Chapter

Additive Manufacturing of Pure Copper: Technologies and Applications

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Abstract

The opportunity to process pure copper through additive manufacturing has been widely explored in recent years, both in academic research and for industrial uses. Compared to well-established fabrication routes, the inherent absence of severe design constraints in additive manufacturing enables the creation of sophisticated copper components for applications where excellent electrical and thermal conductivity is paramount. These include electric motor components, heat management systems, heat-treating inductors, and electromagnetic devices. This chapter discusses the main additive manufacturing technologies used to fabricate pure copper products and their achievable properties, drawing attention to the advantages and the challenges they have to face considering the peculiar physical properties of copper. An insight on the topic of recycling of copper powders used in additive manufacturing is also provided. Finally, an overview of the potential areas of application of additively manufactured pure copper components is presented, highlighting the current technological gaps that could be filled by the implementation of additive manufacturing solutions.

Keywords: additive manufacturing, copper, powder bed fusion, green laser, binder jetting, heat exchangers

1. Introduction

Pure copper is one of the most widely employed materials in electronic, electromagnetic, and heat management applications because it combines superior electrical and thermal properties with high workability and solderability [1]. In recent years, the great advances in additive manufacturing (AM) technologies have shown the ability to create tortuous geometries inconceivable with traditional production methods. AM of pure copper has attracted the interest of both academic and industrial researchers because it now enables the fabrication of complex-shaped components, including novel-design antennas, inductors, radiators, and heat exchangers, with improved performance through topology optimization based on the specific requirements of the application considered.

AM technologies for the processing of pure copper can be roughly classified into powder bed-based and direct deposition technologies. In the first case, the powder is gradually deposited in successive layers and selectively consolidated using an energy source or a polymeric binder. At the end of the printing process, the part is surrounded by the unconsolidated powder bed, from which it is extracted for any subsequent processing steps. On the other hand, in direct deposition processes the material feedstock in powder or wire form is deposited according to the targeted geometry by a printing head (e.g., a laser torch) that enables material delivery and provides the heat required for its consolidation. AM of copper has been studied predominantly in the context of powder bed-based technologies rather than direct energy deposition (DED) methods because they provide higher dimensional accuracy and tolerances [2]. This is of major importance when building tiny intricate features, such as curved channels or lattice structures in complex heat exchangers. On the other hand, flexible DED systems, which use a robotic arm equipped with a nozzle for material dispensing, can more easily create multi-material parts with added functionalities, as each material can be conveniently deposited where needed. This would allow the one-step fabrication of components constituted by dissimilar materials, such as copper and steel, which currently can only be made by other routes through repeated joining operations with high costs and long lead times [3].

2. Additive manufacturing technologies for pure copper processing

Various classes of AM technologies have been employed to successfully fabricate pure copper parts. However, significant processing challenges related to the physical properties of copper and the difficulty of achieving full density in the final parts still represent challenging issues that should be thoroughly investigated for these methods to become established.

2.1 Laser powder bed fusion

Laser powder bed fusion (LPBF) is the most established AM technology for the processing of metallic materials [4]. It uses a laser source to selectively melt the powder spread by a roller system to generate a bed of controlled thickness. Once a laser scan is completed, the build platform is lowered by a distance equal to the layer thickness set for the process, and a new layer of powder is deposited. The process is then repeated layer by layer to build the desired geometry based on the designed STL model. All the procedure is carried out in a closed chamber filled with inert gas to avoid material contamination. The typical setup of LPBF is schematically illustrated in **Figure 1**.

A large number of process variables influence the quality of parts produced by LPBF [5]. Fine powders with an average particle size lower than 50 μm are typically employed [6–8] to allow the generation of thin layer thicknesses, leading to improved resolution and reduced staircase effects, which result in a better surface finish. A major role is also played by the characteristics of the laser and how the material interacts with it. Commercial LPBF machines are normally equipped with infrared laser sources with a wavelength of around 1 μm and power up to 500 W [9]. Although the effective absorbance of the powder bed in LPBF is higher than in bulk materials due to the multiple laser reflections induced by the closely spaced powder particles, it hardly exceeds 30% when processing pure copper powders with infrared lasers [10].

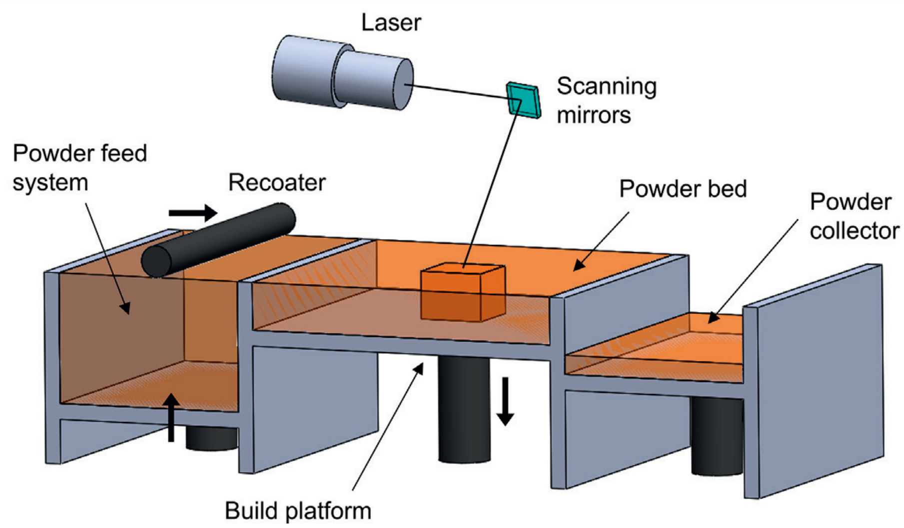

Figure 1.
Schematic layout of the LPBF process.

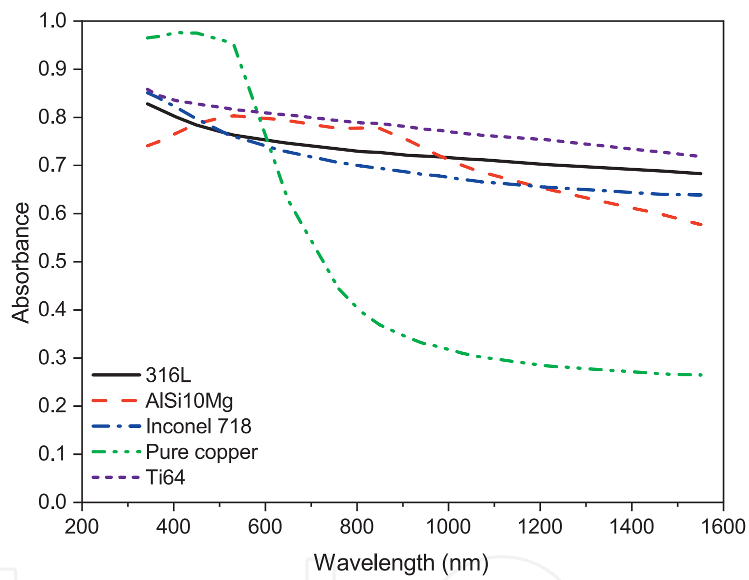

Figure 2.
Absorbance of metal powders in LPBF as a function of laser wavelength. Data extracted from Brandau et al. [10].

This is clearly shown in **Figure 2**, which compares the absorbance of some of the most common metal powders used in LPBF. The poor absorption of the laser energy during the printing process causes incomplete fusion of the powder material. The result is a substantial residual porosity that affects the thermal and electrical performance of the components.

Two main approaches have been adopted to overcome this issue. On the one hand, some researchers [9, 11, 12] have employed high-power infrared lasers combined with low-scanning speeds to ensure complete melting of the powder material despite low absorption. Although relative densities exceeding 99% have been reported, the processing window available for parameter setting is very narrow, and it is difficult to sustain a stable melt track when such high powers are involved, resulting in lower resolution and poor surface finish. Also, the large amount of energy wasted during the printing process leads to high production costs, and the low-scanning speed results in long lead times. The other strategy relies on the use of blue or green lasers with wavelengths of 450 and 515 nm, respectively, for which copper exhibits a higher absorption rate (**Figure 2**). TRUMPF (Germany) recently launched the first series of commercial LPBF machines equipped with a 515 nm wavelength laser for the manufacturing of copper parts [13]. Gruber et al. [14] achieved almost full density and electrical conductivity of 100% IACS in pure copper samples produced with the green laser-based process.

2.2 Electron beam powder bed fusion

Electron beam powder bed fusion (EB-PBF) features a fabrication approach similar to LPBF but uses a high-energy electron beam as the heat source to selectively melt the powder material. The printing process is conducted inside a high-vacuum chamber to prevent electrons from scattering by collision with gas molecules. A schematic representation of the machine setup is illustrated in **Figure 3**.

Although its use has been limited to date due to a relatively lower number of systems available in industrial and academic research centers, the main advantage of EB-PBF for the processing of pure copper, as compared to its laser-based counterpart, is that the energy absorbed from the incident electrons is not affected by the optical reflectivity of the target material. This leads to highly efficient energy transfer during the printing operation (a rate of absorption of around 80% is estimated [15]). In addition, the high-vacuum environment protects the material from oxidation, ensuring high purity of the final parts.

One well-known issue of EB-PBF is the so-called smoking. Due to the incident electrons, a negative charge tends to accumulate at the surface of particles in the powder bed. The mutual repulsion among neighboring particles may cause them to suddenly jump from the powder bed, generating a cloud of powder inside the work chamber, which may impair the smooth processing of the material [16, 17]. Smoking is not a primary issue in the case of pure copper since its high electrical conductivity can prevent the buildup of a strong negative charge. Still, slightly coarser powders than in LPBF are generally used (in the range of 60–105 μm [15, 18, 19]) because they have a lower tendency to smoking compared to fine powders [17]. Also, each powder

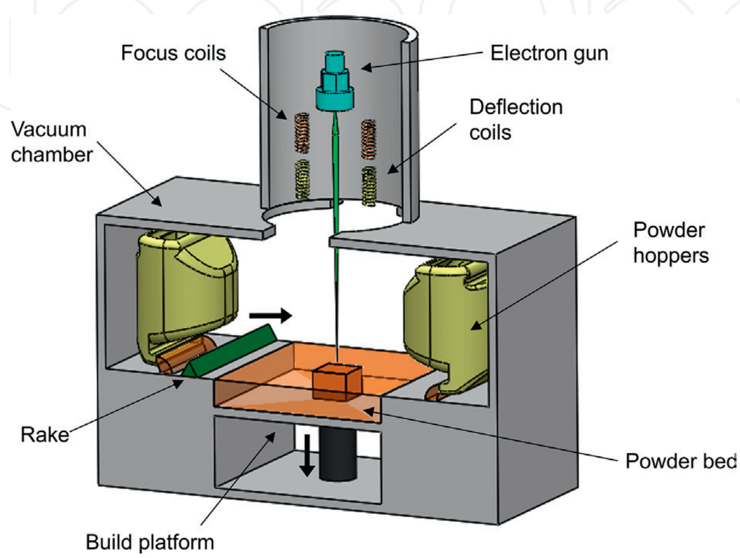

Figure 3.
Schematic layout of the EB-PBF process.

layer is preheated around 400–500°C [18] and partially sintered by the beam itself before the actual scanning operation to provide an even improved electrical connection for electrostatic charge dissipation. One difficulty that arises from the high temperatures at which the deposited material is maintained is that copper particles tend to stick together during the raking operation owing to their high propensity to sinter. Particle clusters may impede the correct deposition of the following powder layers, possibly causing interlayer defects. Also, particles that are partially sintered on the external surface of the as-print parts generate a relatively high surface roughness [18]. The electron beam has a relatively large spot size of about 0.5 mm [20], while beams 30–100 μm in diameter are typically used in LPBF [21]. This restricts the capability of EB-PBF of producing minute details in complex parts, which is a nontrivial limitation, for example, in the fabrication of sophisticated heat exchangers made with pure copper. However, higher production rates can be achieved compared to LPBF because preheating, combined with the more effective energy input, ensures complete powder melting even when selecting high beam scanning speeds during the printing process [19].

Few studies [15, 18, 22] have been conducted so far to identify the main variables that affect the quality and reliability of pure copper parts produced by EB-PBF with commercial machines. Feedstock quality, preheating temperature, beam focal point, and scanning strategy are among the parameters that need to be optimized to ensure a robust production with consistent characteristics across runs. Guschlbauer et al. [15] obtained pure copper specimens with a relative density above 99.5% by conveniently combining the beam power and the scanning speed within the ranges 275–750 W and 250–1500 mm/s, respectively.

2.3 Binder jetting

Binder jetting shares with PBF technologies the powder bed strategy for the creation of three-dimensional parts. However, during the printing process, the powder particles are glued together by water- or solvent-based polymeric binder selectively deposited by a print head instead of being melted by a high-energy beam. A curing treatment at moderate temperature is then applied to eliminate the volatile fraction of the binder and induce polymerization. The reticulated polymer provides the green part with sufficient strength to be removed from the unbound powder bed without breaking. The part is finally subjected to a debinding and sintering cycle to burn off the polymer fraction and densify the material by diffusion-assisted mechanisms promoted by the high temperature. Although there exist several sintering strategies for both metallic and ceramic materials, which may involve for instance the formation of a liquid phase to facilitate interparticle bonding, in the case of pure copper densification is achieved by solid-state diffusion only because no low-melting second phases are present. As-sintered parts normally possess a relatively high surface roughness, especially on vertical surfaces due to the effect of the distinct powder layers they are made of [23]. Postprocessing operations involving vibratory abrasion and chemical treatments [24] may be required to achieve a good surface finish in components with complex geometry and internal features. The flowchart of the binder jetting process is illustrated in **Figure 4**.

Feedstock powders with an average size exceeding 20 μm are normally preferred in binder jetting because their relatively low tendency to agglomerate facilitates the spreading operation [25]. However, the development of vibrating devices for powder sieving and dispensing has enabled the use of finer powders with an average size

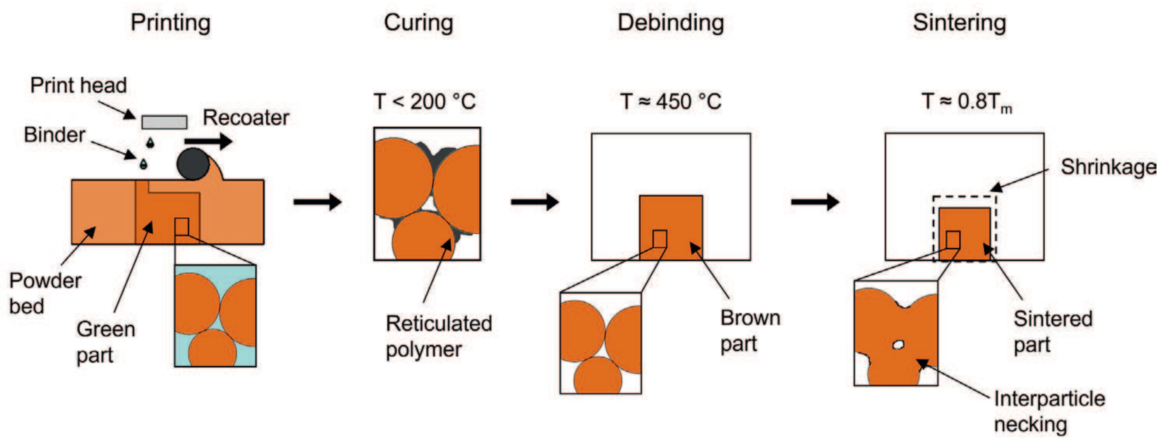

Figure 4.
Schematic flowchart of the binder jetting process.

lower than 5 μm [26, 27] for improved resolution and densification. Bimodal mixtures also showed the potential to improve powder flowability and reduce part shrinkage upon sintering, because particles with different sizes can tightly pack and result in high green part density [28].

The peculiar feature of binder jetting compared to the above-described PBF technologies is that the generation of the three-dimensional geometry and the bonding between powder particles occur in two distinct stages. In addition to those already mentioned, one challenge LPBF faces in processing pure copper is related to its high thermal conductivity. The heat provided by the energy source is rapidly dissipated by the surrounding material. This may cause poor interlayer adhesion and lead to delamination defects in the produced part. Binder jetting does not suffer from this phenomenon, because the material is homogeneously heated in a controlled environment by applying a proper sintering cycle.

Investigation on binder jetting of pure copper showed that the primary challenges consist of attaining complete density and high purity in the sintered parts. The powder particles in the green parts have a low tendency to sinter because they are covered by a low surface energy oxide layer and are not tightly compacted by the recoater during the printing process. Both the surface oxide layer and the large interparticle distance hamper neck formation and growth between neighboring powder particles by solid-state diffusion [25, 29]. In addition, carbon residues may result from incomplete combustion of the polymeric binder during the debinding stage [27], and uneven sintering may occur between the outer and the core regions of the parts due to temperature gradients along the material thickness. Indeed, the rapid stiffening of the outer zones exposed to a higher temperature may hinder inward shrinkage, thus leaving a central volume with a high residual porosity [27]. Therefore, the sintering parameters need to be carefully adjusted in terms of sintering atmosphere, heating ramp, peak temperature, and sintering time to minimize the residual porosity and carbon impurities, which adversely affect the mechanical, thermal, and electrical properties of the final parts [30, 31].

From a design perspective, binder jetting does not require support structures for overhanging features, because the powder bed itself serves as a support. In addition, several parts can be stacked in the vertical direction, allowing the entire volume of the working chamber to be utilized to print large series of parts [32, 33] that can then all be sintered in a single furnace cycle. However, the possible effects of creep activated by the prolonged exposure to high temperatures during sintering need to be taken into account to avoid undesirable deformations of cantilever elements in the final components [34]. In addition, parts shrink as a result of densification. Because back-to-back powder layers are not well consolidated due to limited binder penetration, a larger amount of porosity is observed among them than within individual layers. This causes a larger shrinkage along the build direction than in the lateral directions upon sintering, which is further accentuated by gravity effects [29]. Therefore, a careful design is needed to compensate for these differential changes in the part dimensions upon sintering.

2.4 Laser metal deposition

Laser metal deposition (LMD) belongs to the family of DED processes. It utilizes a coaxial nozzle equipped with a laser source to melt the feedstock material, while it is simultaneously deposited in a series of weld tracks to generate the designed three-dimensional geometry. A carrier gas transports the powder through the outermost annular channel to the melting zone, while a shielding gas is used to avoid excessive oxygen pickup by the melt pool. The use of copper powders with size ranging from 30 to 110 μm have been reported in the literature [35–38]. The setup of the LMD process is schematically illustrated in **Figure 5**.

The main advantages of LMD over powder bed-based technologies are the high productivity and flexibility, the ability to work without closed chambers with protected environment, and the possibility to add features to the existing part. Also, machining tools can be integrated into the printing system to enable hybrid manufacturing [39]. The multi-axis configuration allows the construction of three-dimensional elements even on non-flat surfaces.

LMD is not commonly employed to fabricate individual components from pure copper because it cannot provide the dimensional accuracy and resolution usually required for its typical applications (e.g., heat exchangers, inductors, and electromagnetic devices). In addition, the shielding gas can only partially prevent oxidation [39]. Oxides reduce the wettability of molten copper on solid surfaces [40], leading to poor adhesion between the substrate and the built features.

A great impetus to LMD of pure copper has been given by the recent introduction of green and blue laser sources, for which copper displays a relatively high absorptivity.

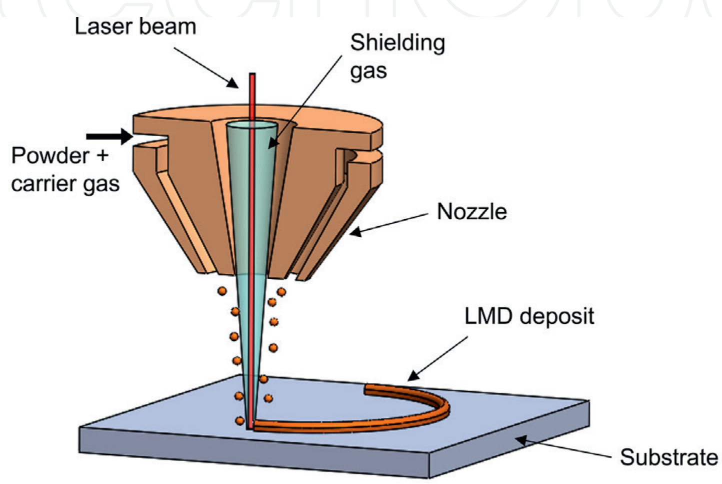

Figure 5.
Schematic layout of the LMD process.

Higher process control can thus be achieved and lower powers are required compared to conventional infrared lasers, ranging from 200 W to 1 kW for green laser sources depending on the physical properties of the substrate material [41] and lower than 87 W for blue diode lasers [35, 36]. However, the real strength of LMD compared to powder-bed technologies is that it enables the relatively easy fabrication of multi-material parts. In principle, different materials can be conveniently placed at specific locations by simply replacing and/or mixing the powder fed during the building process. Therefore, properties such as hardness, thermal and electrical conductivity, or corrosion resistance can be fine-tuned throughout a single component by conveniently customizing its constituent materials.

Copper has been investigated in the context of multi-material LMD mainly in combination with steel. The coupling of copper and tool steels has been proposed to fabricate molds and dies with improved cooling efficiency due to the high thermal conductivity of the copper portion [37, 42]. The more uniform and faster heat extraction would increase both the quality of the formed parts and the productivity. Multi-materials based on copper and stainless steel, on the other hand, may find use in highly demanding applications such as fusion reactors and high-field pulsed magnets [43]. However, the manufacturing of such structures still has to face significant challenges due to the discrepancy in laser absorption, thermal conduction, and thermal expansion behavior between copper and steel and their poor mutual solubility.

3. Recycling of pure copper powders in additive manufacturing

High flowability and chemistry control are key requirements for metallic powders for AM. Gas atomization is normally employed to produce powders for AM, because it can provide higher sphericity, smoother surface morphology, and tighter control of the particle size distribution and the chemical composition, particularly in terms of oxygen content, compared to other processes such as water atomization [44]. Pure copper powders for AM are generally produced from oxygen-free electronic (OFE), oxygen-free, and electrolytic tough pitch (ETP) grades to provide feedstocks with low impurity content despite the tendency to oxidation caused by the large surface area of the fine powder particles [1, 45].

Both the use of high-purity raw materials and the complexity of the gas atomization process result in rather expensive powder feedstocks. While LMD can achieve high material utilization efficiency with optimized process parameters [46], in PBF and binder jetting, most of the powder is used to generate the powder bed. It is a common procedure to collect, sieve, and reuse the excess of feedstock material that is not consolidated during the building process in order to minimize material waste and keep manufacturing costs low. Also, the practice of powder recycling improves the environmental profile of these processes, since gas atomization is a very energy- and material-intensive process [47]. Nevertheless, the powder is normally discarded after a certain number of cycles as it is subjected to various degradation phenomena, depending on the nature of the AM process, which can severely affect the quality of the produced parts. This is particularly critical for materials that are sensitive to oxidation and are used in applications that impose stringent limits on the impurity content, such as pure copper for thermal management and electrical applications.

The complex combination of factors involved in PBF processes can severely affect the quality of copper powders collected after several printing cycles compared to the virgin material. Oxygen pickup occurs due to residual oxygen and moisture in the work chamber and during part recovery at the end of the printing process [48] when the atmosphere control is turned off. As a result, the thickness of the oxide layer that naturally covers the surface of copper powder particles increases significantly [49]. Surface oxides are not easily removed during the fabrication process and may be incorporated into the final parts, affecting their mechanical, thermal, and electrical performance. Hence the need to reduce the oxygen content of the powder before reuse, typically by heating it in a reducing environment containing forming gas [20]. Speidel et al. [50] have proposed a less expensive and more readily scalable method for treating heavily oxidized copper powders for LPBF, based on chemical etching with a dilute solution of nitric acid.

In binder jetting, the powder in the bed is further subjected to oxidation during the curing stage [27], which is normally carried out in the air. In the case of copper, oxidation is additionally promoted when a water-based binder is employed, as copper is highly sensitive to moisture. Binder splashes may generate massive particle agglomerates in the regions of the powder bed next to the boundaries of the printed parts [51]. Also, the powder particles that remain sticked on the surface of cured parts are usually removed with pressurized air. The applied pressure may deform the highly ductile copper particles [52], reducing their sphericity [51]. However, such particles account for a minimal fraction of the total powder collected at the end of a printing cycle and should not affect the overall powder flowability in the next runs. In **Figure 6**, a comparison between fresh copper powder and the feedstock to be recycled after binder jetting is proposed. No significant morphological differences are observed between the two powder batches.

Sieving is normally conducted to break particle conglomerates and eliminate coarsened and partially sintered particles. However, a significant fraction of fine particles may escape the sieve and is lost by dispersion into the air [51]. This may lead to a nonnegligible shift in the median diameter toward higher values and narrower size distribution, as finer particles are preferentially removed from the feedstock. Therefore, the effect of sieving on powder granulometry should be considered when employing recycled powders in AM. In PBF, processing parameters should be adjusted to account for the varying powder bed density from one cycle to next. In binder jetting, a coarser and narrower powder size distribution results in lower green part density and, consequently, higher shrinkage upon sintering for the same final density. In addition, a higher sintering temperature may be required to attain satisfactory densities, because coarse powder particles have a lower tendency to sinter due to the reduced surface area compared to fine particles [26].

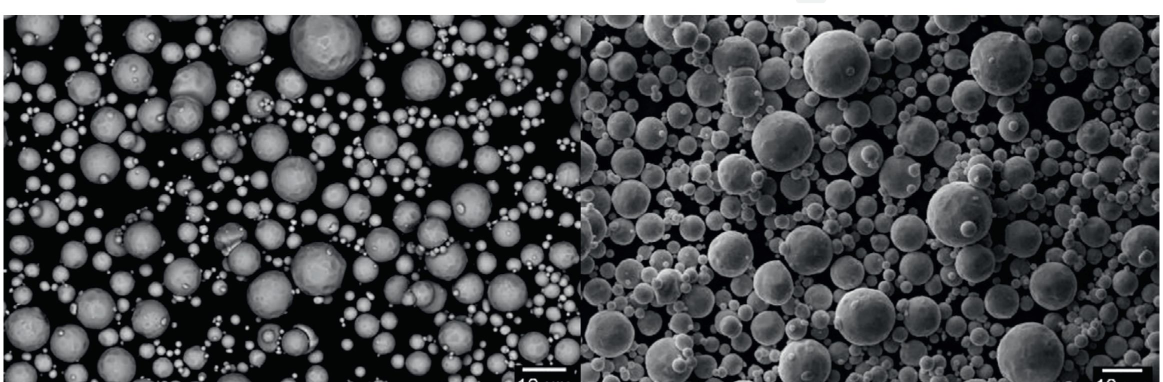

Figure 6.
Copper powder in as-received conditions (left) and collected from the powder bed after binder jetting (right).

4. Applications of additively manufactured pure copper components

In recent years, AM processes have been applied to pure copper, particularly for the manufacturing of high-added-value components for advanced applications in various fields that require excellent thermal and electrical performances. The main barrier to the large-scale adoption of these technologies in the industry is the limited availability of regulations covering the different aspects of AM, including raw material quality, design guidelines, fabrication and postprocessing techniques, material testing, and inspection of the final components. This obliges companies to make considerable efforts in terms of investigation and testing to qualify and certify AM products prior to market launch, which may result in extremely high costs and long lead times [53]. In addition, compared to traditional fabrication methods, AM processes often exhibit poor repeatability and reproducibility [54, 55], and the relationship between manufacturing route, material characteristics, and final product quality still needs to be thoroughly explored [53].

While some standards have already been developed for the AM of metallic materials such as stainless steels and nickel- and titanium-based alloys [53], AM of copper is still in its infancy and is not yet targeted for standardization. However, several examples of additively manufacturing components made of pure copper have already been reported in the literature and in public technical expositions.

4.1 Automotive components

Copper and copper alloys are widely used in the automotive industry to manufacture a variety of vehicle parts, such as electric motor components, ABS and power lock pumps, water and oil coolers, radiators, and heat exchangers for air conditioning [56]. The use of copper in this sector has significantly increased in the past few years with the spread of hybrid and electric vehicles [57].

Pure copper windings and rotors play a key role in the performance of electric motors. Proper winding design optimization can reduce AC and DC loss. However, this is restricted by the limited capability of established manufacturing methods of producing complex geometries with reasonable costs and lead times. Maxwell Motors, a startup based in the USA, recently developed a novel copper winding design to improve the performance of an electric motor that does not use rare-earth-based magnets. They jointly developed and manufactured with ExOne (USA) a monolithic winding assembly by binder jetting, hence obviating the usual steps of manufacturing and welding the individual parts [58]. The same approach can be extended to the fabrication of customized shanks and adaptors for car chassis welding [59].

4.2 Thermal management devices

The high thermal conductivity of pure copper makes it the ideal material for heat dissipation purposes in numerous fields including microelectronics, power plants, and transport. Topological optimization can improve the performance of thermal management devices by maximizing the efficiency of heat transfer. This can be achieved through AM, for instance by building intricate features or even lattice structures with very large specific surface area available for heat exchange [60].

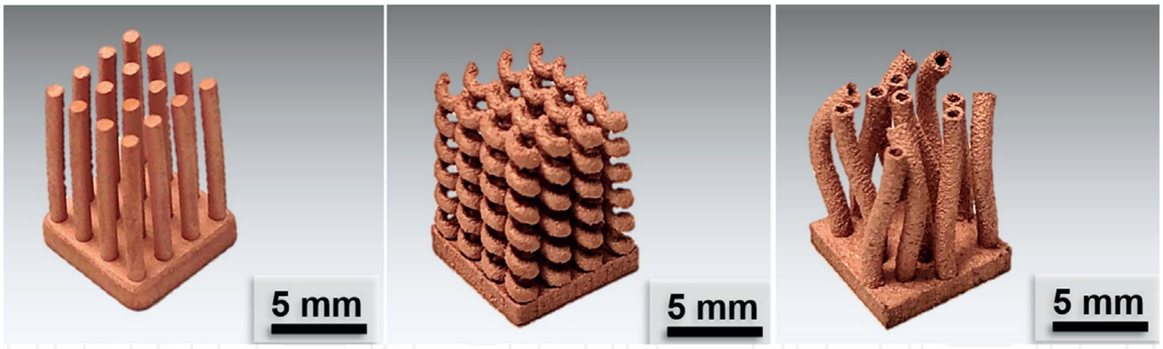

Figure 7.
Columnar (left), helix (center), and bent tube (right) pure copper heat sinks. Adapted from [8].

Constantin et al. [8] fabricated complex-shaped heat sinks consisting of helix and bent-tube structures through LPBF (**Figure 7**). They developed a special experimental setup to evaluate the performance of the additively manufactured heat sinks in comparison with a commercial device featuring a straight columnar structure. Each heat sink was connected to a memory card chip placed on a heater plate and air circulation was provided by a fan. The helix and bent-tube heat sinks exhibited a higher cooling efficiency owing to their larger surface area compared to the commercial device.

Various companies have showcased prototypes of pure copper cooling plates and heat exchangers featuring minute details and mesh structures made by PBF and BJ technologies with optimized processing parameters [61–64].

4.3 Electrical and electromagnetic devices

Due to its remarkable physical properties, pure copper is the preferred material for the fabrication of electrical and electromagnetic devices.

Copper is commonly employed to produce inductors for heat treatments and other hot processes, enabling highly controlled and localized heat delivery to the parts. The shape and size of the coils can be tuned to meet the heat treatment specifications and ensure adequate productivity [65]. Copper inductors are conventionally made by hand-wrapping copper wires on blueprints. Then, individual coils are brazed to match the geometry of the workpiece. This manufacturing route is time-consuming and requires highly skilled labor, resulting in high production costs. Also, the devices have relatively low durability, due to the discontinuities at the brazing joints [66]. On the other hand, monolithic inductors with homogeneous properties could be directly fabricated by AM, resulting in increased productivity and service life. Silbernagel et al. [6] also demonstrated that the cross-section of coils made by LPBF can be conveniently varied to locally control the electrical resistivity. Such inductors may be used in treatments featuring a complex thermal profile or applied to components with variable wall thickness. Hollow structures for cooling fluid circulation can also be produced for applications where particularly high cooling efficiency is required.

The flexibility of AM processes also enables the one-step manufacturing of sophisticated antennas with tunable electromagnetic properties. This would avoid issues, such as uncontrolled shifts in the operating frequency band, which may be caused by imperfect alignment when soldering different pieces. Johnson et al. [67]

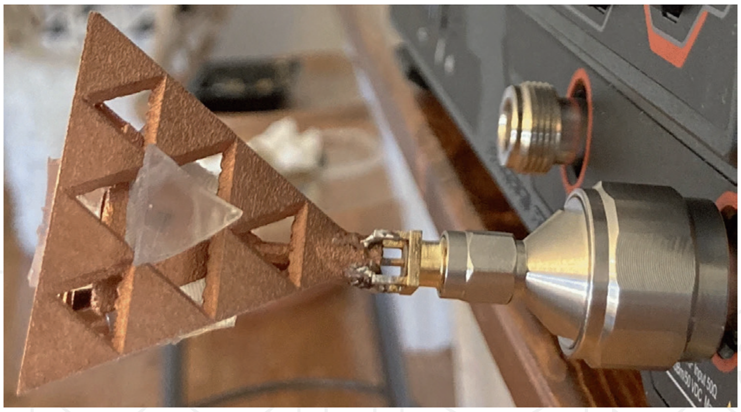

Figure 8.
Pure copper pyramidal fractal antenna made by green laser-based PBF [67].

fabricated a copper pyramidal fractal antenna with an LPBF system equipped with a green laser (**Figure 8**). The radio frequency (RF) performance of the antenna was evaluated with a spectrum analyzer and it was found to be in good agreement with the results of simulations. A novel-design bullhorn antenna made of pure copper has also been manufactured with the high-precision binder jetting technology developed by Digital Metal (Sweden) [64].

4.4 Particle accelerator components

The manufacturing of vacuum devices and particle accelerator components made of pure copper can also benefit from the AM's inherent design freedom and capability of one-step fabrication. Although the market size might appear limited, the sophisticated technologies involved in this sector represent an extremely important test bench for AM development. The layer-by-layer approach of AM technologies facilitates the creation of enclosed envelopes in RF cavities, eliminating the need for sophisticated techniques and highly specialized labor for the assembly of individual parts [66]. This was demonstrated by Mayerhofer et al. [68], who manufactured a monolithic copper RF cavity for a linear accelerator prototype using LPBF. Although the additively manufactured cavity exhibited a slightly lower performance compared to the reference cavity fabricated with conventional methods, the production costs were reduced to a third. Internal channels and lattice structures can also be implemented in RF devices to improve their cooling efficiency, hence eliminating current limitations on the duty cycle and average power [66, 69].

Frigola et al. [69] fabricated a pure copper cathode by EB-PBF and tested it in a RF photoinjector. The performance of the additively manufactured cathode was in line with that of conventionally machined cathodes and it could be further improved by integrating internal cooling channels for liquid helium circulation. Within the frame of the I.FAST project [70], aimed at boosting innovation in the field of particle accelerators, Torims et al. [71] prototyped the quarter sector of a pure copper radio frequency quadrupole (RFQ) by green laser-based LPBF (**Figure 9**). They demonstrated the possibility of rapid manufacturing, avoidance of brazing operations, and improved cooling efficiency offered by AM compared to more restrictive conventional production methods. A full-size four-vane RFQ prototype (**Figure 10**) was recently presented at the 13th International Particle Accelerator Conference (IPAC22) [72].

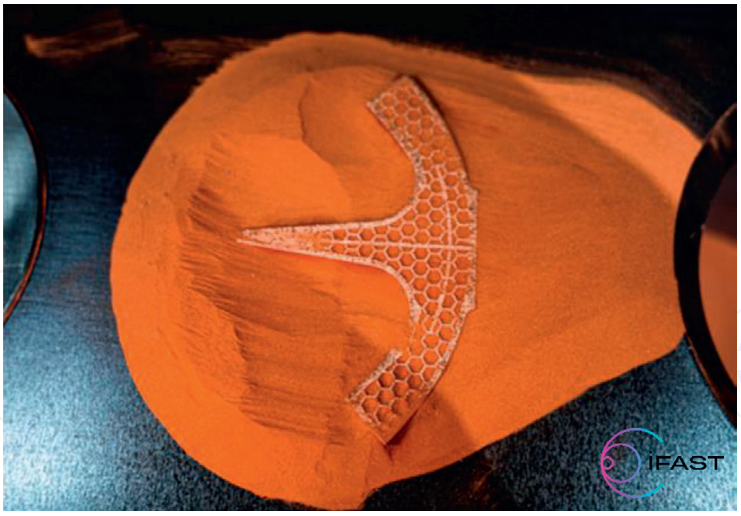

Figure 9.
Manufacturing of a pure copper RFQ section by LPBF with a green laser source [71].

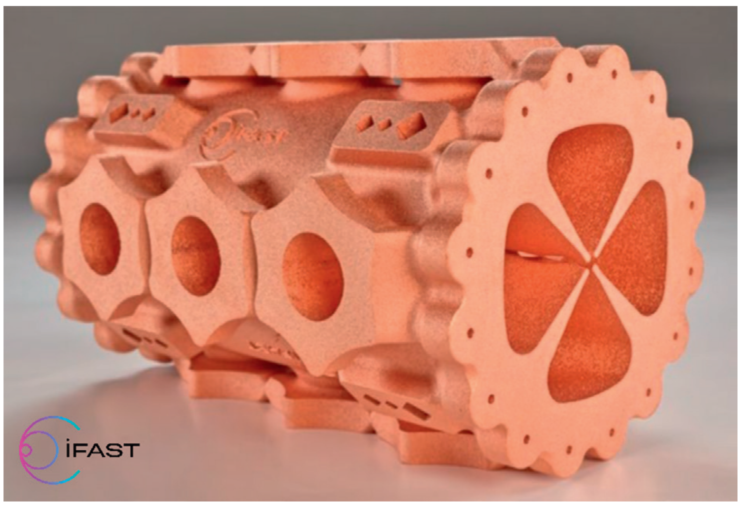

Figure 10.
Additively manufactured pure copper RFQ [72].

5. Conclusion

Additive manufacturing of pure copper has been extensively investigated in the last decade because it has the potential to create complex components with improved thermal and electrical performance. Within this perspective, the component topology can be optimized according to specific needs and requirements, instead of being dictated by the technological constraints imposed by conventional manufacturing methods.

Pure copper has historically been a challenging material to be processed by additive manufacturing. The high reflectivity of pure copper makes the more established laser-based processes difficult to control and energy inefficient. On the other hand, when using an electron beam energy source, high resolution and dimensional accuracy can hardly be achieved due to the relatively large beam spot size and the tendency of copper powder particles to stick on the consolidated surfaces. Binder jetting has also exhibited some drawbacks related to the difficulty in accomplishing adequate density and material purity after sintering.

In the past few years, however, additive manufacturing technologies have made significant progress in the context of pure copper processing. More reliable processes have been developed by optimizing the operating parameters, such as power input, scanning strategy, or sintering setup. In addition, novel robust green and blue laser sources have recently been introduced, for which copper exhibits higher absorption rates. They are expected to extend the stability window for the processing of pure copper so as to create high-quality products competitive with their counterparts produced by more conventional routes.

Several companies and research groups have already showcased a variety of additively manufactured prototypes made of pure copper. These include complex high-added-value components such as heat exchangers, inductors, electromagnetic devices, and motor windings with optimized geometry and tailored functional characteristics. However, the full potential of additive manufacturing still needs to be explored for these methods to truly become an integral part of the industrial supply chain.

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Conflict of interest

The authors declare no conflict of interest.

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