PRINTED CIRCUIT BOARDS BY SELECTIVE DEPOSITION AND PROCESSING

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1 Abstract

With electronic applications on the horizon for AM, comes the dilemma of how to consolidate conductors, semi-conductors, and insulators in close proximity. To answer this challenge, laser printing (selective deposition) was used in tandem with fiber laser consolidation (selective processing) to produce PCBs for the first time. This combination offers the potential to generate tracks with high mechanical integrity and excellent electrical conductivity (close to bulk metal) without prolonged exposure of the substrate to elevated temperatures. Herein are the findings of a two-year feasibility study for a "one-stop" solution for producing PCBs (including conductive tracks, dielectric layers, protective resists, and legends).

2 Introduction

The production of conventional PCBs is highly complex, requires a substantial investment in capital equipment and uses a wide variety of chemicals which are difficult/costly to safely dispose of. Current PCB production methods are "wet" processes consisting of two major steps: a) first a laminate board is clad with copper via electrodeposition and then b) the copper is selectively removed via chemical etching to leave conductive "tracks" of copper desired for the circuitry [1]. Often the ratio of electrodeposited copper to copper used in the tracks is as much as 5:1 meaning that most of the cladding is removed via chemical etching into chloride solutions where is it difficult to reclaim, while very little of the copper ends up in the final product [2].

In an effort to overcome the shortcoming of conventional PCB manufacture there has been significant interest in the direct digital deposition of conductive tracks to form PCBs. Inkjet printing is by far the most widely explored due to its inherent ink formulation flexiblity, scalability and availability of off the shelf print heads (for example Xaar,Cambrige UK) [3-8]. Although significant progress has been made, it is largely predicated on the availability of very expensive gold or silver nanoparticles (desired for their high electrical conductivities, low melt temperatures, lower suceptibilities to oxidation than copper and amenability to suspend in ink formulation)[9]. Moreover, in ink jet printing the proportion of solid material is relatively low (typically < 25 vol.%) compared to the liquid carrier, thus limiting the deposition efficiency of the process [10, 11]. Furthermore, most direct deposition techniques rely on global processing via photonic fusing/curing approaches (such as pulsed light by Xenon) or post deposition furnace sintering (such as High Volume Print Forming by EoPlex) which subject the entire PCB to intense energy exposure [12]. Some alternatives offer room temperature processability such as highly viscous metal flake filled slurries have been deposited as a continuous bead extrusion to form conductive tracks (for example nScrypt Inc,) but this route is too slow to be effective for the manufacture of PCBs for production [13].

In an effort to provide the maximum flexibility for deposition and consolidation of multiple materials side by side, laser printing (selective deposition) and laser melting (selective processing) have been combined for the first time. The speed, resolution and the ability to deposit dry powder provides significant advantages for laser printing in the production of PCBs as recognized by other researchers [14, 15]. The process is highly adaptable to different types of materials; commercial toners are based on polymers but researchers have already shown the potential to deposit metals and ceramics [15-19]. The selective laser melting (SLM) process has proven effective in fusing dry particles of: metal, ceramic, and polymer [20, 21].

A two-year fleet footed feasibility study was undertaken to consider the feasibility of incorporating digital deposition by laser printing and (digital) selective laser melting (SLM) principles into PCB production to provide a simple, low cost, flexible and environmentally friendly production method for low volume, high value PCBs.

In addition to depositing the conductive tracks, the deposition of dielectric layers, etch resists, protective layers, seed layers for overplating, legends, and artwork were also evaluated in the project. This paper will focus on the direct printing and melting of conductive tracks on electronics substrates. Proof of concept within the project was based on the manufacture of single sided boards, but could easily be applied to double sided, through-plated and multilayer PCBs.

3 Selective Deposition of Conductive Tracks

Selective deposition of conductive tracks has been an aspiration of digital printing processes for 30 years. Core to this pursuit is the inverse relationship between particle size and melting temperature, which has driven material development and processing down into the nanoscale.[22, 23]

The direct deposition of silver conductive tracks was planned for this project based on the upcoming commercial availability of conductive toner. A dilemma presented itself when the toner was not forthcoming in the expected timescales. It was decided that the lack of toner was an opportunity to explore the feasibility of developing a conductive toner and evaluate how well it printed.

3.1 Choice of material for conductive tracks

Many researchers have given attention to the direct deposition of gold or silver conductive tracks due to their high conductivity, availability as nano particles, and favorable sintering behavior [4, 8, 16, 24]. Despite the successes demonstrated at research and pilot scales, the cost of precious and semi-precious metals is a significant disincentive for its use in large quantities. At least one major electronics manufacturer has announced its intention to focus on digital deposition of more conventional conductive materials such as copper [25].

Excepting precious metals, copper and aluminum respectively are the next most electrically conductive metals known. The suitability of these for both toner preparation and laser melting were evaluated during the screening steps of the research. Copper was selected as the primary focus due to its universal acceptance in electronics applications, affordability and availability in nano- and micro-scale particles in the range which theoretically can be melted by laser. AlSi12 is a typical aluminum based casting alloy widely used in SLM and was investigated during initial materials screening, but was discontinued due to industrial preference for copper. It also exhibited poor spreading onto unheated electronics substrates.

The particle size range was correlated to the desired thickness of deposited conductive tracks. The thickness of conductive tracks on conventionally produced PCBs is determined by the weight of copper cladding electrodeposited onto it per square foot which is normally 1, 2, or 3 oz. per square foot (equating to a copper thickness of 0.035, 0.070 and 0.105mm respectively). The standard for logic boards with very low operating voltage (typically 5 VDC) is 1 oz./ft^2 (0.035mm) which was the target for these experiments. Assuming a monolayer of spherical toner particles spread on the substrate in a simple cubic lattice with a packing density of 0.524 meant that fully melted particles would theoretically result in a layer that is approximately half the height of the particle mean diameter [26]. Planning to solidify two layers of powder, both the copper and AlSi12 were used in a standard SLM size range with mean particle sizes of ~40 µm diameter. In practice, spreading and substrate adhesion problems obliged the melting of thicker tracks (5-6 layers high).

3.2 Toner preparation and print trials

The laser printers used for these trials are configured with developers for nonconductive toners [27]. This development system requires that individual toner particles be sufficiently nonconductive so that they can be tribocharged (charged by friction) and maintain critical charge levels long enough to travel through the printer and be fixed to a substrate (generally for at least 20 seconds) [28, 29].

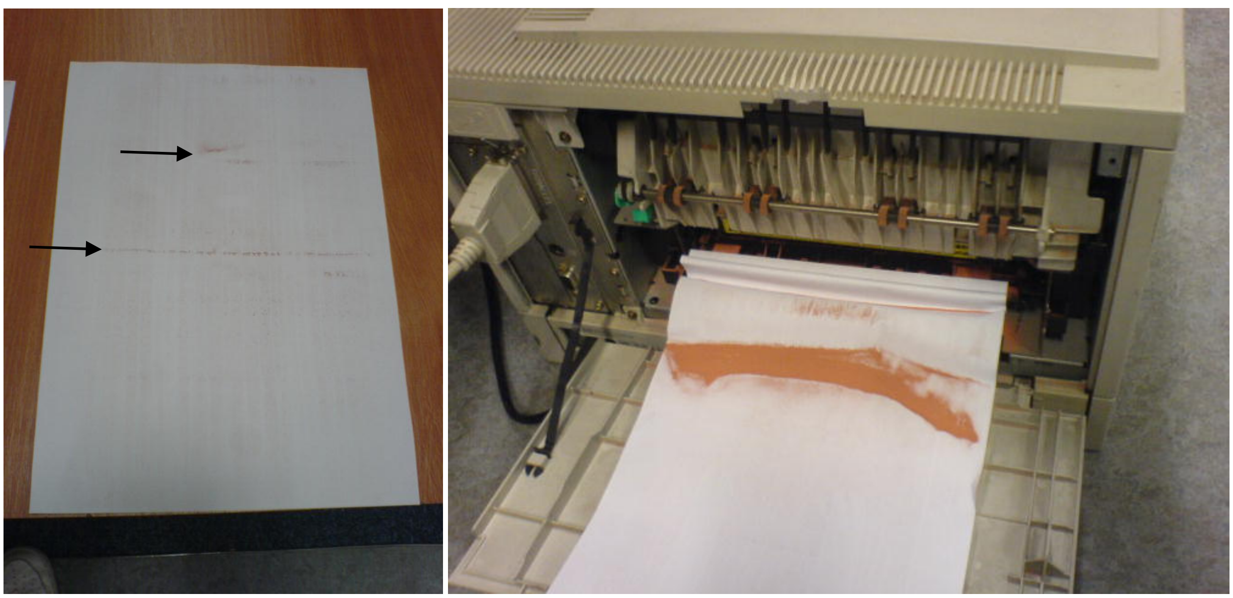

Figure 1 – Attempts to use un-treated copper powder as toner in an HP Laserjet 5 printer.

Initially the untreated metal powder was exposed to the air and subsequently tested to see if the oxidized outer surface of the individual copper particles would sufficiently insulate them from each other enough to allow tribocharging. High conductivity 38-45 µm diameter 99.7% pure copper particles (Sandvik Osprey, Wales) were loaded into the developer unit of a Laserjet 5 printer (Hewlett-Packard, USA) and printing was attempted as shown in Figure 1. Although some deposition of copper particles is evident on the paper (as indicated by the arrows in Figure 1 left) the bulk of the material in the developer leaked out irrespective of the electrostatic latent image generated in the printer (the loose powder contributed to the paper jamming as shown in Figure 1 right). This result indicated that any electrostatic charge generated on the particles in the developer was inadequate in strength and/or duration to control its behavior, and further treatment of the particles would be necessary to enable printing.

The copper particles were next surface coated using metalloid oxide nanoparticles by the technique developed by Banerjee and Wimpenny to improve flow and charge control [30]. Printing was attempted using the same procedure above with similar results. This result again indicated that insufficient charge had been generated and retained on the toner particles.

In order to impart and retain sufficient charge density on the toner particles a procedure to encapsulate each copper particle in polymer was developed. Although the particles were successfully encapsulated in very small batch quantities (<5g), it was outside the scope of the available resource to produce sufficient quantities for full-scale printing trials.

3.3 Selective printing conclusions

Despite reports of successful conductive toner deposition by electrophotography in the literature the current results showed very limited success [31]. Conductive toner development is a highly specialized area and future work would include reduction of the size of the copper powder, surface treatment prior to coating, and upscaling the encapsulation method. Rather than pursue these, the authors were aware of several development initiatives which promised a commercial supply of conductive toners in the near-term which would soon enable more extensive research of toner based electronics applications.

4 Selectively Processing Conductives on Non-conductive Substrates

Despite the possibilities which have been demonstrated using nanoscale particles and flash fusing methods, the conductivity achieved is generally only 10-20% that of the bulk conductive [32]. Furthermore, the mechanical integrity of those tracks was inferior when compared to conventionally processed PCBs, making them unsuitable for use where high-performance or flexible circuitry is specified.

In pursuit of high mechanical integrity and conductivity comparable to bulk copper Selective Laser Melting (SLM) of aluminum and copper powder was attempted. Three different laser melting systems: SLM 100 (Realizer GmBH, Germany), SLM 250 (MTT Technologies Ltd, United Kingdom), and SLM 125 (MTT Technologies Ltd, United Kingdom) were used to explore the most favorable combination of system features and processing parameters.

4.1 Need to use a non-conductive substrate for electronics

In order to produce an electronic circuit, it was necessary to depart from the SLM convention of matching the feedstock powder with a build plate made from the same or very similar material. This practice normally ensures that the thermal characteristics of the substrate and the structure being melted on top of it are similar enough to allow adequate wetting and adhesion while minimizing thermally induced distortion or cracking.

Conventional electronics substrates include: "FR-4" grade glass fiber reinforced epoxy laminate, high temperature polymer film substrates such as Kapton®, ceramic substrates such as LTCC glass ceramic or alumina, and insulated metal substrates which are a sandwich construction consisting of a thin ceramic layer upon which the circuitry is made with a high thermal conductivity metal (such as aluminum) backing to dissipate heat. All of these substrate types were evaluated during the laser melting parameters optimization process.

4.2 Low-temperature substrates in the SLM 100

The initial attempts to use FR-4 and Kapton® film substrates in the SLM 100 with AlSi12 (MTT Technologies Ltd., United Kingdom) highlighted a variety of challenges.

Firstly, FR-4 laminate (1 oz./ft^2 single sided copper clad Kingboard) and Kapton® polyimide sheet (90 µm thick) required CNC routing and cutting respectively to fit onto the circular build platform. A single substrate was attached to the platform using double-sided tape

Spreading the initial powder layers proved problematic because of the smoothness of the substrate in combination with the use of tape which prevented the normal use of the platform heater. The AlSi12 was particularly susceptible to poor flow in the absence of preheat. Only by spreading five to ten 50 µm layers of powder prior to firing the laser was it possible to uniformly cover the platform (the powder distribution was not uniform across the platform because of the recoater pivoting, resulting in higher speeds at one end, as shown in Figure 2 left). However this thickness of a base layer inhibited the bonding of the melted powder to the substrate and any sintered material was swept away with each recoating because it was not anchored down. Increasing the surface roughness of the substrate (by steel wool and sand blasting) helped, but did not resolve the issue. The difficulty was overcome by preheating the upward facing surface of the substrates using a heat gun (Figure 2 right) to approximately 120°C and then transferring them directly into the SLM and starting the melting process immediately after the chamber reached vacuum. Lines 50mm in length with ascending widths were laser scanned at 0.030, 0.050, 0.080, 0.125, 0.200, 0.250, 0.500, 0.750, 1, 2, 3, 4, 5, 7.5 and 10mm all with a 3mm gap between them, and 100W laser power with a maximum power density of 14.1 MW/cm^2.

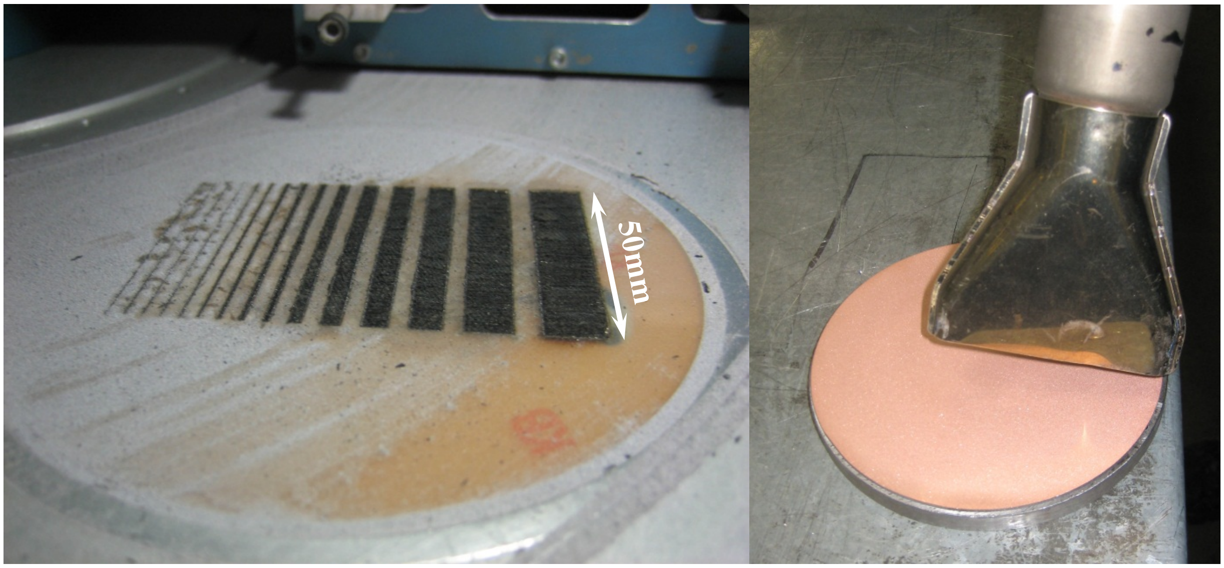

Figure 2 – Powder spreading challenges on FR-4 (left); Off-line substrate preheating (right)

The next challenge was encountered when exposure to the laser caused the substrates to warp which prevented subsequent recoating as shown in Figure 3. Even with the laser power reduced to 50 W with a 30µm spot size scanning at 0.4m/s (with single raster boundaries, all in <0.2% Oxygen), the FR-4 and Kapton® film substrates were thermally damaged before the powder began to fuse. In addition to the need for better thermal management, this highlighted the need to attach substrates to the build platform in a way that kept them flat when heated.

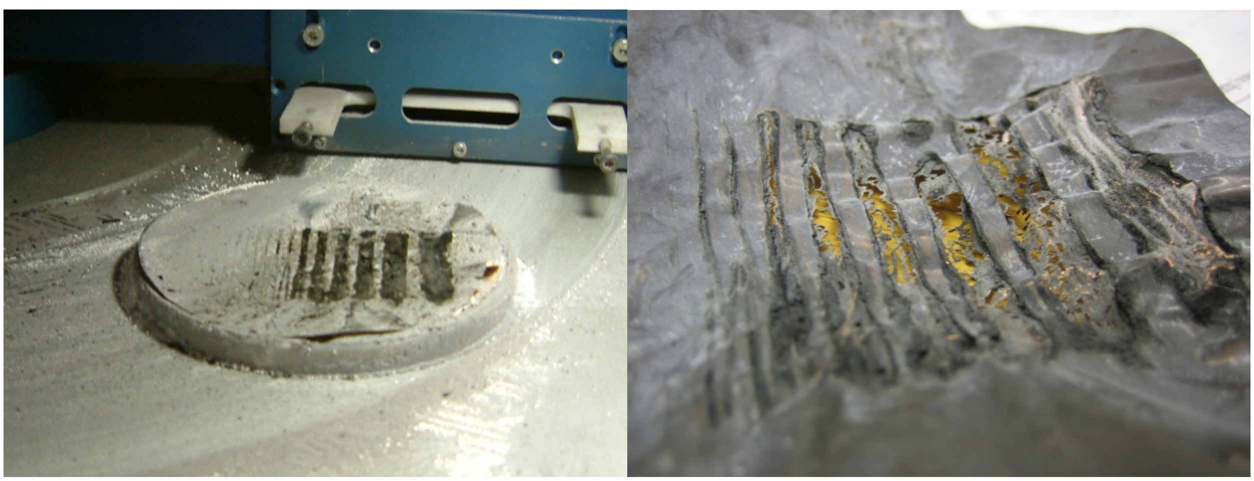

Figure 3 – Kapton® Film substrate warping in SLM (left) and laser induced damage (right)

4.3 Reducing thermal damage using protective layers

After the catastrophic failures of the most common electronics substrates, it became evident that the thermal mass of heated copper powder approaching its melt temperature was sufficient to burn the substrate without any direct contact from the laser. To protect the substrate from thermal damage during the laser melting process it was deemed necessary to deposit a temperature resistant, low thermal conductivity layer which would become the build surface for the conductive track deposition/consolidation.

As a first step to trial the concept of using protective under layers, the copper clad side of a sheet of FR-4 laminate was used with the hope that the copper cladding would act as a heat shield to protect the glass fiber substrate beneath it. Figure 4 (left) shows the sample during processing in the SLM at the same parameters as last time and the resulting thermal damage evident from the backside. For lines with thicknesses below 200 µm less thermal damage occurred (Figure 4 right) and some accumulation of consolidated powder is evident as shown in Figure 5.

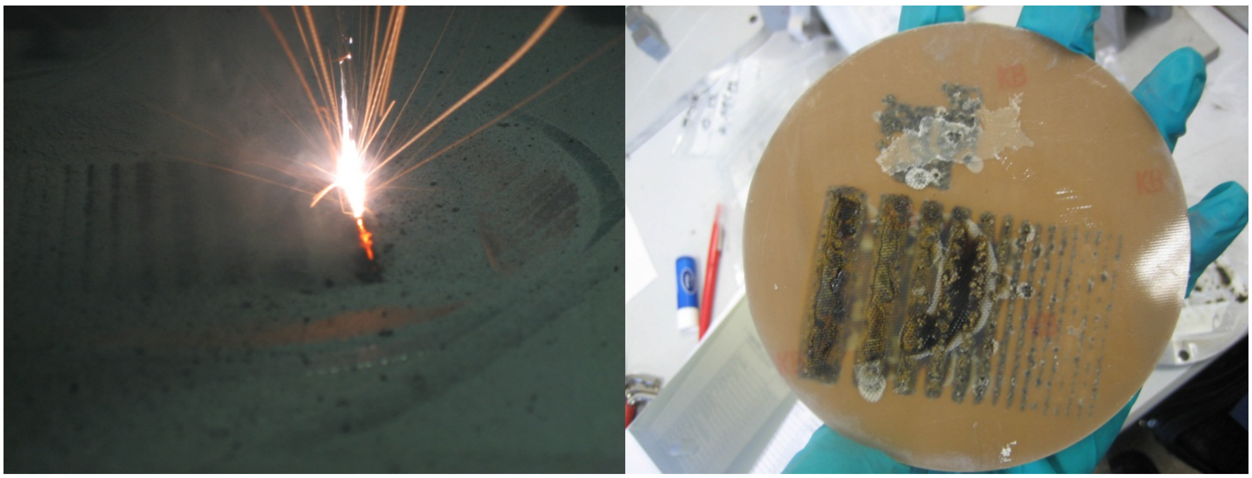

Figure 4 – SLM of AlSi12 onto copper clad FR-4 laminate (left) and thermal damage on the backside of the same sample after processing (right)

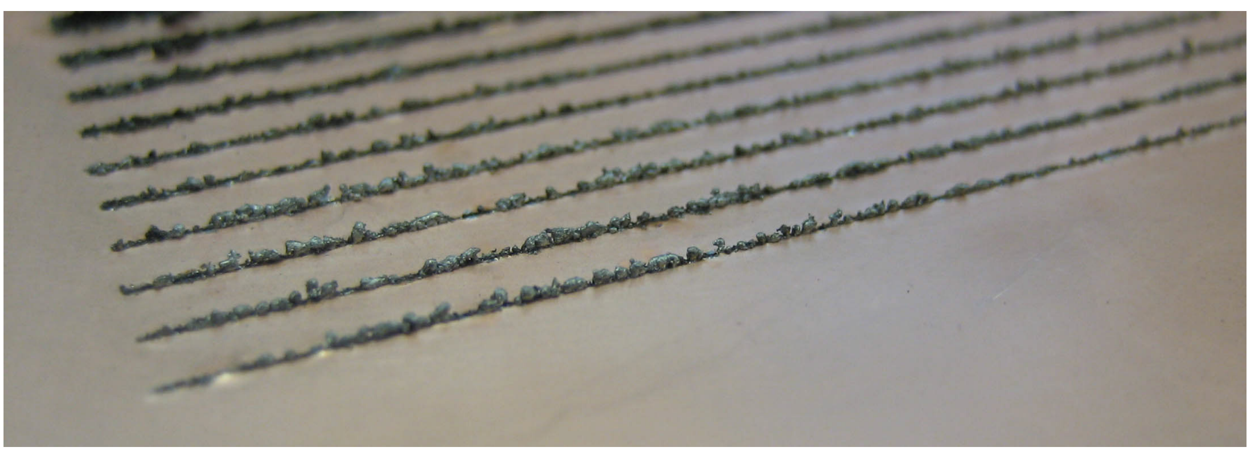

Figure 5 – Deposition of laser melted AlSi12 on copper clad FR-4 laminate

Building on the improved results above, a heat shield layer was applied to Kapton® film and a polycarbonate CD. Although electronic circuits are not generally produced on a polycarbonate CDs, they were exactly the right size and shape to fit on the platform without any routing and provided an approximate indicator of the effectiveness of the protective layer with a melt temperature in the range of FR-4 [33]. A ceramic paste was made using alumina powder (CT3000 SG, Almatis, Germany) and water. The paste was applied to several circular Kapton®

films and polycarbonate CDs and allowed to dry overnight to provide a weakly joined ceramic powder layer up to 500 µm thick. The ceramic covered films and CDs were then loaded into the SLM 100 one at a time and processed with the same parameters as the last two trials.

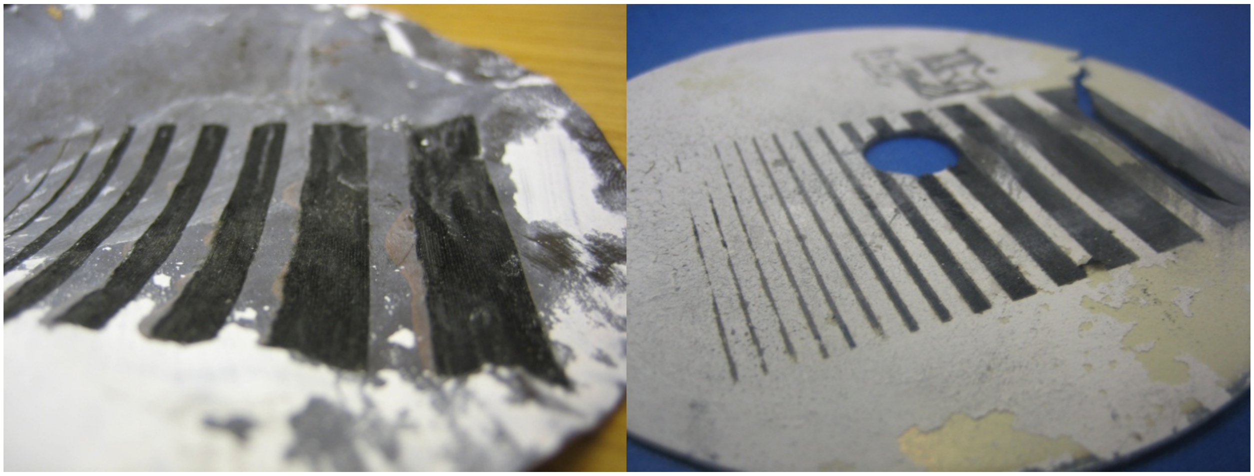

Figure 6 – SLM of AlSi12 onto Kapton® film and a CD, both protected with a ceramic coating

Even with the protective layer, all of the samples made of Kapton® film warped severely (Figure 6 left) after a single pass with the laser which necessitated aborting the build cycle. In each case the warping caused the ceramic layer to crack and delaminate from the substrate. Even though much of the ceramic layer flaked off with the warping and subsequent handling, it did provide a measure of shielding from the laser which is evident when comparing the damage on the coated (Figure 6 left) and uncoated Kapton® films (Figure 3). Virtually no AlSi12 adhered to the substrate.

The nearly pure polycarbonate CDs resisted warping except in the widest of tracks. This allowed recoating so that six layers of AlSi12 were successfully processed with the same laser parameters as the previous trials. After observing significant cracking in the CD (Figure 6), the power was reduced to 20 W which resulted in minimal damage to the CD. As with the Kapton® film samples, it was clear that the protective layer had aided the survival of the substrate . The CDs did have a small accumulation of AlSi12, however, most of the consolidated powder was brushed away during recoating along with some of the protective ceramic coating.

Although the ceramic powder layer was not very durable it did reduce the substrate damage by providing thermal shielding. This was a partial proof of concept toward enabling selective processing of high melt temperature conductives on low-temperature substrates. The next step was to provide a build surface which was stable enough to provide an anchor point for the metal as it solidified and contracted. It was also desirable to have more favorable wetting characteristics for the molten metal.

4.4 Melting copper in the SLM 250 with protective layers

Encouragement from the commercial partners shifted the focus of the laser melting work from AlSi12 to experimenting with copper. Previous work melting copper and copper alloys has been conducted using electron beam, Nd-Yag laser, and high power (1000 W) fiber lasers and full density parts have been difficult to achieve [34-37]. Although the literature provided insights into the difficulties of fully melting copper it did not provide a set of parameters suitable for use with the 200 W pulsed infrared fiber laser in an SLM 250 which was used for the early stages of these trials. The reflectivity of pure copper in the infrared laser range (1060-1090nm) is 71% as measured by Diffuse Reflectance Infrared Fourier Transform Spectroscopy (DRIFTS) [20]. It should be noted that if an SLM machine was intended solely for use on highly reflective materials, a much shorter wavelength would be a far more energy efficient way of melting copper as opposed to using a higher power laser where much of the energy is reflected.

In an attempt to provide a stable build surface as an anchoring point for laser melting, a commercially available insulated metal substrate (IMS-20, CCI Eurolam, France) was trialed. The IMS-20 is sold with a copper foil (35 µm) laminated onto a dielectric insulation layer (~100 µm) which is backed with a sheet of aluminum (1.0mm) to dissipate the heat. Prior to use in the SLM, all of the copper foil was etched away leaving only the insulation layer with aluminum backing. The IMS-20 was mounted with the insulation layer up using screws at the four corners with a specially tapped build plate (Figure 7) which allowed the use of the platform heater.

High conductivity 38 µm diameter 99.7% pure copper particles (Sandvik Osprey, Wales) were processed in the SLM 250 at 200 W with an 80 µm spot size (maximum power density of almost 4 MW/cm^2), scanning at 0.31 m/s for five 50 µm layers (all in <0.1% Oxygen). The build was started on a single layer thickness of powder spread onto the substrate after the platform substrate heater reached a stable 150°C. 5 mm wide tracks were attempted. The high reflectivity of the copper powder, especially when molten, is evident in Figure 7 (left). The result of the initial trial was that the laser had ablated through the insulating layer and into the aluminum and virtually no consolidated copper had adhered to the substrate (Figure 7 right). Another substrate was trialed with double the scan speed (0.6 m/s) and a double layer spread (100 µm) for the first layer with similar results.

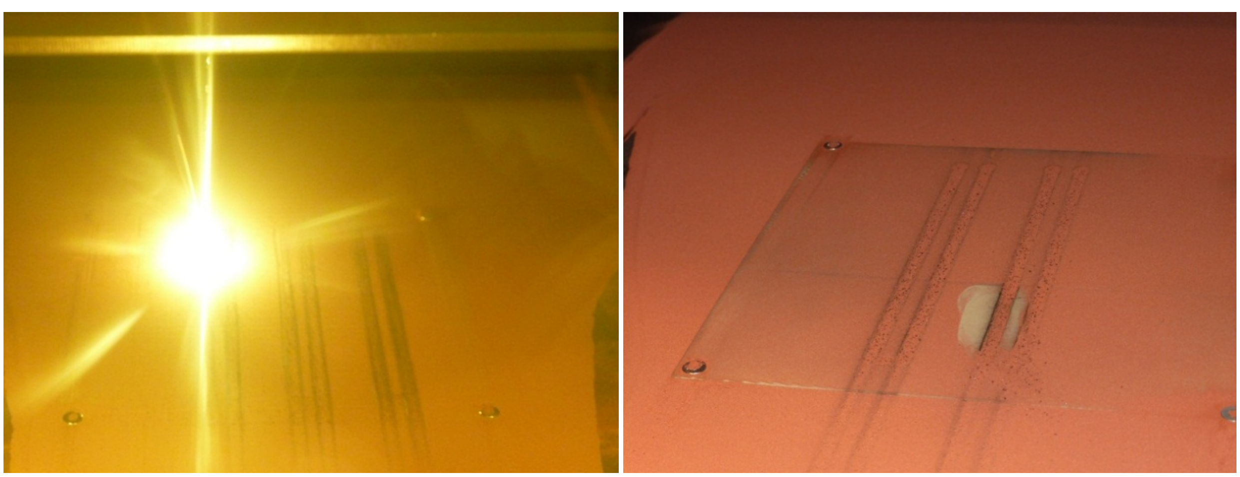

Figure 7 – Laser melting copper onto an insulated metal substrate covered with copper powder (left), and the resulting unintentional laser ablation of the substrate (right).

A trial matrix was run at 0.3m/s and 0.6m/s and 200, 150, 100, 50 W laser powers with no substrate preheat, 0.15mm hatch spacing, a 100 µm first layer thickness, 50 µm layer thickness thereafter, and 50 µm wide tracks (where the laser scanned two lines side-by-side with a 50 µm separation between the centerline of each). Only the highest two power inputs (200 & 150 W at 0.3 m/s) resulted in loosely sintered tracks which could be handled, the rest fell apart.

The results from these trials indicated that the insulating layer in the IMS-20 did not provide as much thermal shielding as the ceramic powder layer used previously. This may be the case for a number of reasons: a) perhaps the loosely bonded powder did not transfer the heat as well as a homogeneous insulating layer, b) the commercially produced insulating layer was only 1/5th as thick as the previous protective layer, c) the dielectric material could not sustain temperatures approaching the melt point of copper (1083°C), or d) the aluminum backing became molten underneath it (at 660 °C, well below the melt point of copper), and unsupported it, fractured and failed. The search for the perfect protective layer was stopped short in the interest of exploring the feasibility of sintering copper into conductive tracks. After all, there is no point to optimize a protective layer if it is not practical to laser melt copper onto it.

4.5 Melting copper in the SLM 250 onto high temperature substrates

In order to have the maximum flexibility to optimize laser processing parameters for copper, independent of the low-temperature substrate limitations, it was decided to use ceramic substrates. Early trials were made on white unglazed decorative tiles until 1 mm thick electronics grade (ADS-96R) alumina (Al_2O_3) substrate (Coorstek, Colorado, USA) was obtained.

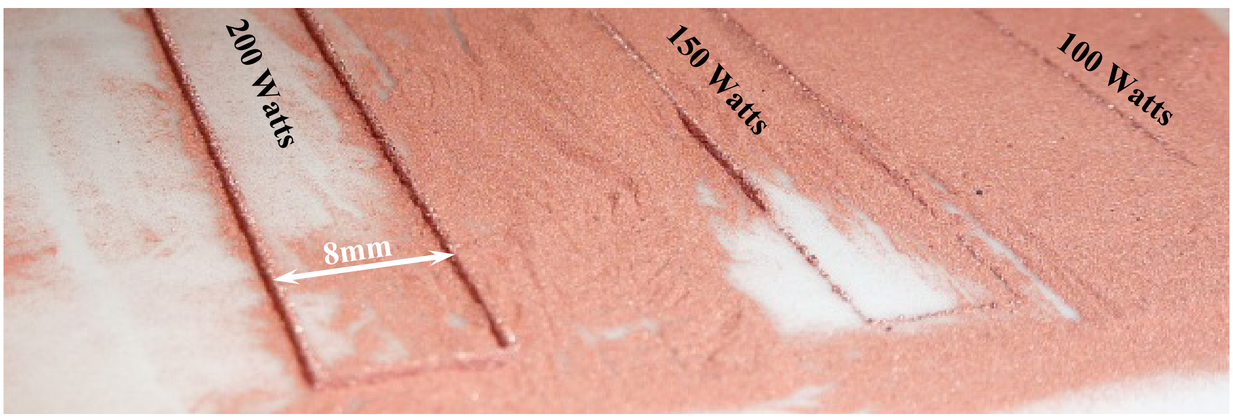

Figure 8 – Early conductive copper tracks on a decorative tile by SLM

Figure 8 shows the results of a trial matrix that was run in the SLM 250 at 0.3m/s and 200 (far left rectangle in Figure 8), 150, 100, 50 W laser powers with no substrate preheat (tile fixed to substrate with double sided tape), a 100 µm first layer thickness, 50 µm layer thickness thereafter, and 50 µm wide tracks (where the laser scanned two lines side-by-side with a 50 µm separation between the centerline of each).

Only the highest two power inputs delivered loosely sintered tracks which could be handled, even though they left much to be desired in terms of mechanical integrity and conductivity.

Using the increasing line thickness test from before, samples were produced at 100 and 200 W power levels. Other conditions were kept the same: no substrate preheat, a 100 µm first layer thickness, 50 µm layer thickness thereafter, 80 µm spot size, and 0.3 m/s scanning speed.

The sample produced at 100 W is shown in Figure 9 and is characterized by electrical continuity to some degree in nearly all of the unbroken tracks and the fact that the substrate was not cracked during laser processing. Unfortunately the sample was broken during removal from the build platform as shown in Figure 9 (right). In the thicker tracks some delamination of the consolidated tracks from the substrate occurred, highlighting the relatively weak bond between consolidated metal and ceramic substrate. Microscopy shows tendencies toward balling and peeling, but overall this result was an encouraging indicator of the potential to laser melt copper.

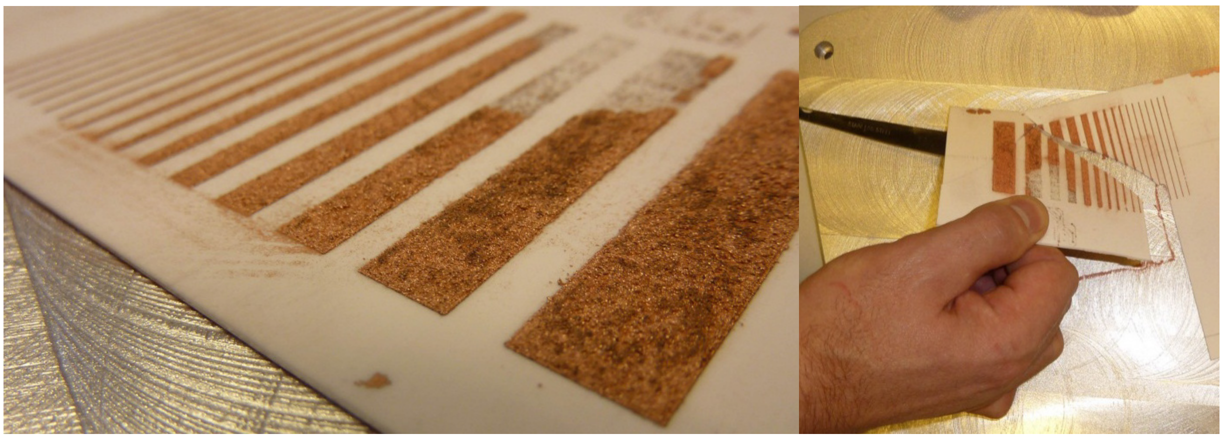

Figure 9 – Copper tracks on Al_2O_3 substrate, laser melted at 100 Watts

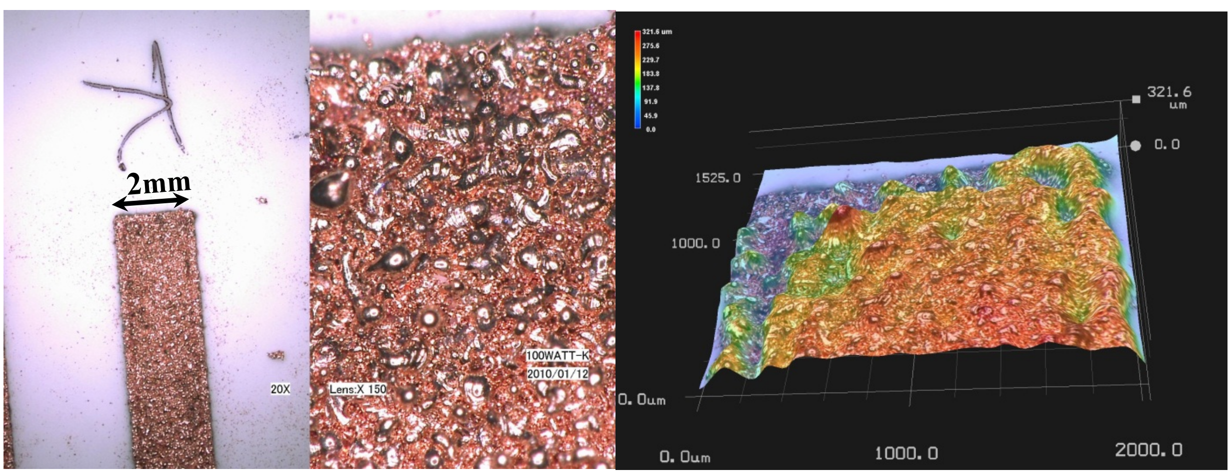

Figure 10 – Microscopy of copper tracks laser melted at 100 Watts (left), dimensional analysis of the end of the same track – notice the variation in track height (right)

Although less double-sided tape was used to secure the substrate for the 200 W sample, enough thermal stress was generated that a large crack propagating from the 7.5 mm wide track developed during laser processing. Despite the substrate failure, many of the thinner tracks (far left in Figure 11) exhibited evidence of more complete melting when viewed under a microscope. The higher laser power and slow raster speed increased balling tendencies due to the surface tension effects on a larger and less stable melt pool (which created more surface roughness - compare the track in Figure 10 left, with the left track in Figure 11 center) [20, 38].

Also, under high magnification surface cracking on melted powder was evident (Figure 11 right – indicated by the arrow).

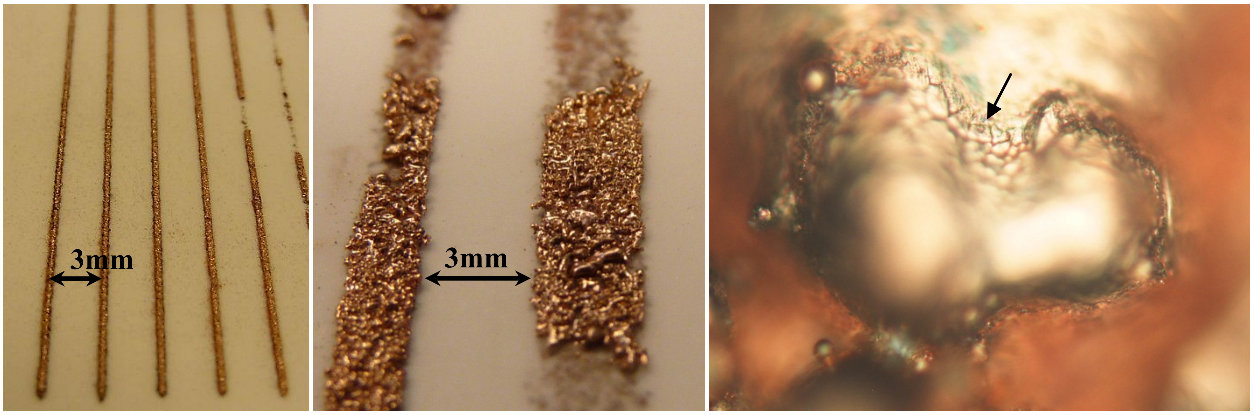

Figure 11 – Photos of copper tracks laser melted at 200 Watts (left & center), microscopy of area exhibiting "balling" and surface cracking as indicated by the arrow (right)

After empirical testing a suitable set of parameters (Table 1) was found to enable fabrication of freestanding features such as the one cubic centimeter sample shown in Figure 12 which was produced with similar settings to before only using a 0.16 m/s scanning speed.

All with: • SLM 250 • 200 Watts power • 0.080mm spot dia. • <0.1% Oxygen		Scan Speed (m/s)						
		0.308	0.286	0.266	0.250	0.235	0.160	0.114
Hatch distance (millimetres)	0.120 mm	□	□	□	□	□	■	◘
	0.140 mm	■	□	□	□	□	▪ (grey)	◘
	0.150 mm	■	□	□	□	□	▪ (grey)	◘

□ = washed away ■ = adhered to substrate ▪ (grey) = build aborted ◘ = cracked substrate

Table 1 – Test matrix: finding a process window for pure copper melted with a 200 Watt fiber laser

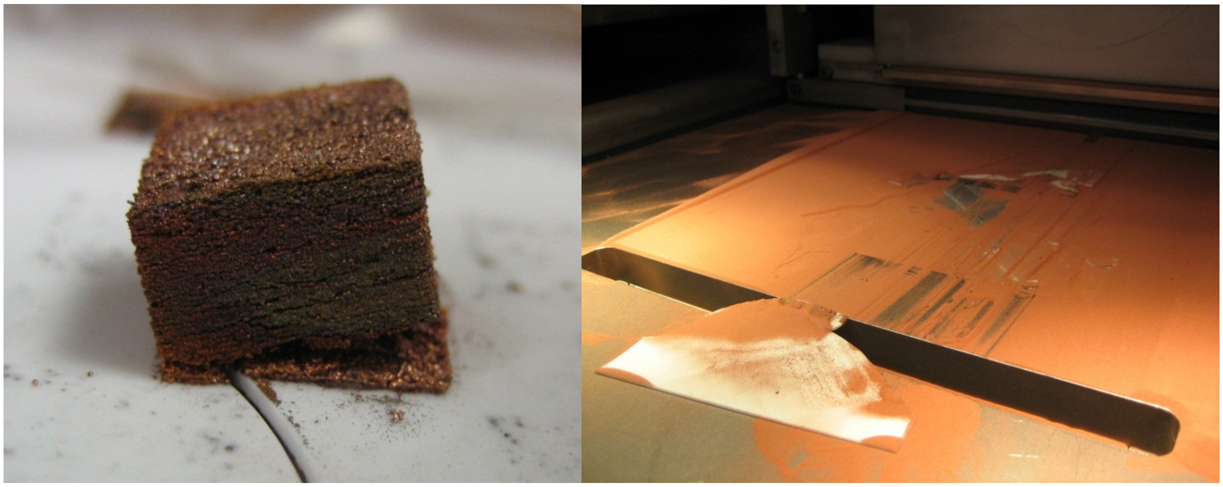

Figure 12 – 1 cm^3 structure (left) and ceramic substrate broken due to thermal stresses (right)

While attempting to increase the density of the melted copper by scanning even more slowly (0.11 m/s) the ceramic substrate cracked and the build was aborted (Figure 12).

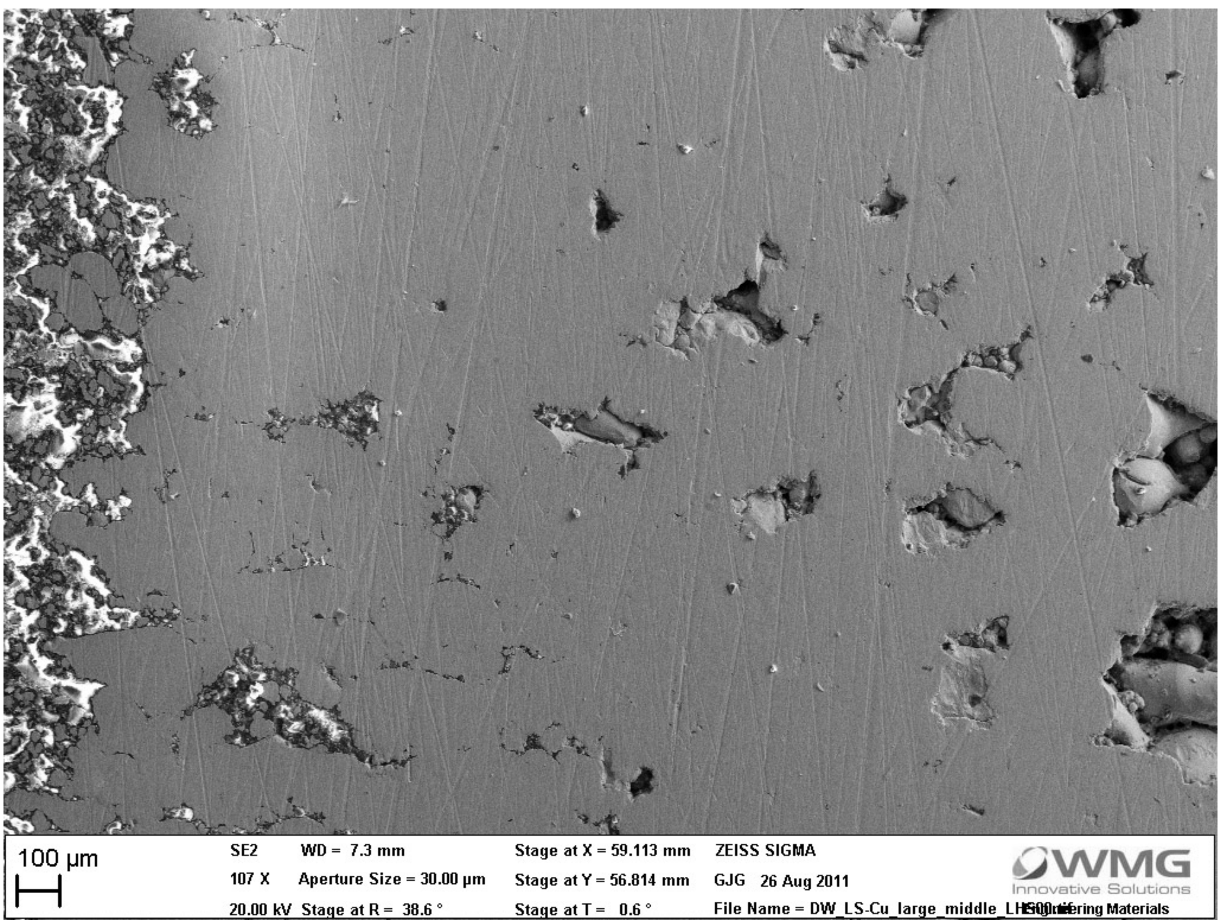

Figure 13 – SEM secondary electron image of the edge of the Cu cube melted with a 200 W laser, 0.16m/s scan speed & 0.12mm hatch distance

The cube was mounted, polished, and inspected via SEM (Gemini, Carl Zeiss, Stuttgart, Germany) as shown in Figure 13. A substantial amount of melting is evident despite some porosity. It is hypothesized that the porosity may be caused by the presence of copper oxide (probably formed on the outer surface of the powder during loading into the hopper which was not performed in an inert environment) which has a higher melt temperature than pure copper. The density of the cube was 6.55 g/cm^3 (measured by direct measurement of volume) making it 73% the full density of pure copper.

4.6 Melting copper in the SLM 125 onto high temperature substrates

The release of the MTT SLM 125 opened new possibilities for sintering copper because higher power densities than before were achievable due to the 200 W laser power and optics focusing it down to a 30 µm spot size (maximum power density of 28.3 MW/cm^2). Additionally the build chamber management maintains the environment at fewer than 5 parts per million oxygen. In order to allow in-process substrate heating in the SLM 125 a bespoke build plate was made which held the ceramic substrates in a recessed pocket alleviating the need for double-sided tape or screws. Lastly, with the SLM 125 it was possible to load powder into the hopper in an inert environment to avoid any contamination to the oxidation prone powder.

A simple circuit was designed as a benchmark to compare laser sintered tracks with tracks made by conductive silicone (SS-26F by Silicone Solutions, Twinsburg, OH, USA). To compensate for the relatively low conductivity of the silicone compared with pure copper, the circuitry tracks were designed with a large cross section (2.28mm^2).

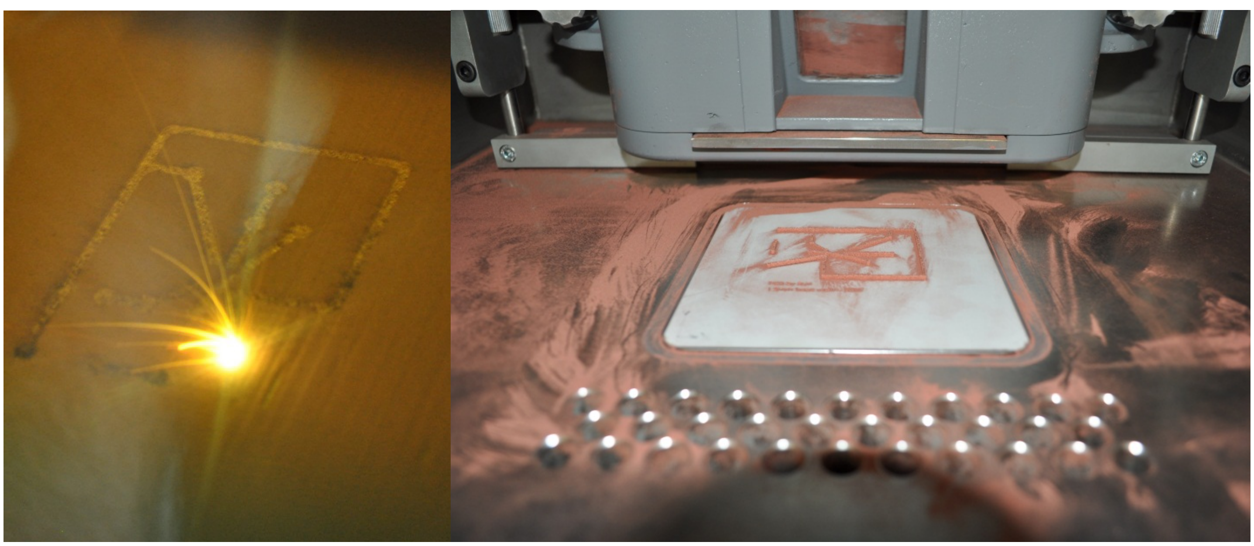

Figure 14 – Laser melting copper tracks in the SLM 125

Parameter optimization for processing the copper material on the new machine was done empirically. The printed circuit board tracks shown in Figure 14 were produced using: the same copper powder as in all trials in this paper, a substrate preheat of 150° C, 200 W of power, 30 µm spot size, 0.5 m/s scanning speed, 0.07mm hatch spacing, a 100 µm first layer thickness and 50 µm layer thickness thereafter.

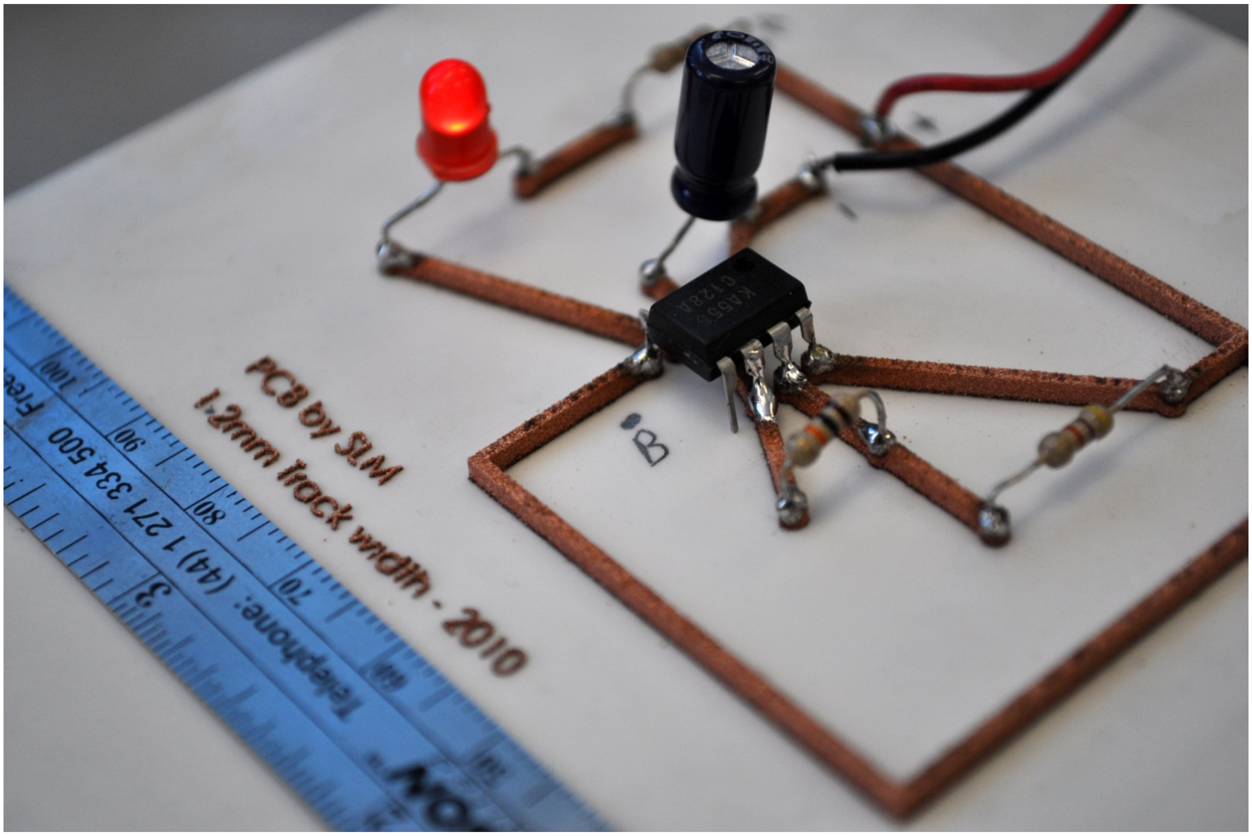

Figure 15 – A fully populated and functional PCB with laser melted copper tracks

The holes for the components were designed into the CAD of the circuitry so that they were incorporated into the copper tracks during the laser melting process and in that way, did not require drilling. Components were soldered on using conventional solder and soldering iron without any problems (Figure 15). The circuit functioned as expected. The higher power density of the laser and lower oxide content improved the result of the laser processing considerably over the tracks melted using the SLM 250. Conductivity measurements on tracks with such a large cross-sectional area ($2.28mm^2$) reached the limit of the resolution of the meter, therefore making it difficult to quantify the expected conductivity reduction due to any oxides and porosity in the laser melted tracks compared to fully dense pure copper.

This is the first PCB of laser consolidated copper tracks made from microscale powder known to the authors.

5 Conclusions: double selection

Producing a PCB by this method can be considered by some measures, as using a sledgehammer to crack a nut. In spite of the failed attempt at selectively depositing metal powder and the costly equipment for selectively melting it, the research journey has illustrated some of the challenges and potential benefits of selectively depositing and processing materials with dramatically different properties in close proximity.

6 Future Work

Full characterization of the electrical characteristics of the laser melted tracks would enable direct comparison against other digitally deposited PCB production methods and act as a means of quantifying the potential benefits.

Laser printing protective layers as powder which are then fused together may impart the thermal shielding and stability required for laser melting. Potential candidate materials include resin bonded ceramic composites. Toner formulations could be devised and tested to assess both their printing efficieny and ability to provide a protective layer. Additionally, by laser printing them the thickness could be varied to fine tune the desired shielding.

In addition to the reflectivity of copper, its excellent thermal conduction properties make it difficult to laser melt because the heat is dissipated so quickly into surrounding particles in the powder bed. Truly selective deposition of copper powder onto a substrate with low thermal conductivity theoretically would localize the thermal input from the laser increasing its effectiveness because by isolating it from the powder bed there would be no other means by which the heat could be efficiently conducted away.

Tailoring the conductive track cross section could also allow high power components to be integrated into the same PCBs as logic boards (operating at 5VDC) eliminating the current practice of producing separate boards for logic and power components.

Mastering conductive tracks paves the way for future digitally printed electronics applications which is/will undoubtedly expand to include: generation of integral passive components (resistors, capacitors), direct deposition of conductive tracks and components onto packaging, production of smart tags/labels (for example RFID, EAS and electroluminescent labels) including potential to directly print onto packaging, generation of SMART devices (for example piezoelectric sensors/actuators) and manufacture of LED and display devices.

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