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Selective laser melting of copper using ultrashort laser pulses

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Abstract

Laser assisted additive manufacturing has attracted a lot of attention during the last decade due to the possibility of creating three-dimensional freeform structures with almost any desired geometry. Selective laser melting using the so-called powder bed method is one of the most established among many laser manufacturing approaches, especially for metal based products. Nowadays, CW and long pulse lasers are commonly used for additive manufacturing technologies. Recently, the application of ultrashort pulse lasers came into focus. In particular, these lasers provide extremely high peak power and offer the potential to control the thermal spreading in the vicinity of the focal region by tailoring the laser parameters. Therefore, also the processing of materials with extraordinary high melting points or the application of new composites come into reach. Additionally, based on the ultrashort pulse durations which are several orders of magnitudes shorter than any thermal relaxation processes the exploitation of thermal non-equilibrium regimes by using extremely fast cooling rates enables the generation of new material systems and the fabrication of highly resolved geometric structures.
Here, we present selective laser melting of copper by using ultrashort laser pulses with 500 fs pulse duration at a center wavelength of 1030 nm. Suitable processing windows have been identified by performing a detailed parameter study. Bulk and thin wall copper parts could be realized by ultrashort selective laser melting.

Keywords: additive manufacturing; selective laser melting; selective laser sintering; ultrashort laser pulses; laser micro processing; copper

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1. Introduction

Over the last decades laser assisted additive manufacturing gained more and more attention, since this technology enables the fabrication of three-dimensional complex free-form structures. Especially for the production of metallic components selective laser melting (SLM) using the so-called powder bed method is one of the most established methods in industry (Kruth et al, 2004). Commercially available SLM systems are commonly based on CW and long pulse lasers working in the near IR (Santos et al., 2006). So far SLM was demonstrated for numerous materials ranging from metals to polymers and ceramics, however, the processing of materials with extraordinary properties, like high melting points and high thermal conductivity still remains challenging (Nie et al., 2014).

Copper is one of these materials, regarding the high reflectivity in the near IR (Joseph, 1998) and high thermal conductivity of 400 W/(m K) (Yoshida et al., 2004) in particular. As a consequence, sufficient energy coupling into the powder turns out to be difficult and reaching the melting point is additionally impeded by the effective heat dissipation into the bulk. Therefore, in contrast to processing of copper based alloys (Gu et al., 2006; Shen et al., 2005), SLM of pure copper is barely investigated. Pogson et al., 2003 tested SLM of pure copper using CW and pulsed laser systems with nanosecond pulse duration, however the fabrication of high dense parts could not be achieved.

With the usage of ultrashort laser pulses (USP) new possibilities in material processing have come into reach. For instance the localized melting of transparent materials (Schaffer et al. 2003) or SLM processing of materials with high melting points like tungsten (Nie et al., 2015) were demonstrated.

In this paper, we present the selective laser melting of copper by using 500 fs laser pulses at MHz repetition rates emitted at a center wavelength of about 1030 nm. In order to identify an appropriate processing window a detailed parameter study was performed including different illumination strategies. We demonstrate the fabrication of bulk copper parts as well as the realization of thin-wall structures featuring thicknesses below 100 µm. This work demonstrates the potential of future SLM fabricated complex copper elements that can be applied in a wide field of application extending from microelectronic functionality to complex cooling geometries.

2. Experimental set up

In our experiments we used a femtosecond fiber laser system from active fiber systems operating at a central wavelength of 1030 nm. The repetition rate of this system can be controlled using an internal acousto-optic modulator (AOM) within the range from of 50 kHz to 20 MHz. A second external AOM allows further reduction of the repetition rate down to single pulse operation and serves as shutter for the whole system.

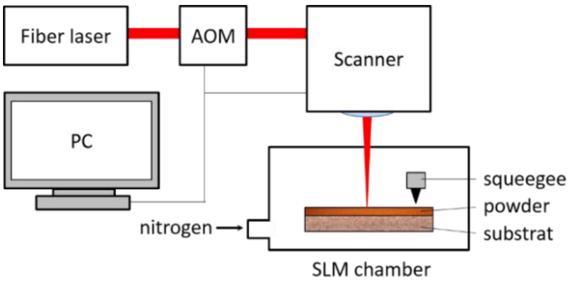

Fig. 1. Experimental set up for SLM.

The laser beam is guided through an optical scanner, which focusses the radiation onto the building platform. The f-theta objective from the scanner with a focal length of 100 mm yields a spot size of 35 µm ($1/e^2$) and supports a scanning area with a diameter of 45 mm. Laser processing is performed inside an isolated chamber suitable to realize different atmospheres. In these experiments, the chamber was filled with nitrogen (oxygen concentration below 1 %) in order to prevent the copper particles from oxidation.

Single powder layers with a thickness of 30 µm were manually prepared with the help of a squeegee. The powder consisted of gas atomized copper from TLS Technik Germany (purity > 99%). The particles exhibit a spherical shape with a maximum diameter of 35 µm. Therefore, the biggest grains are in the range of the laser spot size.

3. Results and Discussion

A preliminary parameter study was performed in order to determine a suitable processing window. Within this analysis we focused on the following process parameters: repetition rate, pulse energy and scan velocity. During the variation of the repetition rate in the range from 200 kHz to 20 MHz different parameter sets were investigated for the processing of 30 µm thick powder layers. At lower repetition rates preliminary sintering occurs or no connection of melted powder to the building platform could be realized, which implies no sufficient melting. By increasing the repetition rate up to 20 MHz and applying pulse energies around 1.0 µJ sufficient bonding to the platform could be achieved. At pulse energies higher than 1.5 µJ blasting and ablation effects dominated. The successful bonding at higher repetition rate is based on the so-called thermal accumulation effect. It was also apparent that at higher line energies the heat affected zone became larger, which is detrimental to the local precision. As a consequence the line energy was kept below 100 J/m in further experiments.

Within the identified processing window at a repetition rate of 20 MHz the fabrication of bulk and thin wall structures was investigated. In both cases the layer thickness was kept constant to 30 µm. Fig. 2 (a) shows a sample with various 3D parts processed by different laser parameters. During hatching of the bulk elements a scan pattern with 4 hatching levels and a hatch distance of 15 µm was chosen. A supporting structure in grid geometry was needed to compensate the strain and to avoid break off of the cuboids. The results can be seen in Fig. 2. The SEM picture in Fig 2 (b) offers a closer look to the cuboids surface morphology.

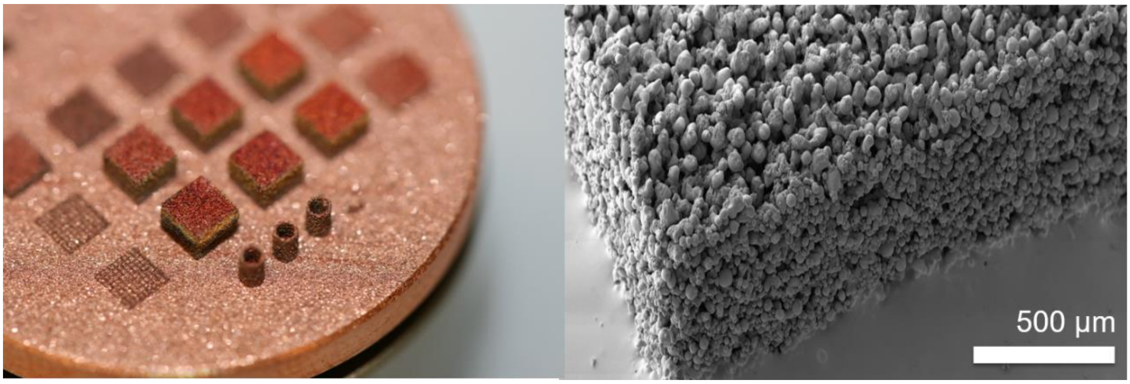

Fig. 2. (a) Sample with fabricated cuboids with 2x2 mm^2 base and a height of 1.4 mm. (b) SEM image of a cuboid processed with a repetition rate of 20 MHz, pulse energy of 1.25 µJ and scan velocity of 833 mm/s.

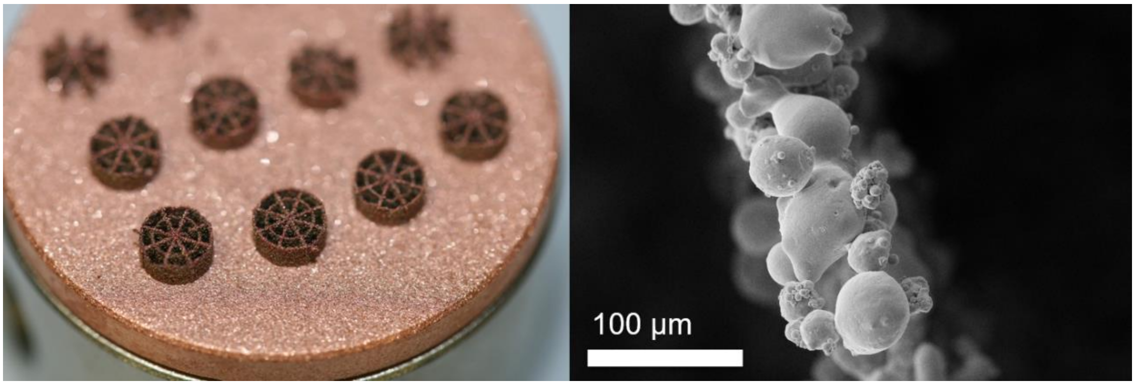

Fig. 3. a) Sample of different thin wall structures with a diameter of 3 mm. (b) SEM image of a single wall of such a web-like structure processed by 1.0 µJ pulse energy and 666 mm/s scan velocity.

At first appearance it seems that copper particles are just sintered together but during further analysis with focus on shape and size of the grains it turned out that the porous structure consists of melting beads which are formed during powder melting.

The thin wall structures shown in Fig. 3 (a) were processed by single line scans. Their morphology is equal to the bulk structures (see Fig. 3 (b)). It has to be emphasized that stable free-standing walls with an aspect ratio of 15:1 and thickness below 100 µm could be realized. Representatively, such a single wall fabricated with a pulse energy of 1.0 µJ and 666 mm/s scan velocity is displayed in Fig. 3 (b).

The reason of the porosity of the fabricated part can be attributed to the ratio of particle size and laser spot diameter. Consequently, not enough powder particles are illuminated simultaneously and due to the fact that the heat transfer between neighboring particles acts very inefficient the melt pool does not extent. Instead of a homogeneous melting track beads are formed governed by surface tension forces.

4. Conclusion

Selective laser melting of pure copper by using ultrashort laser pulses at high repetition rates was demonstrated. As a result, bulk and thin-wall structures with wall thicknesses below 100 µm could be realized. These results are based on an extensive parameter study involving different parameter sets with focus on pulses energy, repetition rate and scan velocity. Best results were achieved at high repetition rates around 20 MHz and pulse energies of about 1 µJ. Within our study, the heat accumulation effect turned out to be essential for building up robust 3D geometries.

Due to the application of comparatively large copper grain sizes in the range of the focal diameter (35 µm), the fabricated copper elements revealed a porous character. In contrast to selective laser sintering, here, the melting beads are well connected resulting in free standing structures with high aspect ratios. In one of our next studies powder with smaller grain sizes and different grain size distribution will be applied in order to improve the lateral connections and increase the overall density, respectively.

In particular, with respect to the extraordinary high thermal conductivity which in general prevents the additive manufacturing of copper with high precision, this work demonstrates the potential of ultrashort laser radiation for future highly resolved products that can be applied in a wide field of application extending from microelectronic functionality to specifically designed elements with complex thermal functionality.

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References

Chichkov, B. N., Momma, C., Nolte, S., von Alvensleben, F.,Tünnermann, A., 1996. Femtosecond, picosecond and nanosecond laser ablation of solid, Applied Physics A 63, p. 109.

Gu, G. G., Shen, Y. F., 2006. Development and characterisation of direct laser sintering multicomponent Cu based metal powder, Powder Metallurgy 49, p. 258.

Joseph, G., 1999. Copper, Its Trade, Manufacture, Use, and Environmental Status, ASM International, New York, 1998, p. 53.

Kruth, J., Froyen, L., Vaerenbergh, J. V., Mercelis, P., Rombouts, M., Lauwers, B., 2004. Selective laser melting of iron-based powder, Journal of Materials Processing Technology 149, p. 616.

Nie, B., Huang, H., Bai, S., Liu, J., 2015. Femtosecond laser melting and resolidifying of high-temperature powder materials, Applied Physics A 118, p. 37.

Nie, B., Yang, L., Huang, H., Bai, S., Wan, P., Liu, J., 2015. Femtosecond laser additive manufacturing of iron and tungsten parts, Applied Physics A 119, p. 1075.

Pogson, S., Fox, P., Sutcliffe, C., O'Neill, W., 2003. The production of copper parts using DMLR, Rapid Prototyping Journal 9, p. 334.

Santos, E. C., Shiomi, M., Osakada, K., Laoui, T., 2006. Rapid manufacturing of metal components by laser forming, International Journal of Machine Tools and Manufacture 46, p. 1459.

Schaffer, C. B., García, J. F., Mazur, E., 2003. Bulk heating of transparent materials using a high-repetition-rate femtosecond laser, Applied Physics A 76, p. 351.

Shen, Y.-F., Gu, D.-D., Wu, P., Yang, J.-L., Wang, Y., 2005. Microstructural Evolution during Direct Laser Sintering of multi-component Cu-based Metal Powder, Transactions of Nonferrous Metals Society of China 15, p. 1309.

Yoshida, K., Morigami, H., 2004. Thermal properties of diamond-copper composite material, Microelectronics Reliability 44, p. 303.