Whitepaper

TruPrint 1000 Green Edition

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Additive Manufacturing

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Abstract

We present advances of pure copper, copper alloys and precious metal additive manufacturing with green, frequency doubled disk lasers, achieved by the exploration of process parameters to specifically address the unique laser processing challenges of this class of highly reflective, highly conductive materials. Results are presented for the analysis of samples made from pure copper, and from the CuCr1Zr alloy. The material properties density, electrical conductivity, and sample properties as well as geometrical resolution and surface roughness are presented. Part performance in application is discussed.

Introduction

Only recently, the established 3D process of laser powder bed fusion [1] (also called as Laser Metal Fusion) has been applied to the manufacturing of challenging materials for laser processing such as copper [2] or gold and platinum alloys. Processing these materials with the 1um wavelegth of most industrial solid state lasers is difficult due to their low absorptivity. At 1 µm wavelength the absorptivity of copper powder is below 10 %, whereas at around 500 µm it rises six-fold to about 60 % [2]. Nonetheless, there is a large interest in additively manufactured parts specifically from metals with high electrical or thermal conductivity, coinciding with low absorption in the red to near infrared wavelength range. The geometric freedom of additive manufacturing matches requirements for near-contour fluid channels for liquid cooling devices. High heat conductivity calls for high power density to overcome heat diffusion and lack-of-fusion porosity. In addition, an increase of absorptivity with temperature in conjunction with a decrease in thermal conductivity enhances instabilities in weld depth [3], resulting in keyhole porosity. These are the three main reasons why it has been difficult to find a robust and stable process for powder bed fusion of copper with low porosity.

Different approaches have been investigated for pure copper powder bed fusion. Increasing laser intensity in continuous wave, ultrashort pulse laser melting, and short wavelength sources have been investigated. The porosity of additively manufactured pure copper could be reduced to about 1 % by increasing the laser power level to 1 kW [4], while ultrashort pulsed laser sources cannot provide sufficient average power to achieve low porosity [5]. Blue diode lasers have been employed for copper processing as well [6], yet the brightness of such devices is not sufficient to be used with scanners, although improvements are expected through ongoing laser development. For this work, we use a high brightness, high power frequency doubled disk laser to solve the main issues in copper powder bed fusion. With the TruDisk 1020, a 1 kW industrial green laser source, we demonstrated previously that short wavelength lasers can improve the laser welding process of copper drastically [7]. In this contribution we will show that high quality, high productivity powder bed fusion of pure copper and alloys can be performed. After describing the setup for powder bed fusion with a TruPrint 1000 and a TruDisk 1020, we will present and discuss the results in the processing of pure Cu ETP and alloys.

MACHINE SETUP

Motivated by the growing demand in laser welding applications of Cu, TRUMPF developed the TruDisk 1020, a high-power CW laser system emitting in the green at a wavelength of 515 nm. Based on a Yb:YAG thin disk laser platform with intracavity frequency doubling, the concept is simple and robust since no external cavity for resonant enhancement of the second harmonic generation is needed, as opposed to concepts for frequency doubling in high power fiber lasers. The TruDisk 1020 is a continuous-wave laser delivering a maximum output power of 1kW at 515 nm, and higher power levels have already been demonstrated using the same platform [7].

The TruDisk 1020 has quickly become established for high power industrial copper welding processes. Providing a brilliant beam with a brightness of 2 mm × mrad, delivered by beam delivery fiber, it is a perfect laser for remote scanner applications – such as powder bed fusion.

The TruPrint 1000, a small-format powder bed fusion printer, has been developed to manufacture small parts. With its build volume of 100 mm diameter x 100 mm in height, it found widespread use to manufacture dental implants and jewelry, smaller general industry parts and R&D applications. The machine has been designed for easy manual operation and is ideally suited for the process development of new materials and applications. TRUMPF adapted the standard optical setup, the scan system and the control software to integrate the TruDisk 1020 instead of the 200 W TRUMPF fiber laser fitted in the standard machine configuration. Up to 1000 W of 515 nm continuous laser radiation is provided by the laser to the machine via fiber-optic beam delivery cable. The beam is collimated and deflected via a pair of galvanometer scanners and focused by a f-theta lens to a spot of 200 µm diameter with top-hat intensity distribution in the processing plane.

The machine provides a process environment with inert argon atmosphere for a controlled oxygen level below 100 ppm. Suitable shield gas flux is provided across the powder bed and process chamber to remove process emissions and to avoid interference with the processing beam and contamination of the optical window. The parts are printed in the build cylinder on a retractable substrate plate. The powder is provided to the process by a raisable supply cylinder and is applied to the pre-determined layer thickness by a rubber coater. For consolidation by powder bed fusion, the powder is melted through the focused laser radiation which is scanned across the powder bed to create the subsequent layers of the part in the geometry to be manufactured [1].

Figure 1: The TruPrint 1000 Green Edition uses the frequency doubled green TruDisk 1020 (right) which is integrated with the TruPrint 1000 (left) to provide an AM system for copper and other high reflective materials.

ADDITIVE MANUFACTURING OF PURE COPPER AND ALLOYS

Properties of Cu in laser processing

Only as pure, electrolytic copper, it provides the high values of thermal conductivity at 394 W/m×K and electrical conductivity of 100 %IACS (International Annealed Copper Standard), corresponding to 58 MS/m at room temperature. Even low concentrations of alloying elements or unwanted impurities reduce these values. The reflectivity of copper is high at the most common wavelengths of Yb-based solid state and fiber lasers around 1030-1080 nm. That makes coupling laser power into the material difficult. In conjunction with the high heat conductivity, a laser process requires much higher intensity for initiation as compared to most other metals. In iron-based steels, thermal conductivity is twenty times lower. The absorption in the near infrared is temperature-dependent, destabilizing the formation of either a keyhole or conduction welding zone, and a low ratio of viscosity and surface tension increase the tendency of balling [3]. The main advantage of a 515 nm short wavelength laser in Cu processing is the six- to ten-fold higher absorptivity for additive manufacturing powder and flat surface material. With sufficient laser power, a highly stable welding process can be established [7] similar to the common laser welding processes in steels.

Additive manufacturing of pure copper

Additive manufacturing enables geometric design freedom, internal structures, and functional integration. There are many applications which benefit from the combination of these advantages and the excellent thermal and electrical properties of pure copper. Most frequently, industrial customers request new ways to manufacture inductor coils for heating or hardening, and components for demanding cooling applications such as power electronic devices and opto-electronics.

For these applications, we developed parameters for the processing of highly conductive pure copper ETP (EN CW004A) with a specified Cu content of > 99.9 % and less than 0.04 % oxygen mass percentage. The aim is to achieve lowest porosity and highest electrical conductivity, so that manufactured parts show identical material properties to bulk material used for powder atomization. We found that powder with a grain size distribution of 10-45 µm gives best results regarding powder spreading versus processability. Layer thickness was determined to be 30 µm for most consistent material properties. The process parameters were optimized with a design-of-experiment approach by varying laser power, scan speed and hatch distance. Target of the optimization is to achieve electrical conductivity of 100 %IACS and porosity levels well below 0.5 %.

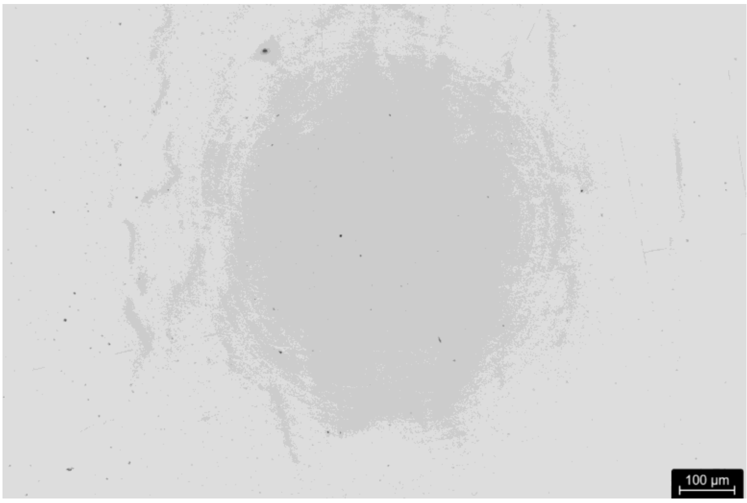

Figure 2:
Micrograph of copper sample manufactured with optimized parameter set from DOE. The density is 99.9 %.

The parameter set, which was determined to achieve maximum electric conductivity, resulted in a density of larger than 99.5 % (typically 99.8 % ± 0.1 %), at a build rate of 8 cm^3/h and a volume energy of 225 J/mm^3 (calculated with incident laser power). The density was measured using micrograph analysis. A set of micrographs used for density analysis is shown in Figure 2. Mechanical properties of copper samples have been analyzed for two parameter sets with different electrical conductivity and built rate. Young's modulus E, yield strength $R_{p0.2}$, tensile strength R_m and elongation at break A have been measured for tensile specimens built in horizontal and vertical orientation and are summarized in Table 1. For both orientations mechanical values lie within in the range of mechanical properties of soft annealed Cu ETP as specified in EN CW004A for the various formats of half-finished goods [8].

Conductivity [%IACS]	Build Rate [cm³/h]	Orientation	Young's modulus ***E*** [GPa]	Yield Strength $R_{p0.2}$ [MPa]	Tensile Strength R_m [MPa]	Elongation at break ***A*** [%]
100	8	0° (horizontal)	141 ± 5	138 ± 5	235 ± 5	57 ± 3
		90° (vertical)	131 ± 5	135 ± 5	214 ± 5	64 ± 3
95	16	0° (horizontal)	130 ±5	147 ± 10	232 ± 5	47 ± 3
		90° (vertical)	120 ± 5	139 ± 10	204 ± 5	40 ± 3

Table 1:
Mechanical properties of Cu ETP tensile test specimens built with two parameter sets in horizontal and vertical orientation.

Electrical conductivity was measured by phase sensitive eddy current method (Fischer Sigmascope SMP350) and determined to 101 %IACS. To our knowledge, such high density and conductivity values have not been published previously with copper manufactured by powder bed fusion.
With slight decrease in thermo-electrical performance and density, the build rate can be increased to 16 cm^3/h for 95 %IACS. When layer thickness and laser power are increased beyond the standard settings, the conductivity at this high build rate can be increased to 99 % IACS. After multiple powder reuse cycles, the electrical conductivity was not affected. This is an important result, since it confirms that oxygen or humidity pick-up is controlled to an acceptable level and does not require extended precautions beyond standard procedures of machine inertization and powder handling. The surface roughness of as-built, unfinished samples in vertical orientation made with a 10-45 µm powder fraction and 30 µm layer thickness is R_a= 14 µm. The smallest feature size, determined by assessing the minimum wall thickness that can be built, is below 0.4 mm. For illustration, Figure 3 shows the top surface of a part manufactured with a 200 µm spot size at 140 µm hatch distance. The right picture shows microscopic images of single vector walls printed at the same focusing condition at reduced laser power and scan speed.

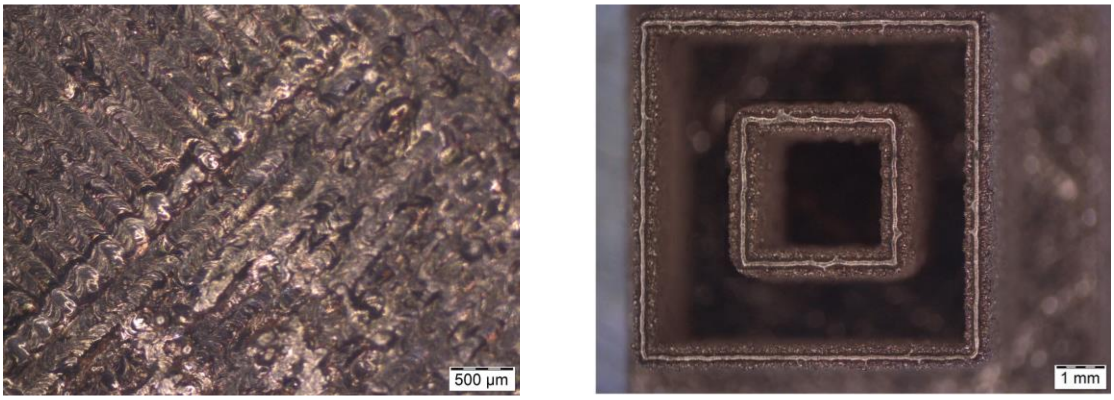

Figure 3:
Microscope images of top surface showing melt tracks for the volume parameter, and single vector walls built with reduced line energy.

Applications of pure copper parts

We have manufactured parts for different applications on the TruPrint 1000 Green Edition System. Typical applications are inductors for heating and hardening and heat exchangers. In Figure 4, three of these components are shown. The requirements in induction hardening are tough, because the inductive heat has to be applied rapidly at very high currents and RF powers. Ohmic losses would limit the maximum heating power and would increase the thermal load and thermo-mechanical stresses in the inductor. Inductors are shaped individually to match the geometry of the workpiece to be heat treated. They are either assembled from several individually milled and soldered parts or are bent to the required shape in a time consuming, manual process. Hence, the fabrication of inductors is an application that benefits from the design freedom of additive manufacturing. The fork inductor in the center of Figure 4 is an example for such a component. It holds water pressures of 10 bar in the cooling channel. In a single build job taking 9h 10 min, three parts can be built on a TruPrint 1000 using 30 µm layer thickness. On the right of Figure 4, a heat exchanger is shown as it is used for cooling of high-power electronic components. The cooling channels are optimized for heat transfer and for support-free printing to minimize post processing. The wall thickness of the structure is below 1mm to maximize heat transfer from the component to the cooling fluid, while the heat exchanger holds cooling water pressures of 10bar. Five of these heat exchangers are built within 15h.

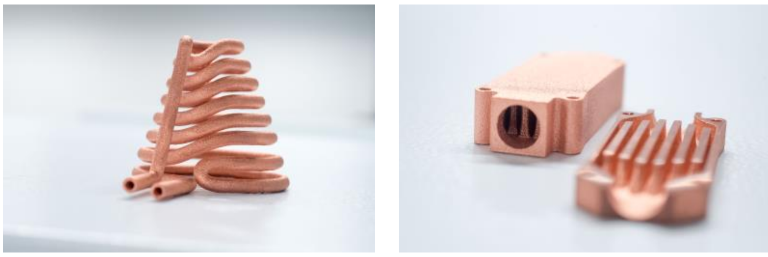

Figure 4:
Application parts of pure copper made with 100 % IACS parameter set:
left and middle: heating inductor (build time 9h 10 min, 3 parts),
right: heat exchanger (build time 15h, 5 parts)

Additive manufacturing of Cu alloys and other materials

Alloying of Cr to copper increases its mechanical strength, a requirement in applications where highly conductive material needs to support structural strength. These can be combustion parts which have to maintain mechanical integrity during high temperature stress, and other components with mechanical load in high temperature environment. An alloy used for electrical contacts is CuCr1Zr (CW106C) [8], with a nominal 0.5-1.2 % Cr content and a small percentage of Zr of 0.03-0.3 %. The material composition is a good trade-off between conductivity (up to 43 MS/m) and mechanical strength, which is almost three times higher than pure copper. For this investigation of the manufacturability of CuCr1Zr parts using a green TruDisk 1020, we used powder with a grain size distribution of 10-45 µm. In a design-of-experiment parameter study, we developed the process parameters by varying laser power, scan speed, and hatch distance. Just like in the pure Cu study, the layer thickness used was 30 µm providing high consistency in material properties and good geometrical resolution at a high build rate.

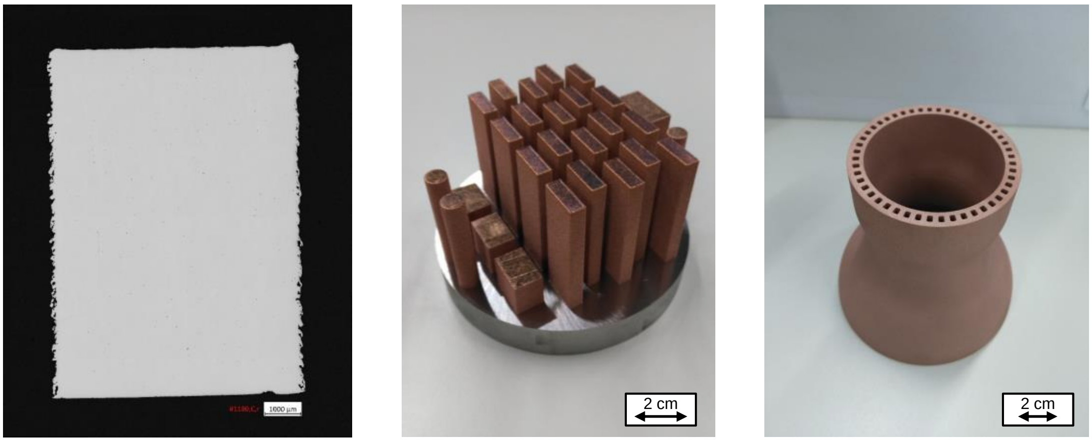

Figure 5:
Left: Micrograph of qualification sample for CuCr1Zr. The density is 99.9 %.
Middle: build job with test samples for density, conductivity and mechanical analysis.
Right: 100 mm high demonstrator for a combustion chamber (build time 10h 40min)

As a result of the process development, we identified parameters for the manufacturing of highly dense specimens with a relative density of 99.9 % at build rates of 17 cm³/h. A micrograph of such a sample is shown in Figure 5 (left). With an as-built R_a= 14 µm and R_z= 70 µm in vertical areas, the surface roughness is very similar to the pure copper process. Vertically oriented samples for mechanical testing have been manufactured and analyzed. The testing was performed by MBFZ toolcraft [9]. Before tensile testing, the samples were subjected to heat treatment for precipitation-hardening, which is a common procedure for parts made from CuCr1Zr to improve mechanical properties. The measured values are given in Table 2. Young's modulus, yield and tensile strength are in good agreement with expected mechanical properties from conventionally manufactured material of this alloy [8].

CuCr1Zr (precipitation hardened)	Young's modulus ***E*** [GPa]	Yield Strength $R_{p0.2}$ [MPa]	Tensile Strength R_m [MPa]	Elongation at break ***A*** [%]
	114 ± 5	383 ± 10	470 ± 10	26 ± 5

Table 2:
Mechanical properties of printed CuCr1Zr qualification samples. Before mechanical testing, the samples were heat treated for precipitation-hardening.

These results demonstrate that by using a green laser source, it is possible to manufacture parts with highest density made from low alloy copper material, such as CuCr1Zr, at high build rates of 17 cm³/h. Density and mechanical properties match the expected values of bulk material data. Hence, additively manufactured parts fulfill the mechanical requirements just like conventionally manufactured parts in applications such as electrical contacts and cooling of thermo-mechanically stressed combustion components. Using the TruPrint 1000 Green Edition and its powder bed fusion process, parts in this material class are produced in higher quality, less time, and at a lower cost. These advantages result from higher absorptivity, therefore better process efficiency, and an inherently more stable fusion process at the short laser wavelength.

We have applied the green laser system to the processing of other materials. A common copper alloy is CuNi2, where first tests have shown similar advantages in build rate.

Furthermore, we extensively studied the processing of precious metals, and could successfully process gold and platinum alloys, fulfilling the highest material standards for the jewelry industry.

Conclusions

By using the green TruDisk 1020 for powder bed fusion in a TruPrint 1000, we were able to show the advantages of this combination for the processing of highly reflective materials. The outstanding positive effects of green laser radiation on metal welding processes have been transferred to powder bed fusion successfully. The higher absorption rate at the shorter wavelength improves the energy coupling significantly, which is particularly important for the fusion of materials with high heat conduction like pure and low alloy copper, as well as precious metals. As a result, the fusion process becomes more stable, meaning larger process windows and consistently high density values. The higher absorption rate also improves process efficiency and build rate. The material properties of the manufactured parts in pure copper are, to our knowledge, superior to parts manufactured with infrared lasers. For the first time, we can present pure copper parts made by powder bed fusion with a density of 99.9 % and electrical conductivity of 101 % IACS. Build rates of 8 to 16 cm³/h have been demonstrated for Cu ETP and 17 cm³/h for CuCr1Zr. The application of green TruDisk 1020 lasers in powder bed fusion will enable new applications for parts made from an extended range of materials which were not able to be successfully manufactured in the past.

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