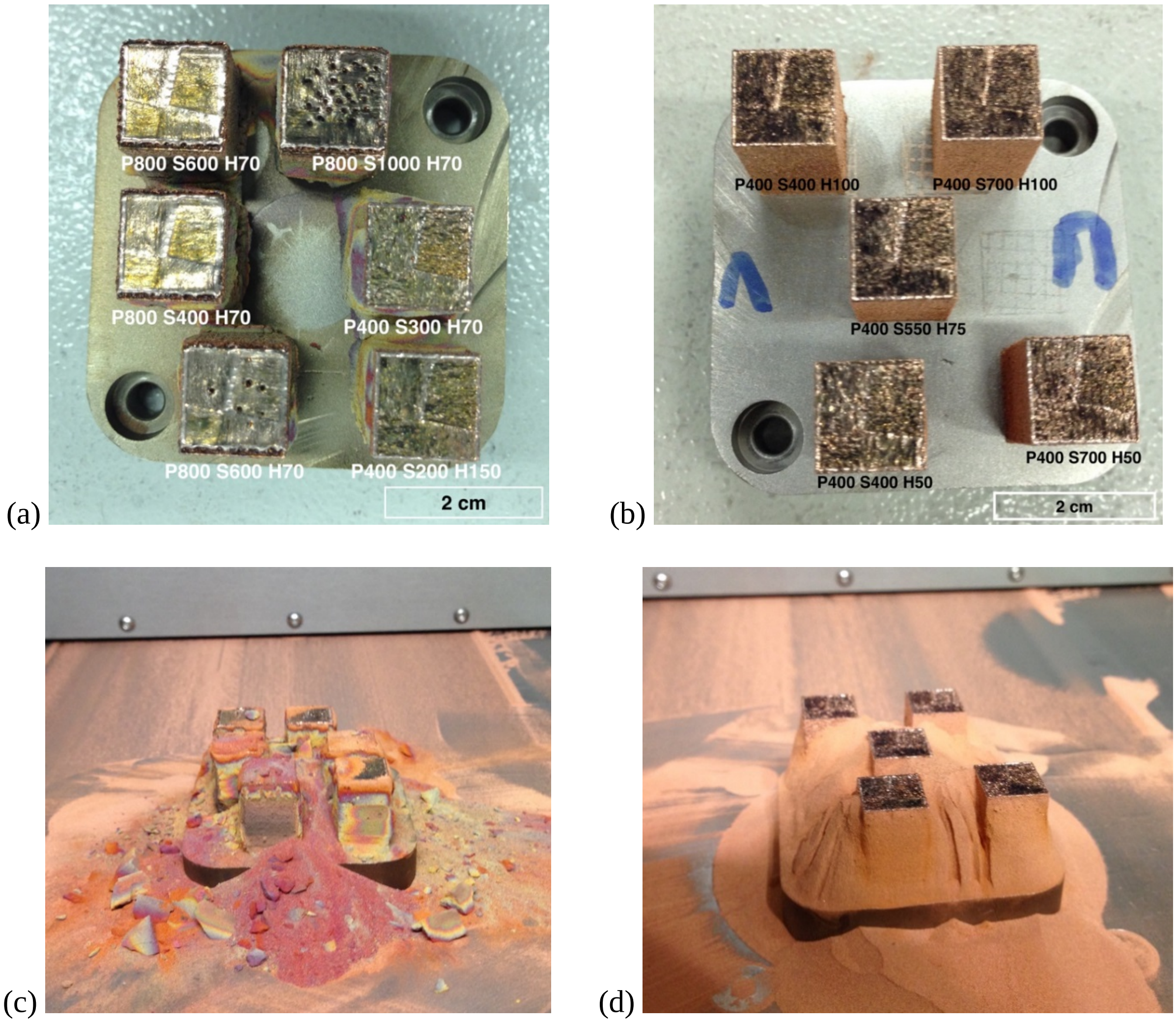
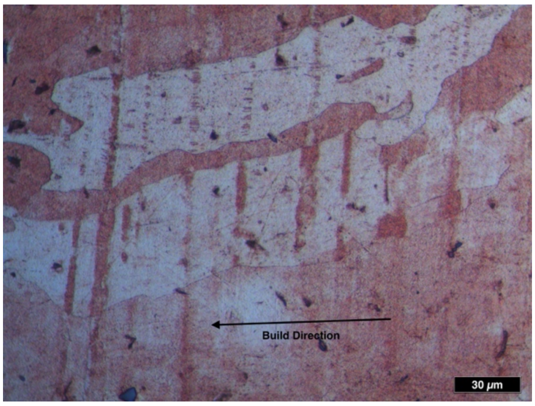


Fig. 4. Images of the Cu-Cr-Zr-Ti specimens, produced by SLM using different process parameters: (a, c) the laser with uniform beam profile with the laser power up to 800 W was used; (b, d) the laser with Gaussian beam profile with the laser power of 400 W was used

Microstructure of the Cu-Cr-Zr-Ti alloy after SLM and etching (Fig. 5) features elongated grains, whose orientation is determined by the direction of heat dissipation during SLM process and coincides with the build direction of the specimens. The grain size is approximately in range from 30 to 250 μm. There are characteristic lines on the microstructure which correspond to the layers' boundaries in areas of their remelting during SLM. Also there are micropores of different sizes seen on the microstructure.

(a) 

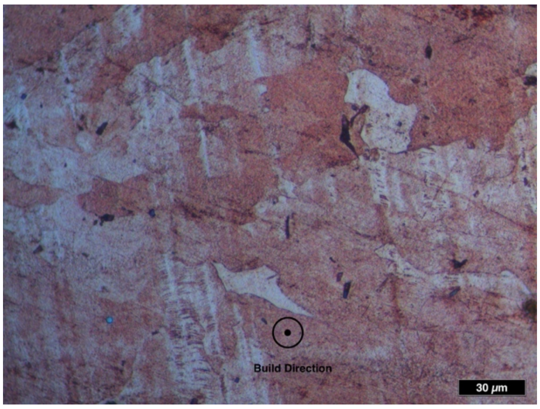
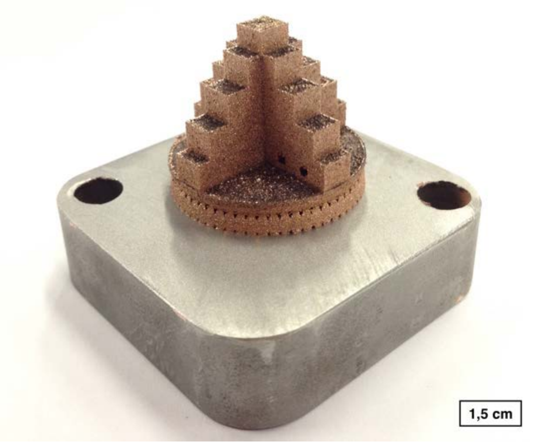
(b) 

Fig. 5. Microstructure of the etched Cu-Cr-Zr-Ti alloy after SLM parallel (a) and perpendicular (b) to the build direction

Using the obtained process parameters, which allow producing bulk material with the highest relative density, a test part for evaluating geometrical accuracy was manufacturing. Figure 6 shows the images of the test part for geometrical evaluation (Fig. 6, a) and a lattice structure (Fig. 6, b) produced by SLM to show the possibility of building complex-shaped parts from Cu-Cr-Zr-Ti powder.

(a) 

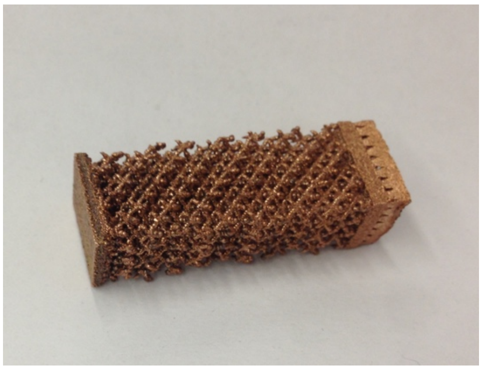
(b) 

Fig. 6. Test part for evaluation of geometrical accuracy (a) and a lattice structure (b) made of Cu-Cr-Zr-Ti alloy by SLM

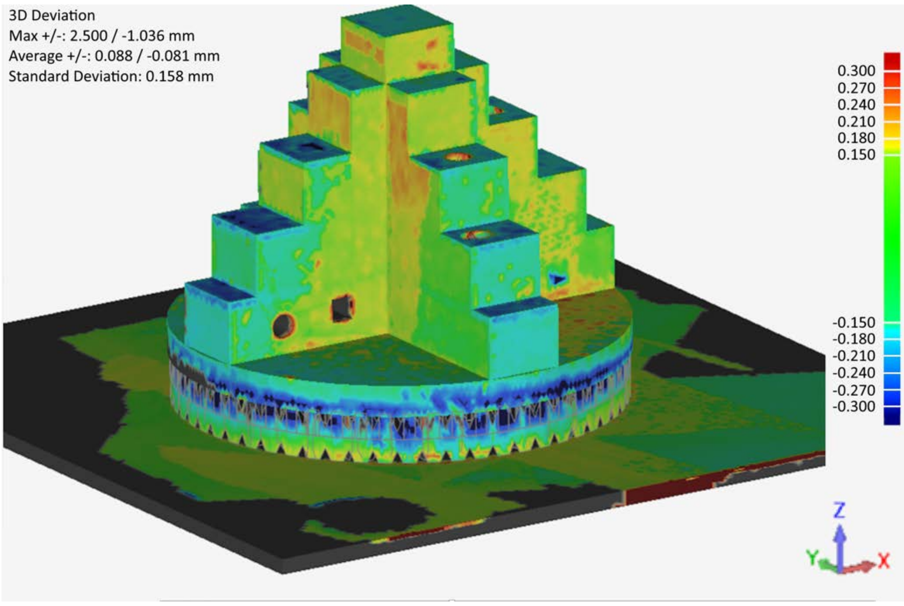


Fig. 7. Deviation colour map of the Cu-Cr-Zr-Ti test part

Comparison of the geometrical dimensions of the test part with the data from STL-file (Fig. 7) showed that the part, produced by SLM with the optimized parameters set, has a high geometrical accuracy. There is a small widening in some areas along X-Y plane, while the width of the lowest part area near the supports deviates into negative direction, which might be the result of residual stresses during SLM [14]. The average deviation is +88 µm / -81 µm.

4. Conclusions

Cu-Cr-Zr-Ti alloy parts were manufactured with a high relative density of 99.2% by SLM. The influence of process parameters of the SLM process on the relative density of the material was shown.

While applying the laser with uniform beam profile and 800 W laser power it is possible to obtain copper alloy parts with high relative density, however the geometrical accuracy decreases compared to the laser with Gausian beam profile, a partial sintering of the powder along parts' surface occurs. While applying the laser with Gaussian beam profile no sintering of the powder along parts' surface occurs, which allows producing parts with complex shape along with high relative density.

Microstructure of the material after SLM consist of grains elongated along build direction with the size in range from 30 to 250 µm.

The obtained parameters set were used to produce the test part from Cu-Cr-Zr-Ti alloy powder to evaluate its geometrical accuracy. The average deviation is +88 µm / -81 µm.

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