Additively Manufactured Copper Components and Composite Structures for Thermal Management Applications

F. Singer, D. C. Deisenroth, D. M. Hymas, S. V. Dessiatoun, and M. M. Ohadi
Smart and Small Thermal Systems Laboratory
Department of Mechanical Engineering
University of Maryland
College Park, MD 20742
Email: fsinger@umd.edu

ABSTRACT

Recently additive manufacturing (AM) has brought significant innovation to thermal management devices and electronics. Among the most influential innovations are additively manufactured copper/copper alloy components and composites that benefit from the superior thermal, electrical and structural properties of the material. Cu is widely used in electronics, HVACR, radiators, charge air coolers, brazed plate heat exchangers, and oil cooling. Ongoing research is extensively studying, in parallel, Cu properties/characteristics and the different AM process parameters required to enhance the quality of the manufactured Cu components and to optimize their performance/applications. In this paper, we report various AM techniques and AM-based hybrid processes used to produce high-density Cu components. Selective heat exchanger/thermal management applications progress is also reviewed. It is then shown that additively manufactured, dense Cu can generate low mass structures and polymer/metal composites that promise to revolutionize developments in thermal management applications. Studies on the effect of the material properties such as the Cu particle morphology and size distribution are also reported. The major studies that report using Cu to address the challenges of electronics fabrication and cooling, which directly affect system-level performance and reliability, are also discussed. A novel AM process that facilitates microchannel cooling with Cu structures and new processes that allow embedding copper wires into thermoplastic dielectric structures are discussed to further emphasize the potentially transformative advances in additively manufactured electronics and thermal management devices using Cu/Cu alloy composites.

KEY WORDS: Additive Manufacturing, Copper, Thermal Management, Electronics, Composite Structures, Embedded Structures.

INTRODUCTION

Additive manufacturing (AM), as referred by ASTM F2792, is the official industry standard name of all applications of the technology defined as the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies [1]. Most common synonyms of AM are 3D-printing and freeform fabrication.

AM first emerged as a novel technology with applications limited to design and modeling, fit, and function prototyping. Within the last two decades, AM has been developed to create functional parts without the dedicated tooling and high costs of conventional fabrication techniques [2]. As AM changed the way parts are designed and manufactured, end use products came into the view, supported with extensive ongoing research and investigation [3]. With manufactured components spanning the different commercial, industrial, medical, and thermal domains, AM is revolutionizing fabrication concepts and capabilities and creating an immense range of applications that were once bound by conventional and traditional manufacturing techniques [4].

The pace of the developments in AM technology is increasing each year, and limitations of the process and the materials used are being overcome, and eliminated in some cases [5,6]. Until few years ago, AM of copper and its alloys was considered as one of the major limitations of metal AM. The superior properties of copper such as its high thermal and electrical conductivities make it a preferred material for thermal and electrical applications. However, several properties of pure copper cause processing challenges for direct metal AM. Mainly, the high thermal conductivity of pure copper (401 $W.m^{-1}.K^{-1}$ at 300 K) which, while ideal for thermal management applications, rapidly conducts heat away from the melt area, resulting in local thermal gradients, which lead to layer curling, delamination, and ultimately, build and part failure. On the other hand, copper's high ductility hinders post-build powder removal and recovery. Particles also tend to agglomerate, reducing overall flowability and impeding powder deposition. The sensitivity of Cu to oxidation requires care in handling and storage before, during, and after part fabrication. In most cases, the low laser absorption has hindered the ability of metal AM process to provide the required energy input to successfully print Cu components [7,8], which has prevented much progress in different applications, especially thermal management and electronics technologies, the focus of our paper.

To benefit from AM capabilities, researchers have been investigating its use in 3D electronics fabrication since 1998 [9, 10]. The first attempts used stereolithography (SL), a vat photopolymerization technology [11-15], while other attempts used Fused Deposition Modeling (FDM) with aerosol-sprayed conductors [16-17]. The shortcomings of these processes such as the limited types of materials and the maximum temperature of the thermoplastics hinders the fabrication of high-power and high frequency substrates. These limitations, and the rising need to produce functional circuits, electronics, and energized devices of high-performance and superior electrical, thermal, and mechanical properties, directed the R&D focus towards more reliable materials, and AM processes capable of integrating discrete materials during fabrication [18,19]. Additively manufacturing copper, which is a preferable material when it comes to electronics and electronic cooling [20], is an important development in AM that opens the door to new possibilities.

The use of AM in different thermal management and heat exchange applications has attracted attention in the past years, and increasing numbers of research projects and funding dollars are being recorded each year [21-30]. The ability of AM to fabricate complex geometries is driving scientists to design geometries that will ensure an optimized performance. Major breakthroughs are being recorded by teams developing AM processes beyond their previous limits and additively manufacturing thermal management devices and heat exchange components [21-25]. For example, Arie et al. [21] used direct metal powder bed fusion to fabricate a manifold-microchannel titanium heat exchanger, which would be impossible to fabricate using conventional methods. The performance of this HX was experimentally demonstrated to be superior to conventional HXs [21]. Arie et al. [22] also investigated the capability of AM to fabricate a polymer HX and showed through experimental testing the excellent performance of this HX due to the optimized design/geometry, which overcame the limitation of the low thermal conductivity of polymer [22].

In parallel to all these advancements, and since Cu remains the preferred material for thermal transfer, extensive research has been conducted to overcome all the limitations of its 3D printing.

In this paper we report some of the most successful AM methods in printing Cu/Cu alloys, Cu composites, and embedded components for thermal management, electronics and electronic cooling applications.

I. Additive Manufacturing of Cu/Cu alloys

The growing interest in AM of copper and copper alloys [33-35] rises from the need of various applications for optimized cooling and thermal performance. Different groups have addressed the challenges of Cu 3D printing by either studying the process parameters, or by investigating the effect of the powder/material characteristics. In this section, we report some of the most critical studies, which set a base for future Cu 3D printing.

Thermal management devices

One of the significant achievements of AM of copper has been recently announced by 3T RPD® [36], a market leading production AM company. 3T RPD® manufactures metal and plastic parts for end usage and prototypes. The R&D team at 3T RPD claimed to have successfully additively manufactured the first pure copper component, a concept HX shown in Fig. 1, using Direct Metal Laser Sintering (DMLS) [37]. DMLS had proven viable before to produce copper alloy components and products but never a pure copper part, mainly due to copper's reflectivity. To enable the printing of pure copper the team claimed to have modified the DMLS machine and to have accurately calibrated the parameter set, in addition to modifying the approach of creating the support structures to overcome the challenges imposed by the soft nature of copper compared to harder metals such as titanium. Details of these modifications were not published or specified, but the team claims to proceed in refining the process to optimize the surface finish, and material properties and to advance the capability to a fully functional, production-ready material [37].

Fig. 1: 3T RPD® pure Cu concept heat exchanger fabricated by 3T using DMLS [37].

Until 2011, it was not possible to use the Selective Lase Melting (SLM) method to fabricate copper alloys. However, researchers at the Fraunhofer Institute for Laser Technology ILT [38] have modified the process to solve the technical problems. SLM enables manufacturing of complex shaped components which would be produced with conventional technology only at the highest cost or even not at all. The research team at Fraunhofer ILT in Aachen showed for the first time the successful modification of the SLM process to become suitable for copper materials [39, 40]. With the high thermal conductivity of Cu and Cu alloys, their inability to absorb the laser light, and their high heat dissipation, it was not yet possible to apply SLM to these materials. The SLM modifications included using a uniform beam profile laser with 1000-W power instead of the 200-W laser, which is the standard in SLM. This compensated for the high heat dissipation and the low absorption rate of the copper during melting. Hovadur K220 (a copper-nickel-silicium alloy) showed excellent results, and the team successfully printed tool inserts with internally located cooling structures that were almost 100 percent dense, as shown in Fig. 2 [39,40], which deems the process ready for industrial use. This advancement opens the door for various applications, such as cooling semiconductor components, and enables the quick cooling of hot spots, thus reducing the cycle time and any minimizing warpage.

Fig. 2: Tool inserts with internal cooling structures made from Hovadur K220 by SLM [39,40].

The aerospace industry has always been a major explorer of AM processes and capabilities. NASA is one of the leaders in additively manufacturing parts and components for aerospace. Among the "milestones" that NASA has achieved in this field was successfully building the first full-scale, copper rocket part with AM techniques. The engines used to provide the thrust that powers rockets are composed of many complex parts made of various materials. For this reason, NASA is pushing the limits of AM to fabricate some of these parts and to benefit from the potential of reduced time and cost. NASA's Marshall Space Flight Center in Huntsville, Alabama [41] demonstrated the successful fabrication of a copper liner found in rocket combustion chambers where super-cold propellants are mixed and heated to the extreme temperatures needed to send rockets to space Fig. 3 [42]. The combustion chamber liner has more than 200 intricate cooling channels built between the inner and outer liner wall. The NASA center reported that fabricating these tiny passages with complex internal geometries was a challenge. An SLM machine and GRCo-84 C alloy, created by materials scientists at NASA's Glenn Research Center in Cleveland, Ohio were used in fabricating the chamber of 8,255 fused copper-powder layers, over almost 11 days. Extensive materials characterization was conducted to validate the 3-D printing processing parameters and to ensure the build quality. Additively manufacturing the copper liner is only the first step of the "Low Cost Upper Stage-Class Propulsion" Project funded by NASA's development program in the Space Technology Mission Directorate. to revolutionize future space endeavors, including NASA's journey to Mars.

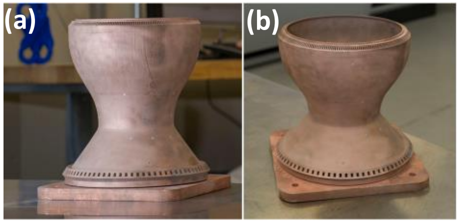


Fig. 3: (a) The first full-scale copper engine part, a combustion chamber liner that operates at extreme temperatures and pressures fabricated by NASA. (b) Cooling inlets are visible along the top rim of the chamber [42].

The increasing capabilities of the AM processes have triggered a growing interest in fabricating Cu/Cu alloys components of novel geometries for optimized performance in thermal applications such as mesh structures for high-surface area heat exchangers [43].

Metallic cellular and hollow structures offer different advantages over regular structures, mainly lower weight, lower mass, and high strength. In thermal and heat transfer applications, cellular structures offer the additional advantage of high heat transfer coefficient and rate due to the large surface area. Copper, due to its high thermal conductivity, is a first choice for cellular structures for next-generation heat exchange devices. Bai & Kumar [44] demonstrated the feasibility of using the binder jetting (BJ) AM process in fabricating copper cellular structures, shown in Fig. 4. Binder jetting is an AM process in which a liquid binding agent is selectively deposited to join powder particles; material layers are then bonded to form an object.

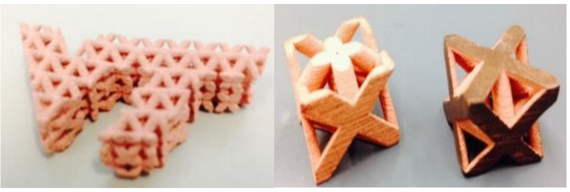
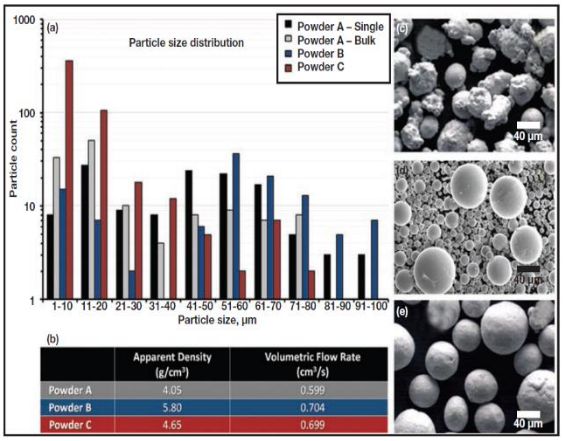


Fig. 4: Cellular hollow Cu structures fabricated using the binder jetting AM process [44].

Process and Material Parameters Study

Along with the extensive validation of AM processes capable of successfully printing Cu components, attention has also been paid to the effect of the process and the materials parameters on the quality of the final 3D printed parts. Researchers became aware recently that adjusting and controlling the AM process parameters and the Cu powder characteristics could lead to an optimized case where the additively manufactured Cu components acquire the best possible quality. Different AM processes and Cu alloys were involved in these studies.

A parameter study has been conducted on the Electron Beam Melting (EBM) process, by a research team at RadiaBeam Technologies LLC [45]. The teamaimed to explore the use of AM to fabricate complex RF photoinjectors with geometries optimized for thermal management, where the spatially optimized internal cooling channels may be fabricated without the constraints typically associated with traditional manufacturing methods. The research goal wasn't just to test the EBM capabilities in printing pure copper components, but also to study the particle morphology and the size distribution that directly affect developing EBM process parameters. Cu powders were obtained from three manufacturers and labelled A, B, and C; their purity was 99.99%, 99.99% 99.8% , respectively Fig. 5 [46]. Among the parameters that should be investigated are the relative packing density and the contact area between particles, which influence flowability, thermal conductivity, and melt pool liquid flow. SEM images showed that powder parameters, mainly the oxide/oxygen content and the EBM build parameters should be considered and monitored to ensure a successful fabrication of products with desirable properties, particularly high electrical conductivity. EBM was then used to additively manufacture copper structures, where for each printed layer, the authors calculated and adjusted the EBM process parameters such as beam current and speed to maintain a stable process. Fig. 6 shows comparative 3D optical metallographic image composites of three different structures fabricated of three different powder mixtures, which illustrates the oxide-influenced, directionally solidified microstructures or microstructural architectures [46]. The ability to fabricate complex geometries incorporating internal cooling channels was then demonstrated as a copper block was additively manufactured with three different channel sizes created straight through the part in three orthogonal directions that curve through the part with 90° elbows, as shown in Fig. 7. It was concluded that high vacuum and critical care in the reuse of powder should be considered, as high oxygen or dense oxide content produces columnar oxide architectures that affect both thermal and electrical conductivity. The quality of the 3D printed parts was comparative to that of the wrought Cu parts and showed the success of the AM process, as summarized in Table 1 [46].



	Apparent Density (g/cm³)	Volumetric Flow Rate (cm³/s)
Powder A	4.05	0.599
Powder B	5.80	0.704
Powder C	4.65	0.699

Fig. 5: Measurements of particle size distribution for each powder type (1a). Table defines average apparent density and average volumetric flow time (1b). Micrographs show shapes of three different powder types—powder A (1c), powder B (1d), and powder C (1e) [46].

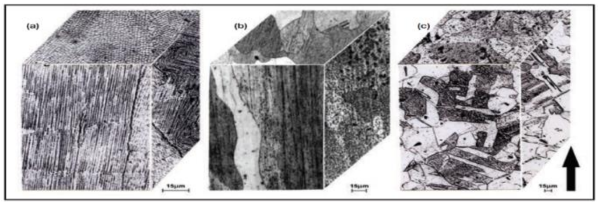


Fig. 6: 3D construction shows EBM-built Cu components from a mixture of 99.80% Cu powder C and a prior, high oxide powder A (a); 99.99% Cu powder B (b); and 99.99% Cu powder B built at elevated temperature (c). Arrow denotes build direction [46].

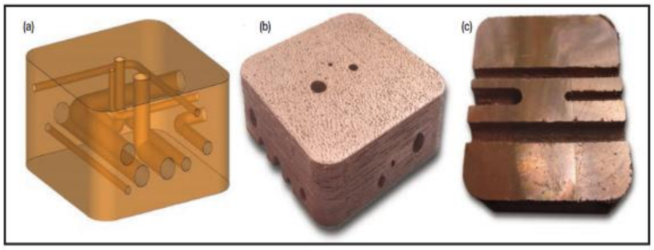
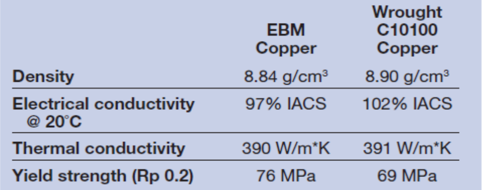


Fig. 7: 3D CAD model of the cooling channel test block shows internal cooling channel geometry (a); photographs of the sectioned EBM-fabricated test blocks show cooling channels of 1.5, 4, and 7 mm in diameter (b and c) [46].

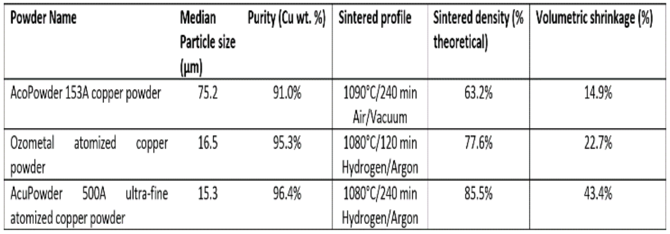
Table 1: Summary of measured EBM-fabricated Cu material properties compared to wrought copper [46].



	EBM Copper	Wrought C10100 Copper
Density	8.84 g/cm³	8.90 g/cm³
Electrical conductivity @ 20°C	97% IACS	102% IACS
Thermal conductivity	390 W/m*K	391 W/m*K
Yield strength (Rp 0.2)	76 MPa	69 MPa

Bai & Williams [47] investigated the ability to additively manufacture copper structures of high purity, using the BJ process, while also emphasizing the importance of studying different powder and process parameters. Binder jetting produces complex parts in industrial-grade materials. Another advantage is the ability to print very large objects [48]. Since copper cellular structures are expected to be successfully used in complex heat exchangers of power generators for portable electronic devices that use hydrocarbon fuels, Bai & Williams [47] demonstrated the ability of BJ process to successfully manufacture Cu cellular structures with an achieved density as high as 85.5% of theoretical density. They also studied the effects of varying the copper powder size, the sintering profiles, and atmospheric control on the final part density and shrinkage. In binder jetting, particles larger than 20 μm are typically preferred so that the powder can be successfully spread during the recoating step. A spherical particle shape is preferred because it tends to flow during recoating and it is more easily wetted with binders. Taking these conditions into consideration, gas atomized spherical copper powder and three different powders were explored to determine the effect of powder size distribution on part processing, as summarized Table 2. Samples using these powders were 3D-printed to study the powder composition and the effect of the process parameters on the quality of the obtained product, shown in Fig. 8 [47]. The quality of the obtained coupons and their strength were also characterized. On the other hand, the microstructural features of the sintered samples were examined by microscopy. The results show that reducing sintering atmosphere can achieve a purity of up to 97.3% while the controlled sintering atmosphere with the presence of hydrogen can increase the purity of copper by up to 3.9% and can improve the sintered density by up to 25.3%. The tensile strength of printed sintered copper parts was 55.6% of the theoretical value due to the porosity. One major conclusion was the challenge facing the binder jetting in sinterability and densification, so this should be investigated in the future.

Table 2. Powder particle size distribution, packing density and purity. The highest achievable sintered density and volumetric shrinkage [47].



Powder Name	Median Particle size (μm)	Purity (Cu wt. %)	Sintered profile	Sintered density (% theoretical)	Volumetric shrinkage (%)
AcoPowder 153A copper powder	75.2	91.0%	1090°C/240 min Air/Vacuum	63.2%	14.9%
Ozometal atomized copper powder	16.5	95.3%	1080°C/120 min Hydrogen/Argon	77.6%	22.7%
AcuPowder 500A ultra-fine atomized copper powder	15.3	96.4%	1080°C/240 min Hydrogen/Argon	85.5%	43.4%

Fig. 8: Sintered copper part samples (AcuPowder 153A copper powder sintered in pure hydrogen at 1000 °C for 8 hours) [47].

In another study also entailing BJ of Cu, Bai et al. [49] investigated bimodal powder mixtures as detailed in Table 3. Their study revealed that the copper bimodal powder mixtures are capable of improving spreading, powder bed density, and sintered density compared with the constituent powders. By using bimodal powder mixtures, the powder flowability is improved by up to 15% (30+5 µm powder). For small particle size ratio mixture (3-6 when 15 µm powder or 30 µm powder is mixed with 5 µm powder), the powder bed density is improved by up to 16.2%. This dramatic increase in the powder bed density has failed to improve the sintered density when large particles (75 µm powder) are present, as they formed a rigid section and limited the contribution of fine powders to overall densification, as shown in Fig. 9 [49]. In other words, widening particle size distribution without shifting median particle size via bimodal mixtures (e.g., 30+5 µm powder) is a successful strategy and has shown an increase of sintered density up to 12.3 % depending on the sintering condition. These results provide a framework for powder optimization to achieve high sintered density in binder jetting of bimodal metal powders. The authors look to explore the effects of different printing parameters and optimize sintering profiles on final part density in future work [49].

Table 3: A summary of the size and density of the powder and bimodal powder mixtures [49].

Mixture number	*Median size (D50)*	*Standard deviation*	*Powder components*	*Apparent density*	*Tapped density*	*Hausner ratio*
1	77.9 µm	23.2 µm	75 µm	56.1 %	64.9%	1.16
2	27.0 µm	39.2 µm	75 µm (w.t.73%)+15 µm	59.7 %	66.9%	1.12
3	26.4 µm	10.9 µm	30 µm	48.5 %	60.8 %	1.25
4	17.4 µm	12.4 µm	30 µm (w.t.73%)+5 µm	53.7 %	63.9 %	1.19
5	17.0 µm	6.7 µm	15 µm	52.9 %	65.1%	1.23
6	10.8 µm	4.7 µm	15 µm (w.t.73%)+5 µm	54.6 %	67.4 %	1.23
7	8.3 µm	15.4 µm	5 µm (w.t.73%)+30 µm	54.4 %	61.2 %	1.13
8	5.8 µm	2.7 µm	5 µm (w.t.73%)+15 µm	47.3 %	60.5 %	1.28
9	5.5 µm	N/A	5 µm	41.7 %	55.6 %	1.33

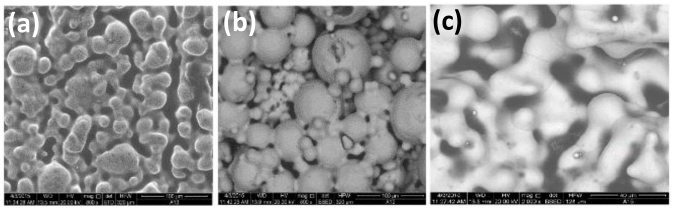


Fig 9: Sintered structures of the primitives in (a) 15+5 µm powder and (b) 75+5 µm powder, (c) 30+5 µm powder, sintered at 1060 °C for 120 minutes [49].

Other attempts to 3D print Cu alloys and to enhance the resulting part quality were made by Song et al. [50]. Thin-wall components of W-Cu alloy were manufactured by SLM while the effects of size and overlapping of melt pool on the thickness of single-track wall were analyzed, shown in Fig. 10. The study revealed that the energy input of the laser directly affects the thickness of single-track wall; while other parameters such as laser power and scanning speed, need to be selected appropriately to obtain a good single-track wall. A part of the study included examining the SLM process of multi-composition alloy, such as CuW-CuP-CuSn, where the authors concluded that in such cases, the powder adhesion is better than single-composition powder, due to the difference in melting points [50].

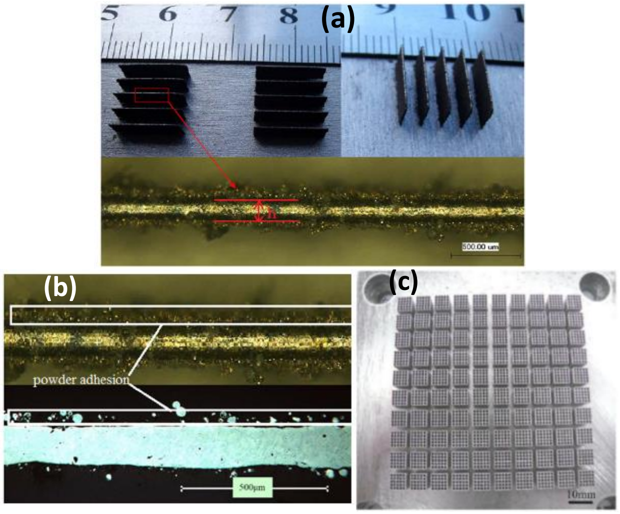


Fig. 10: (a) Thin walls manufactured by SLM. (b) Powder adhesion. (c) Mass production of thin wall heat sink by SLM [50].

Another study that investigated the SLM of copper alloys was performed by Popovich et al. [51]. The authors studied the SLM of Cu-Cr and Cu-Cr-Zr alloys that are widely used in the aerospace and nuclear industries. They showed that by calibrating the parameters of the SLM, specifically the laser power to overcome the difficulty imposed by the high thermal conductivity and the low laser absorption of the Copper alloys, bulk Cu-Cr-Zr-Ti alloy specimens with high density (97.9%) could be successfully manufactured, as shown in Fig. 11 [51]. The mechanical tests revealed that the samples fabricated parallel to the build direction showed UTS and elongation at break slightly higher than that of components fabricated perpendicular to the build direction. In general, the UTS of the SLM fabricated copper alloy samples was approximately 20–25% lower than that of the conventionally fabricated hot-rolled samples, summarized in Table 4. The authors suggested that the difference in values could be due to residual porosity in the SLM material and would eventually need to be reduced by better optimizing the process parameters or by applying the hot isostatic pressure post-treatment [51].

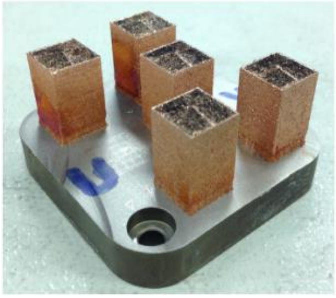


Fig. 11: Cu-Cr-Zr-Ti specimens fabricated using SLM [51].

Table 4: Mechanical properties of the SLM Cu-Cr-Zr-Ti samples after heat treatment [51].

Specimen type	UTS, MPa			Elongation at break, %		
	20 °C	600 °C	800 °C	20 °C	600 °C	800 °C
Perpendicular to build direction	195.1–198.0	69.5–86.2	31.3–33.3	10.8–11.7	4.4–5.7	6.3–12.0
Parallel to build direction	210.0–211.0	82.2–82.3	41.2–46.6	13.1–15.8	4.2–7.7	7.8–12.1
Hot-rolled + heat treated	249	107	–	40	6	–

II. Additive manufacturing of Composite and Embedded Copper structures

The need for innovative designs and optimized performance of electronics and electronic cooling drives a big part of the AM research to develop novel processes producing composite structures and embedded components. Many of these processes have successfully included Cu parts, thus taking advantage of the geometry of the structure and the superior characteristics of the material.

One of the most recently reported processes is Embedded Fiber Composite Additive Manufacturing (EFCAM), designed and developed by Hymas et al. [52]. This innovative hybrid AM process is capable of fabricating polymer-metal composite structures by utilizing a standard FDM printing assembly to construct the main body of the part, in conjunction with a specialized metal fiber print head, designed, developed and created by Hymas et el. [53], that can embed fibers of various materials into the polymer structure in-situ [52]. EFCAM is currently being used to produce specimens of a cross-media fiber heat exchanger [53], which rely on copper or aluminum fiber fins passing directly through the polymer walls of the fluid channels, as shown in Fig. 12 [52]. This process produces a lightweight and low-cost structure capable of outperforming many industry-standard technologies in the field of low-grade heat rejection. As EFCAM technology advances, it will enable many tasks such as structural reinforcement for parts built using the FDM process, along with other highly desired applications such as embedded circuitry.

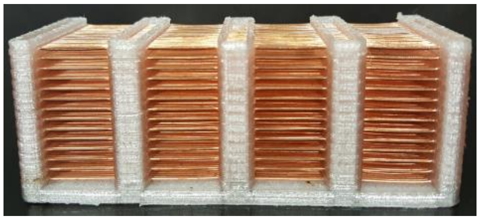


Fig. 12: PETG-copper composite structure built using the embedded fiber composite additive manufacturing process [52].

Another emerging AM technology in composite and embedded 3D printing is the ultrasonic additive manufacturing (UAM) process, one type of laminated object manufacturing (LOM). UAM uses the power of sound to merge layers of metal foil for true metallurgical bonds with full density, including copper, stainless steel, aluminum and titanium. The ultrasonic vibrations create a friction-like relative motion between two surfaces that are held together under pressure. This action, in turn, causes shearing and plastic deformation between asperities of the opposing surfaces, which disperses surface oxides and contaminants. As the asperities collapse, metal-to-metal contact is increased, creating solid-state bonding between the parts through heat and pressure. This type of AM is usually combined with conventional fabrication methods, leading to a hybrid manufacturing system Fig. 13 [54]. With all design freedom and capabilities provided by the UAM, Fabrisonic LLC [55], a 3D metal printing service for equipment and contract services companies, investigated its capabilities to develop and build complex components with unique features. Fabriconic's UAM printer fabricated parts using aluminum and copper with complex internal channels of different sizes Fig. 14 [54-56]. The obtained parts are claimed to be of the same internal surface finish and repeatability as traditional CNC machining. One important application to benefit from this technology is the advanced heat exchangers whose manufacturing using CNC machining limits the shape of the internal passageway to planar arrays of cross-drilled holes. Since the hybrid UAM machines are based on traditional 3-Axis CNC mills, the welding process can be stopped at any point and three dimensional channels can be machined. Subsequently, the additive process continues to build up metal sealing in complex 3D flow paths. The x-ray image of Fig. 15 [54,55] illustrates the ability for complex internal flow paths which are impossible with traditional manufacturing methods.

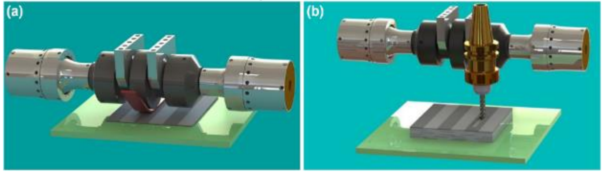


Fig. 13: Illustration of UAM process: (a) welding of aluminum tape and (b) periodic machining operations [54].

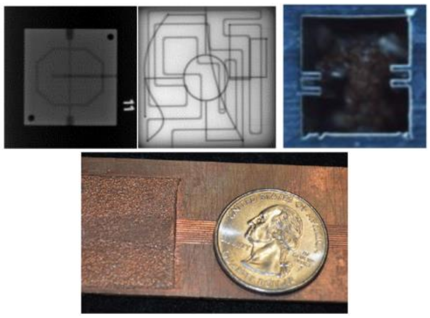


Fig. 14: Complex internal channels and Cu microchannels (of order of 0.1 to 0.5 inch) fabricated using UAM [54,55].

Composite AM allows UAM to form the joints of dissimilar metals, or inter-metallics. A wide range of material combinations have been successfully bonded using ultrasonics. Al/Cu, Al/Fe and Al/Ti are routinely joined. Aluminum and copper composite structures are successfully fabricated using UAM, as shown in Fig. 15 [56]. Fabriconic claims that this technology allows manufacturing aerospace components with burst pressures in excess of 3000 PSI, with 4000 PSI in similar copper structures. Another application made possible by UAM is wave guides used in radio frequency devices, antennas, and transmitting/receiving devices for optimal power transmission.

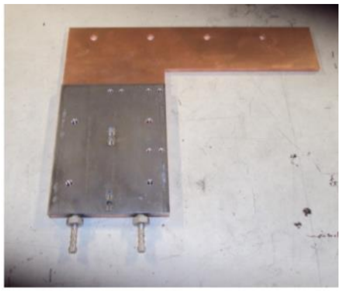


Fig. 15: Multi-metal heat exchanger. Fabrisonic's process can print multiple metals together without causing metallurgical problems. In this structure the high heat areas are made of copper and the rest of the structure is made of aluminum to reduce weight [56].

Embedded 3D printing is also possible by UAM. In fact, all kinds of wires, fibers, and sensors could be embedded into a metallic substrate due to the solid-state nature of Fabrisonic's UAM bond. As the metals need not be heated for bonding, many electronics can be embedded within the metallic layers without damage. This enables sensors, communication circuits, and actuators to be embedded into fully dense metallic structures [55]. Fig. 16 shows a copper component containing an embedded thermocouple. This allows for a wide range of applications that were almost impossible before.

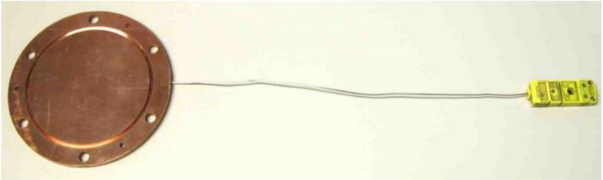


Fig. 16: Thermocouple embedded in copper component using UAM [55]

One study that aimed to address the challenges of future 3D-printed electronics, and to assure their reliability and durability, was conducted by Espalin et al. [19]. They developed a next-generation machine called the multi3D system, which denotes the use of multiple technologies to produce 3D, multi-material, multifunctional devices. The machine is composed of a material extrusion system based on fused deposition modeling (FDM) technology and integrates other technologies to compensate for FDM's deficiencies in surface finish, minimum dimensional feature size, and porosity. On the other hand, to minimize the use of conductive inks, the system includes a novel thermal embedding technology that embeds and submerges copper wires into the thermoplastic dielectric structures during FDM process interruptions, which improves the mechanical properties of the structure while providing high performance, robust interconnect, and ground planes. It was also necessary to introduce a micromachining high-resolution subtractive method, CNC micromachining, demonstrated by the current system and laser ablation for a future system to achieve channel widths of ~100 µm and even smaller. Components can thus be connected either through conductive inks dispensed in channels or by high-performance, high-gauge wires embedded within the substrate and joined by using laser welding. The system is thus capable of fabricating 3D electronics structures composed of substrates with enhanced dielectric and mechanical properties and the required dimensional accuracies. The authors argue that among the various advantages of their system is the benefit of thermoplastics, over the thermosetting photopolymers usually used in SL methods employed in 3D printing of electronics. Thermoplastics allow solid wire conductors to be thermally embedded into the substrate without affecting planarization. Consequently, wires can be successfully integrated and the use of conductive inks as interconnect can be eliminated. Figure 17 shows a conceptual model of a potential fabrication where dielectric materials can be placed with full 3D freedom [19]. Modern electronic components and sensors as well as the high-performance interconnect can be embedded during process interruptions as shown in the center of the image.

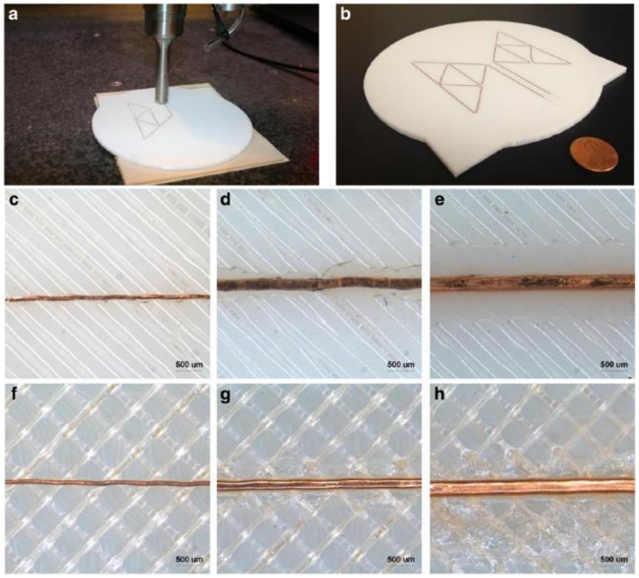


Fig. 17: (a) Demonstration of embedded copper wires in ULTEM 9085 and polycarbonate (PC) substrates: an ultrasonic embedding setup, (b) antenna pattern on PC substrate, (c) 40 gauge copper wire in PC, (d) 32 gauge copper wire in PC, (e) 28 gauge wire in PC, (f) 40 gauge copper wire in ULTEM, (g) 32 gauge copper wire in ULTEM, and (h) 28 gauge wire in ULTEM [19].

The authors noted that unit-level customization can be enabled by their transformational technology, including human anatomy-specific biomedical devices or rapidly deployed mission-customized spacecraft [19].

Other hybrid methods composed of AM processes combined with a conventional process are being explored extensively for achieving novel 3D printing of electronics. One of these hybrid processes was developed by Sarobol et al. [57], in which they fabricated at room temperature mesoscale circuits and devices on Cu foils via a combination of established electroplating and sputtering processes and the aerosol-deposited (AD) process shown in Fig. 18. The multilayered devices were fabricated layer by layer by employing AD to deposit ceramic films, including high-permittivity BaTiO3 dielectrics and low permittivity alumina dielectrics. Photolithography was performed for patterning and dry chemical (HF/HNO3) etching to selectively remove materials. Electroplating or sputtering is then employed to deposit internal conductors such as Cu. Finally, a post-process annealing treatment was performed The final grain size of the film was found to be between 60 to 150 nm. The authors showed that the physical and dielectric properties of the annealed AD BaTiO3 films were similar to those of bulk pressed and sintered BaTiO3. It is worth mentioning that integrating ceramics onto conductors as demonstrated above is not possible using conventional fabrication methods because bulk sintering of (pressed) alumina and BaTiO3 is usually performed at 1,600 ◦C and 1,400 ◦C, respectively, well above the Cu melting point of 1,083 ◦C. As this method is considered to establish a path forward to embedding such structures in a resin-based electronic packaging, a similar approach is anticipated to be feasible in depositing multilayered, solid-state lithium ion batteries directly onto polymer substrates or FPC [57].

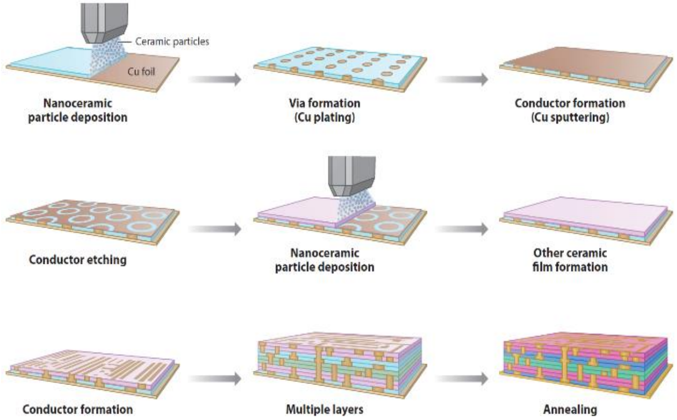


Fig. 18: Schematics of multilayered electronic device fabrication by aerosol deposition to deposit ceramic films, photolithography for patterning and dry chemical (HF/HNO3) etching, and electroplating/sputtering to deposit internal conductors [57].

In addition to the hybrid manufacturing methods being currently investigated, various non-classical AM processes are being developed, increasing the possibilities of novel manufacturing techniques, especially in the continuously demanding electronics/electronic cooling domain. Kaestle et al. [58] demonstrated one of these non-classical AM processes which includes Cu as the main material substrate. One of the most focused-on interconnect technologies in power electronics is wire bonding, and demands on advancing this bonding method using copper instead of aluminum bond material drove this research. The authors proposed the use of cold active atmospheric plasma printing of copper layers in complex and highly integrated power devices, so that connections between the printed structures and active components such as bare dies or LEDs and the peripheral package would be successfully established. In their work, the authors additively printed Cu layers on Al_2O_3 ceramic substrates Fig. 19 [58]. To ensure an optimized process, the different parameters influencing the process were investigated. The authors concluded that ideal wire bonding is achieved due to high adhesive strength and a low porosity of the printed Cu layers, accompanied by a sufficient layer thickness, a tolerable waviness and surface roughness. It was demonstrated that wire bonding was possible on copper coatings acquiring a clearly oxidized surface; nevertheless, the tolerable oxidization level and its effect on mechanical joint strength require further examination. The authors pointed out also that different post-processing steps should be further investigated as well. In other words, separate investigation of all factors and parameters should be performed to ensure a successful correlation between the coating parameters, the resulting copper layer properties, and the final bondability complex process. Fig. 20 [58] shows an accumulation of the layer properties that need to be investigated and therefore controlled to develop a stable bond process. An example of a successful process combination is shown in Fig. 21 [58], where an Al wire bond loops on the printed copper layers. In order to increase technological performance and system reliability, the authors will investigate the copper wire bonding to take advantage of copper's superior material properties and the possibility of developing a mono-metallic joint system [58].

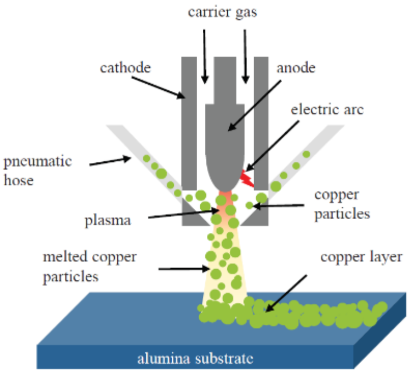


Fig. 19: Schematic representation of the Plasmadust® process within the plasma nozzle [58].

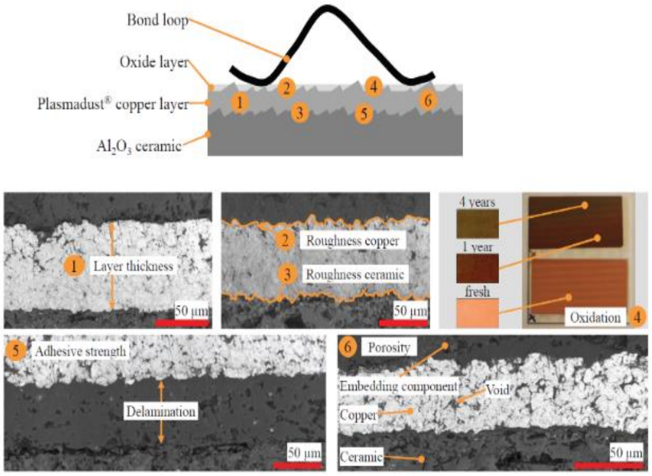


Fig. 20: Aggregation of the process influencing quality factors for realizing bondable plasma-printed copper layers [58].

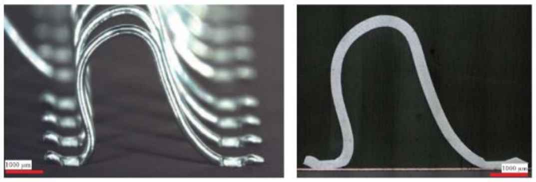


Fig. 21: (a) Wire bond loops (300 µm) on printed copper layers. (b) cross section of a bond loop on a printed copper layer on alumina [58].

Summary & Conclusions

In this paper we reported some of the major influential work conducted in the field of copper additive manufacturing. The studies included major breakthroughs in overcoming the process and material difficulties that hindered successful 3D printing of copper structures. Novel processes that enable fabricating composite and embedded structures were also highlighted. These studies pave the way for innovative design and manufacturing of optimized applications in thermal management and electronics/electronic cooling fields. The approaches followed in these studies, especially the research tackling the effects of the material characterization and the AM process parameters, set a base for researchers aiming to advance the field of additive manufacturing of copper and copper composite structures.

Acknowledgments

The authors would like to thank the International Copper Association for their support on this work.

References

[1] https://wohlersassociates.com/additive-manufacturing.html Last visited on January 11, 2017.

[2] Additive Manufacturing and 3D Printing State of the Industry, Wohlers Report. 2013.

[3] J. Scott et al., Additive Manufacturing: Status and Opportunities. 2012.

[4] State of the Industry, Wohlers Report. 2007.

[5] DOE, Quadrennial technology review an assessment of energy technologies and research opportunities; Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing 2015.

[6] Royal Academy of Engineering, Additive manufacturing: opportunities and constraints: A summary of a roundtable forum held on 23 May 2013 hosted by the Royal Academy of Engineering.

[7] D. Q. Zhang, Z. H. Liu, and C. K. Chua, “Investigation on forming process of copper alloys via Selective Laser Melting”, High. Value Manuf. Adv. Res. Virtual Rapid Prototyp., 285–289, 2014.

[8] Z. H. Liu et al., “Interfacial characterization of SLM parts in multi-material processing: metallurgical diffusion between 316L stainless steel and C18400 copper alloy”, Mater. Charact. 94,116–125, 2014.

[9] L. Weiss and F. Prinz, “Novel applications and implementations of shape deposition manufacturing”. Naval Research Reviews, Office of Naval Research 1998.

[10] J. Cham et al., “Layered manufacturing with embedded components: process planning considerations”. Proceedings of DETC99: 1999 ASME Design Engineering Technical Conference.

[11] J. A. Palmer et al., “Mesoscale RF relay enabled by integrated rapid manufacturing”. Rapid Prototype J., 12,148–155, 2006.

[12] F. Medina et al., “Integrating multiple rapid manufacturing technologies for developing advanced customized functional devices”. Rapid Prototyping & Manufacturing 2005 Conference Proceedings 10–12.

[13] F. Medina F et al., “Hybrid manufacturing: integrating stereolithography and direct write technologies”. 16th Annual International Solid Freeform Fabrication Symposium 2005, 39–49.

[14] A. J. Lopes et al., “Expanding rapid prototyping for electronic systems integration of arbitrary form”. 17th Annual International Solid Freeform Fabrication Symposium 2006.

[15] A.J. Palmer et al., “Stereolithography: a basis for integrated meso manufacturing” 16th Annual Solid Freeform Fabrication Symposium 2005, 476–483.

[16] J. DeGrange and B. Macy, “Smart parts: Additive manufacturing for integrated electro-mechanical devices” [webinar] 2012. Retrieved from http://www.stratasys.com/Resources/ Webinars/Smart-Parts.aspx

[17] J.A. Paulsen et al., “Printing conformal electronics on 3D structures with Aerosol Jet technology”. Future of Instrumentation International Workshop (FIIW),1–4, 2012.

[18] K. Takagi , H. Honma, and T. Sasabe, “Development of sequential build-up multilayer printed wiring boards in Japan”. IEEE Electr. Insul. Mag., 19, 27–56, 2003.

[19] D. Espalin et al., “3D Printing multifunctionality: structures with electronics”, Int J Adv Manuf Technol, 72, 963–978, 2014.

[20] G. Ghosh, J. Miyake, and M.E. Fine, “The systems-based design of high-strength, high-conductivity alloys”, JOM 49 (3), 56–60, 1997.

[21] M. Arie, A. Shooshtari, S. Dessiatoun, and M. Ohadi, "Performance Characterization of an Additively Manufactured Titanium (Ti64) Heat Exchanger for Air-Water Cooling Application," Proceedings of the ASME Heat Transfer, Fluids Engineering, and Nanochannels, Microchannels and Minichannels Conference, Washigton D.C. 2016, HT/FE/ICNMM2016, pp. 1-13.

[22] M. Arie et al., "Experimental Characterization of Heat Transfer in an Additively Manufactured Polymer Heat Exchanger," in review in Applied Thermal Engineering.

[23] M. A. Arie, A. H. Shooshtari, S. Dessiatoun, and M. M. Ohadi, "Experimental Characterization of An Additively Manufactured Heat Exchanger for Dry Cooling of Power Plants," Applied Thermal Engineering. (Manuscript submitted for publication).

[24] M. A. Arie, A. H. Shooshtari, V. V. Rao, S. Dessiatoun, and M. M. Ohadi, "Air-Side Heat Transfer Enhancement Utilizing Design Optimization and an Additive Manufacturing Technique," Journal of Heat Transfer, 139, no. 3, 031901, 2016

[25] M. Arie, "Heat transfer enhancement of air-side heat exchanger using advanced heat transfer surface design and an additive manufacturing technique," PhD thesis 2016, University of Maryland.

[26] Modern Machine Shop, “Why Is Additive Manufacturing Important?”, 2012.

[27] D. Cook et al., “Unit-Cell-Based Custom Thermal Management through Additive Manufacturing”, Proceedings of the 23rd Annual Solid Freeform Fabrication Symposium, 2012.

[28] S. Ashman and S. G. Kandlikar, "Review Of Manufacturing Processes for Microchannel Heat Exchanger Fabrication", Proceedings of ICNMM 2006, Fourth International Conference on Nanochannels, Microchannels and Minichannels.

[29] B.G. Carman et al., "Impact of a ceramic microchannel heat exchanger on a micro turbine." American Society of Mechanical Engineers, International Gas Turbine Institute, Turbo Expo IGTI., 1, 1053- 1060, 2002.

[30] M. Lohtander, S. Valkeapää and J. Varis, "The Capability of the Laser Based Additive Manufacturing Process in the Manufacture of Fractal like Heat Transfer Devices." Key Engineering Materials, 572(1), 605-608, 2013.

[31] M. Wong et al., "Selective laser melting of heat transfer devices", Rapid Prototyping Journal, 13, 291-297, 2007.

[32] S. M. Thompson et al., "Additive manufacturing of heat exchangers: A case study on a multi-layered Ti–6Al–4V oscillating heat pipe", Additive Manufacturing, Volume 8, 163–174, 2015.

[33] P. Frigola, et al., "A Novel Fabrication Technique for the Production of RF Photoinjectors, Proceedings of EPAC08, Genoa, Italy, 751-753, 2008.

[34] D.A. Ramirez, et al., "Open-Cellular Copper Structures Fabricated by Additive Manufacturing Using Electron Beam Melting, Mater. Sci. and Eng. A, J28A, 5379-538, 2011.

[35] D.A. Ramirez, et al., "Novel Precipitate-Microstructural Architecture Developed in the Fabrication of Solid Copper Components by Additive Manufacturing Using Electron Beam Melting", Acta Mater., 59, 4088- 4099, 2011.

[36] http://www.3trpd.co.uk/ Last visited on January 11, 2017.

[37] http://www.3trpd.co.uk/3t-success-with-pure-copper-am-production/ Last visited on January 11, 2017.

[38] http://www.ilt.fraunhofer.de/ Last visited on January 11, 2017.

[39] AM of copper components, Fraunhofer Institute for Laser Technology ILT, www.ilt.fraunhofer.de, DQS certified by DIN EN ISO 9001, Reg.-No.: DE-69572-01, 2010.

[40] Additive Manufacturing of Copper Components with Selective Laser Melting, Fraunhofer Institute for Laser Technology ILT, www.ilt.fraunhofer.de DQS certified by DIN EN ISO 9001, Reg.-No.: DE-69572-01, 2011.

[41] https://www.nasa.gov/centers/marshall/home/index.html Last visited on January 11, 2017.

[42] http://www.nasa.gov/marshall/news/nasa-3-D-prints-first-full-scale-copper-rocket-engine-part.html Last visited on January 11, 2017.

[43] https://camal.ncsu.edu/research/material-development/ Last visited on January 11, 2017.

[44] http://www.me.vt.edu/dreams/693/ Last visited on January 11, 2017.

[45] http://www.radiabeam.com/ Last visited on January 11, 2017.

[46] P. Frigola, et al., "Fabricating Copper Components with Electron Beam Melting", 2014.

[47] Bai, Y. and Williams, C.B., "An exploration of binder jetting of copper", Rapid Prototyping Journal, 21, No. 2, 177–185, 2015.

[48]http://www.exone.com/Resources/Technology-Overview/What-is-Binder-Jetting Last visited on January 11, 2017.

[49] Y. Bai, G. Wagner and C. Williams, "Effect of Bimodal Powder Mixture on Powder Packing Density and Sintered Density in Binder Jetting of Metals", Design, Research, and Education for Additive Manufacturing Systems Laboratory Department of Mechanical Engineering Virginia Tech, 2015.

[50] C. Song et al., "Study on manufacturing of W-Cu alloy thin wall parts by selective laser melting", Int J Adv Manuf Technol, 78, 885–893, 2015.

[51] A. Popovich et al., "Microstructure and mechanical properties of additive manufactured copper alloy", Materials Letters, 179, 38–41, 2016.

[52] D. Hymas et al., "Enhanced Air Side Heat Transfer in an Additively Manufactured Polymer Composite Heat Exchanger", submitted to The Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems ITHERM conference 2017.

[53] Cheiros (Technology) Ltd., "Heat Transfer", US 6,994,155 B2, 2001.

[54] M. Norfolk and H. Johnson, "Solid-State Additive Manufacturing for Heat Exchangers", JOM, 67, No. 3., 2015.

[55] www.fabrisonic.com Last visited on January 11, 2017.

[56]http://www.makepartsfast.com/creating-multi-metal-custom-heat-exchangers-3d-printing/ Last visited on January 16, 2017

[57] P. Sarobol et al., "Additive Manufacturing of Hybrid Circuits", Annu. Rev. Mater. Res., 46, 41-62, 2016.

[58] C. Kaestle et al., "Evaluation of Influencing Factors on the Heavy Wire Bondability of Plasma Printed Copper Structures".978-1-4244-5100-5/09/$26.00©2009 IEEE, 2015 17th Electronics Packaging Technology Conference.