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Selective laser melting of pure Cu with a 1 kW single mode fiber laser

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Abstract

Complex geometries and fine critical features enabled by the powder bed fusion technologies are highly appealing for heat exchanger manufacturing. Copper is the main metal of choice for such applications. However, its processability using Selective Laser Melting (SLM) systems is limited by its high reflectivity at 1 µm, the emission wavelength of the laser sources commonly employed. Furthermore, the high conductivity of the pure copper, desirable for the final use of the products, causes instability and difficulties in the powder bed solidification. Resultantly, high density components are difficult to obtain. In this work, a 1 kW single mode fiber laser is used to process pure Cu powder with 99.9% purity. The high power is required to overcome the low efficiency of the process due to the high reflectivity. A prototype SLM machine is employed allowing for a flexible manipulation of the process parameters. The densification phenomenon is discussed as well as the causes that lead to porosity.

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Keywords: Selective laser melting; additive manufacturing; porosity; heat exchangers.

1. Introduction

The increasing diffusion of metal additive manufacturing technologies has been enabled by their capability of proposing innovative solutions and inherent advantages with respect to conventional routes of fabrication. Amongst these novel solutions, Selective Laser Melting (SLM) is one of the processes most widely exploited for the realization of high performance mechanical components and has been employed to deposit a wide variety materials ranging from stainless steels and Nickel based super-alloys and to aluminum and titanium alloys as well as biodegradable materials (1–5).

One of the limitations of the SLM technology is related to the processable material availability, where great challenges remain with regards to the processing of copper and its alloys. The thermal properties of Cu make it highly appealing for heat exchange applications, where the design freedom allowed by AM technologies could improve the performance by the use of internal conformal cooling channels and increased surface to volume ratio. Nonetheless, in literature only a small minority of authors have attempted to process pure Cu by means of SLM(6–8). This is due to the fact that laser based manufacturing of copper and its alloys often results in unstable conditions due to the high reflectivity and high thermal conductivity of the material. In the field of laser welding, a process considered analogous to selective laser melting, problems related to back reflection of the emission radiation and melt pool instability due to rapid dissipation of the incident heat input have often been identified (9,10). As a matter of fact amongst the earliest publications related to the field of selective laser sintering, Shiomi *et al.* showed the first results in the aggregation of Cu powder by the use of a pulsed wave Nd:YAG laser source (11). However, only sintering of the powder bed could be achieved due to the low beam quality factor and low duty cycles of the laser source employed.

Lykov *et al.* attempted at processing pure Cu powder by means of SLM system with a CO_2 laser source but did not achieve relative densities above 90% (6). With the

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implementation of contemporary high brilliance laser fiber sources there is evidence of the SLM processing of copper alloys, by Sabelle *et al.* and Gustmann *et al.*(12,13). Low values of porosity were achieved indicating a high densification of the powder bed yet this is aided by the presence of alloying elements which increase the weldability of such materials. Ikeshoji *et al.* demonstrated the processability of pure Cu achieving a 96.6% relative density value but do not report the influence of power, layer thickness and scanning speed(8).

Amongst innovative solutions to increase further the powder bed densification of pure Cu is the use of blue diode laser source (i.e. emission wavelength at λ=450nm) by Masuno *et al.*(7). The higher absorptivity of pure copper at the emission wavelength certainly allows for an elevated process efficiency, thus leading to a higher process stability. Nonetheless, the authors do not declare the quality of the results although a demonstrator of a geometry was realized indicating an overall elevated process stability.

Another possibility to improve the processability of pure Cu in SLM is to exploit high power single mode fiber lasers. Most of the common SLM systems employ moderate laser power levels between 200 W to 500 W. In the case of pure Cu, the use of higher power levels is required for overcoming the melting point and generating stable processing conditions.

The aim of the present research, therefore, is to assess the capability of a single mode 1kW fiber laser source for the processing of pure Cu powder. The system was installed onto a flexible prototype SLM system and a wide range of experimental parameters (namely power, scan speed and layer thickness) were varied to define the process stability region. A qualitative assessment of the specimen realized was thus conducted, with a phenomenological analysis of the causes that determined the process outcome. It was possible to show that a large process feasibility area is enabled by the implementation of this new laser source. Preliminary analysis of cross-section indicates that high relative density values are achievable and finally a demonstrator workpiece was realized showing the potential of the present technological innovation.

2. Materials and methods

2.1. Pure Cu powder

In the present research, a pure Cu powder (99.9% purity) was employed (LPW Technology, Runcorn, UK) with particle size ranging from 16 to 45 µm. SEM image of the powder employed is shown in Fig. 1.

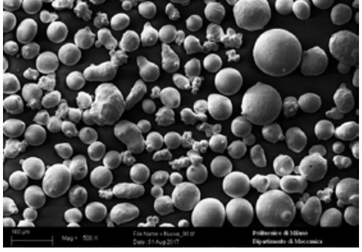

Fig. 1 SEM image of the pure copper powder with 500X magnification

2.2. Open SLM platform

In order to perform the selective laser melting process, an open system, namely Powderful, developed in-house at the Politecnico di Milano was employed. The reconfigurable set up operates under inert Ar atmosphere using an automatic powder delivery system presented in previous publications (3,14). In the current study, a 1kW single-mode fibre laser source (n-Light, Vancouver, WA, USA) was implemented. Beam manipulation occurred with the Smart Scan SH30G-XY2 scanner head (Smart Move GmbH, Garching bei München, Germany), with an optical path which consisted in a 75 mm collimating lens and a 420 mm F-theta focusing lens. Therefore, from theoretical calculations, it was possible to determine the beam diameter on the focal plane, d_0= 78 µm.

Table 1. Principal characteristics of *Powderful*, the in-house developed prototype system for SLM at the Politecnico di Milano

Parameter	Value
Laser emission wavelength, λ [nm]	1070
Max laser power, P_{max} [W]	1000
Beam quality factor, M^2	1.19
Collimating lens, f_c [mm]	75
Focal length F-theta lens, f_{foc} [mm]	420
Nominal beam diameter, d_0 [µm]	78
Build volume (DxWxH), [mm^3]	60x60x20

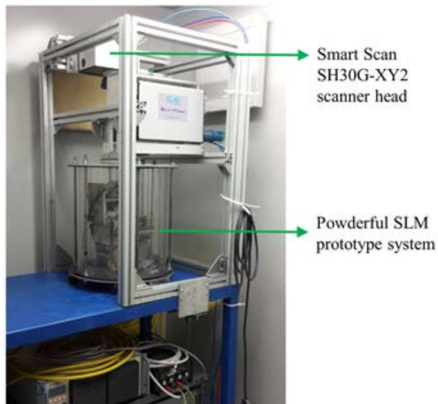

Fig. 2 SLM reconfigurable cell at the Politecnico di Milano. Operating systems employed in the present research are indicated in the image.

2.3. Experimental design

For the determination of the process feasibility region, a set of cubic specimen 5x5x5mm^3 were realised by printing layerwise square cross-sections with 45° hatch rotation between successive depositions. The experimental design consisted in an explorative campaign whereby a wide range of parameters was attempted. Hatch distance was maintained fixed, two levels of layer thickness were varied (i.e. 50 and 100 µm) whereas laser power was varied from 200 to 1000 W and scan speed between 1000 and 4000 mm/s. In total, this resulted in the processing of 70 experimental conditions that were investigated in two successive prints (respectively for the two levels of layer thickness). The substrate material chosen for the present experimentation was AISI 316L, due to its compatibility with pure Cu, as also done by Matsuno *et al.*(7). The list of fixed and varied factors is reported in Table 2.

Table 2. List of fixed and varied parameters in the experimental plan

Fixed factors	**Value**
Process gas	Argon
Substrate material	AISI 316L
Hatch distance, h [μm]	70
Hatch rotation angle, α [°]	45
Variable Factors	**Levels**
Laser power, P [W]	200; 400; 600; 800; 1000
Scan speed, v_{scan} [mm/s]	1000; 1500; 2000; 2500; 3000; 3500; 4000
Layer thickness, z [μm]	50; 100

3. Results

3.1. Qualitative assessment of instability types

In order to evaluate the process window of pure Cu as a function of process parameters, a qualitative assessment of the specimens realised was conducted. Visual analysis of the cubic samples allowed for the classification of the process outcome into three categories:

1. Not fused – refers to the process condition whereby insufficient solidification or sintering of the powder bed occurs, leading to the impossibility of depositing material onto the substrate
2. Delamination – corresponds to the specimens which solidified but nonetheless showed the presence of the delamination defect (i.e. insufficient interlayer bonding)
3. Acceptable – whereby the process resulted being stable and no evident defect could evicted visually (further analysis required in order to validate the goodness of the result)

3.2. Identification of the feasibility window

The results from the qualitative assessment of the process stability conditions are reported graphically in Fig. 3. The red cross indicates the "Not fused" condition, yellow squares indicate the presence of the "delamination" defect whilst the "acceptable" deposition are represented by green triangles. As can be clearly evinced from Fig. 3, the process stability region is notably wider with a 50 μm layer thickness of the powder bed. Considering this aspect and that a smaller layer thickness corresponds to a higher process resolution due to the step stair defect in additive manufacturing, 50 μm can be considered a better compromise in terms of layer thickness.

The "delamination" defect was extensively denotable at both levels of layer thickness, demonstrating the importance of inter-layer bonding in achieving a stable powder bed densification. This phenomenon occurs when low values of power are employed thus implying that the process melt pool is unstable and create a strong interlayer bond (as it is possible to view Fig. 4)

It can be taken into account that the high thermal conductivity of the previously deposited solid layer can generate elevated thermal cooling hindering melt pool stability. If the inter-layer defect is formed, the presence of thermally insulating gas in between layers may be found. If the melt pool is unable to fully penetrate the previous inter-layer defect then the delamination condition may be further worsened by the generation of thermally induced stresses thus leading to part deformations and worsening of the defect formation. This type of defect formation may be linked to melt pool instability conditions which have been denoted during the laser welding of Cu alloys(9).

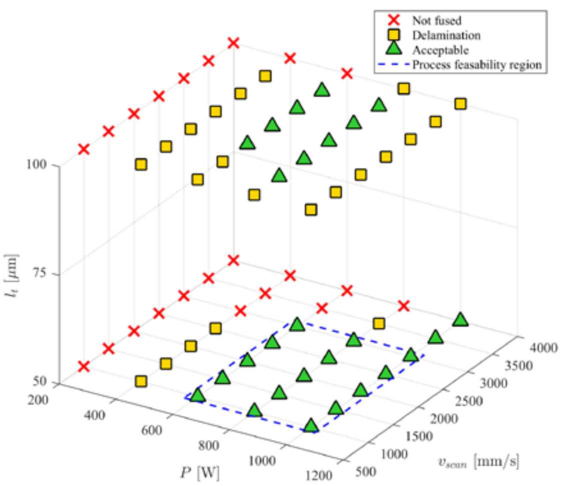

Fig. 3. Qualitative categorisation of process outcome. Feasibility region for SLM of pure Cu indicated by dashed blue line.

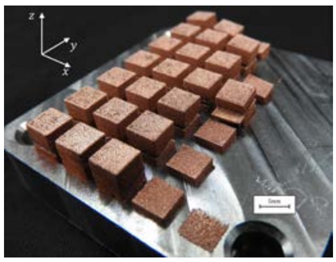

Fig. 4. Build plate realised with a layer thickness of l_t=50 μm. Z-axis indicates the build direction. Decreasing values of power along the X-axis, whilst increasing levels of scanning speed along the Y-axis.

On the other hand, it is possible to denote that for the "acceptable" processing condition (as seen in Fig. 5), major inter-layer defects cannot be identified. Apparent density was evaluated as a function of energy density calculated as

$$E = \frac{P}{v_{scan} \cdot l_c \cdot h} \quad (1)$$

As reported in Fig. 5, the density results yield up to 97.8±0.4% comparable to the values reported by Ikeshoji *et al* (8). The core volume of sections has been measured separately from the border (as seen in Fig. 6). The latter resulted always affected by higher porosity, which can be related to the temperature differences between the central parts and the border of the scanned layer. As modelled also by Saprykin *et al.*(15), during a Cu powder layer scanning, higher temperatures are reached in the most internal region in respect of the border due to thermal accumulation. During the scanning, borders are always in contact on one side with powder belonging to the rest of the powder bed, which is at lower temperature. This, coupled with the high thermal conductivity of the metal, may lead to a strong thermal dissipation producing partial melting and, consequently, higher porosity in these areas. It should be noted that border scan parameters require further investigations, which has not been the principal target of this work.

The resulting amount of density is low for most of the common structural applications. However, the impact of porosity on thermal and electrical properties require further investigations. The present preliminary assessment show promise for future process improvements in terms of part density.

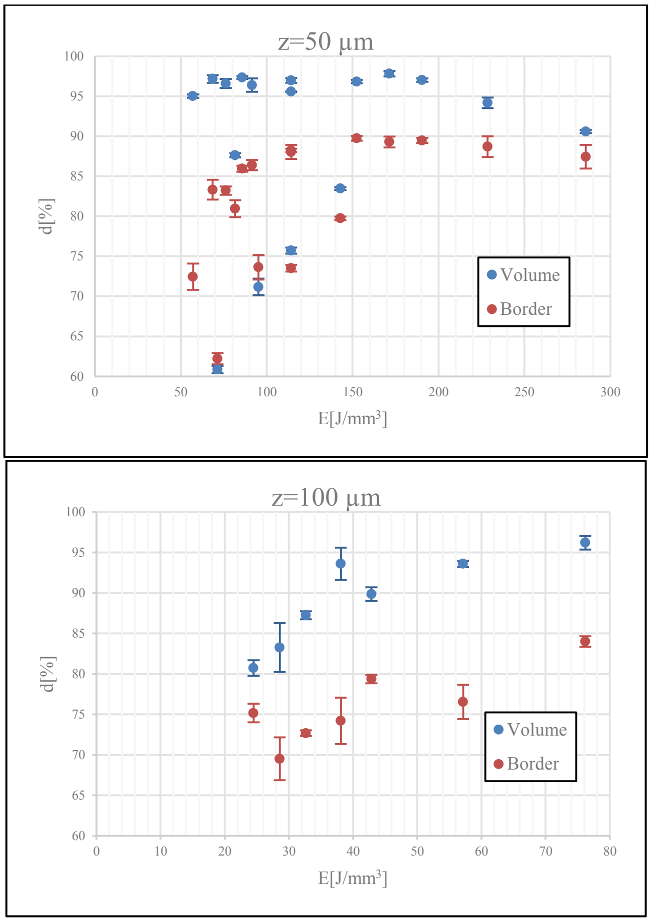

Fig. 5 Apparent density distributions against energy density for "acceptable" conditions

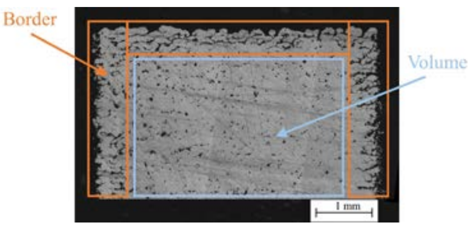

Fig. 6. Cross-section of a cubic specimen representative of the an “acceptable” processing conditions. Process parameters for the specific sample correspond to $P=600$ W, $v_{scan}=1000$ mm/s achieving a relative density of 97.8±0.4%

3.3. Demonstrator of process stability

In order to demonstrate the feasibility of producing complex forms by SLM of pure Cu, a demonstrator piece was realized. The logo of the Politecnico di Milano, using $P=600$ W, $v_{scan}=1000$ mm/s. In Fig. 7, the final demonstrator is shown. The fine details of the logo was realized in an area of 40 mm x 30 mm with a final height of 4 mm. The finest wall thickness obtained was approximately 0.4 mm.

Fig. 7. Final demonstrator of pure Cu powder processability. Macro view (left) and optical microscopy image of the thin walls (right).

4. Conclusions

In this work the processability of pure Cu powders in SLM using a 1 kW single mode fiber laser was assessed. The results imply that the use of 1 μm wavelength is feasible despite the high reflectivity of the material if high power levels are employed. The process stability is achieved around 600 W at high scan speeds, showing that low power, low scan speed combinations which are compatible with conventional SLM systems are not highly suitable for this material.

In this preliminary phase, the process feasibility window was determined. Within the “acceptable” processing conditions high density (>97%) specimens could be produced indicating the effectiveness of the technology in achieving an elevated densification of the powder bed in stable processing conditions. Nonetheless, further investigations are required in order to define the highest achievable value and establish process repeatability. In particular, inter-layer bonding appears to be the cause of defect formation throughout the printing process and more studies regarding the thermal history influence should be conducted. Nonetheless, it is possible to state that results are promising even for the realization of fine features and complex geometries, as shown by the fabrication of the demonstrator piece.

Acknowledgments

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