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DIGITALLY-DRIVEN HYBRID MANUFACTURE OF CERAMIC THICK-FILM SUBSTRATES

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Abstract — Ceramic substrates are commonly used in the electronics industry across a range of applications such as automotive, aerospace, industrial monitoring, power electronics and electromagnetic devices due to their ability to withstand high temperatures, pressures, radiation and mechanical shock. This paper will present the development of a new digitally- driven hybrid manufacturing process which overcomes many of the current limitations of stand-alone Additive Manufacturing for the production of precision engineered ceramic substrates and packages. This is achieved by interleaving ceramic paste extrusion with sacrificial support printing and micro-machining to produce a three-dimensional ceramic green-state part. A number of substrates were fabricated using a high viscosity, non-Newtonian paste consisting of 96wt% alumina. Thermally processing the substrate at temperatures in excess of 1400°C yields a monolithic ceramic substrate with resultant shrinkages of ~18% and part densities of ~99.8%. The 3D ceramic part is then processed using computer-controlled equipment to selectively dispense a conformal circuit using silver thick film conductor paste, followed by solder dispensing and pick and place surface mount assembly of components. This fully digitally driven approach enables new design freedoms and customization currently not possible with conventional template driven manufacturing methods of ceramic electronic packages.

Keywords — Hybrid, Additive Manufacturing, Ceramic, Electronic Substrates

I. INTRODUCTION

Thick film ceramic substrates and packages are used in a number of high performance and harsh environment electronics applications [1]–[3]. Predominant methods of manufacture are reliant on templates and tooling, which require volume production to be economically viable, impose significant design constraints and increase development lead times and cost. Typically, devices fabricated using thick film approaches are planar, 2.5D geometries owing to the substrate manufacture and screen/stencil printing process used to create the electronic circuits.

Conventional, thick film manufacturing of ceramics involves the deposition of conductive, resistive and dielectric materials onto a ceramic substrate. These substrates are commonly produced using 94-98wt% alumina with a particle sizes ranging from 3-5µm. The substrates are formed using templates and tooling before being thermally processed to sinter the ceramic and yield a monolithic component. Subsequent deposition of thick film pastes by screen and stencil printing form the electronic elements of circuit with typical thicknesses ranging from 5-20µm. Further thermal processing is used to sinter the deposited material and create permanent adhesion to the ceramic substrate.

Digitally-driven fabrication methods such as additive manufacturing produces components directly from digital data without the need for component specific templates and tooling. These approaches enable responsive, rapid production of geometric complex parts. A number of these processes have been adapted to facilitate the processing of engineering ceramics such as alumina, zirconia and silicon carbide ceramics [4]–[6] Direct processing of ceramic feedstock is highly challenging, largely due to the very high stresses from direct thermal processing the inferior mechanical properties achieved [7]–[9] hence the reason why most AM processes typically use an indirect method to produce a green part.

Stereolithography is the most widely researched ceramics additive manufacturing approach due the resolution achievable. This process involves dispersing the ceramic material within a photo curable monomer, and selectively curing individual layers to build up a 3D green component. Due to the dispersion of light and high loading of ceramic material, during thermal processing, high shrinkages of up to 30% are common increasing the formation and propagation of cracks within the part [10]–[12]. The process is additionally material limited due to the effect of colour and absorption characteristics of the feedstocks. Consequently, a number of challenges exist around the processing of dark materials, thus limiting the range of processible materials.

Powder based processes such as selective laser sintering typically requires the ceramic feedstock to be coated with a sacrificial polymer binder in order to lower the sintering temperatures [13]–[15]. Once the green component has been fabricated it is thermally processes to remove the polymer and sinter the ceramic. Alternatively, binder jetting selectively dispenses binding agent onto the powder bed and consequently doesn’t require modification of the ceramic feedstock [16]. However, both SLS and binder jetting require the feedstock to retain sufficient flowability to ensure the production of uniform layers. Furthermore, the processing of dry powder feedstocks results in fabricated components which are not fully dense, have a rough surface finish and poor dimensional accuracy. Ceramic slurries have demonstrated improved flowability, density and surface finish but issues with agglomeration and cracking remain [17].

Material extrusion is one of the most versatile configurations for the production of ceramic components owing to the wide range of machine configurations and feedstocks available. Various feedstocks exist that can be processed using material extrusion hardware. Typically, feedstocks can be classified as a loaded polymer filament or a high viscosity paste. Whilst these systems can obtain higher loadings of ceramic material, typically up to 75vol%, these systems demonstrate poor dimensional accuracy with significant stair stepping [18][19].

Despite the relative merits of the aforementioned processes, the shortcomings of additive manufacturing are compounded when processing ceramic materials due numerous material and processing challenges that often result in high shrinkages and porosity. Moreover, limited multi-material compatibility inhibit the production of more functional components including electronics.

Hybrid manufacturing is an emerging field of digital manufacturing, which interleaves multiple manufacturing processes into a single, integrated system [20]–[22]. This paper will present the development of a hybrid manufacturing system combining high viscosity paste dispensing, Fused Filament Fabrication (FFF) printing of a sacrificial support material and micro-machining to produce geometrically complex ceramic substrates. Figure 1 illustrates the key elements of this bespoke manufacturing apparatus.

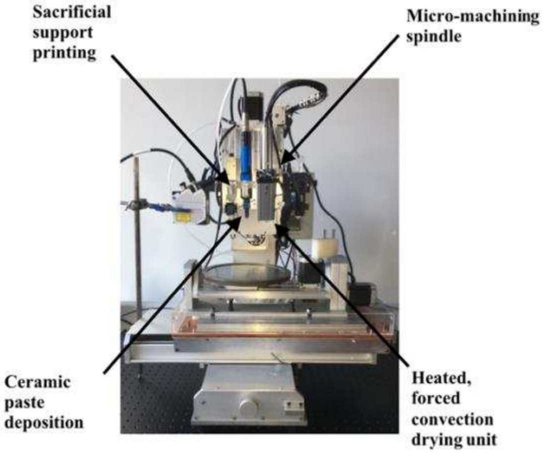


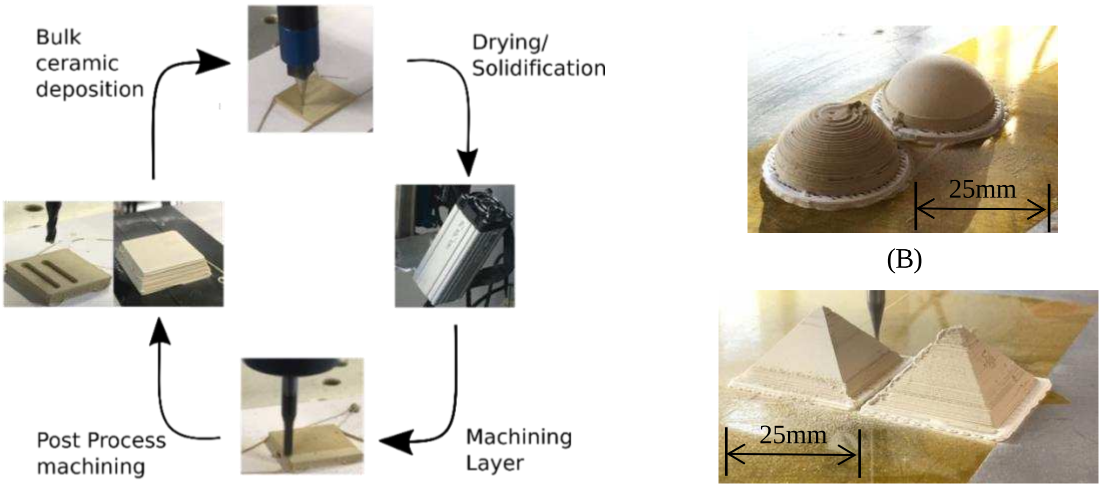
Figure 1 - Manufacturing apparatus that combined ceramic paste deposition, micro-machining, sacrificial support generation and accelerated drying capability.

II. METHOD

The system was developed using 96wt% alumina with an average primary particle size of 2-12µm that had been formulated into a high viscosity, aqueous paste with a measured moisture content of between 18-22%, using a binding medium developed by Morgan Advanced Materials using a proprietary composition. Characterisation of the paste confirmed the pastes non-Newtonian properties and thixotropic response.

The hybrid manufacturing system is mounted to a bespoke CNC controlled 3-axis stage that has been specifically developed to interface with the different manufacturing elements. Extrusion of the ceramic paste is achieved using an auger screw, high viscosity paste dispenser (Eco-pen 300, Germany) using interchangeable luer lock nozzles. During the optimisation stage, 25 gauge (437µm) tapered nozzle with extrusion rates between 80 to 120µL/min and nozzle speeds between 380 and 470mm/min as these were found to produce the most consistent results. Further optimisation of the processing parameters identified a nozzle speed of 410 mm/min with an extrusion rate of 104µL/min as being optimum for this process. Micro-machining capability is obtained using a high-speed spindle with automatic tool change attachment (Nakanishi, Japan) and CVD diamond tool bits. Components are manufactured on a substrate of PLA polymer, deposited by an FDM hot end with 0.4mm nozzle (E3D, UK) and extruder (Bulldog Lite, UK) using 1.75mm filament. Sufficient adhesion between the PLA and ceramic material enabled the use of the PLA as a sacrificial support structure for the production of overhanging and internal cavities. The various elements of the process are controlled and actuated using commercially available CNC control software that has been modified for this application (Newfangled Solutions, USA). Toolpaths are generated using process specific software that are post processed and amalgamated into a single file.

The fabrication of the green components involves the selective deposition of ceramic material with a controlled excess to ensure sufficient scope to planarize the surface. Once sufficient drying of the layer has occurred, the machining stage is initiated to remove excess material. Sacrificial PLA support structure can be deposited onto the substrate if required. Once fabricated, the green components can undergo post process machining to remove stair-stepping and other defects. Following a standard production thermal cycle, in which temperatures exceed 1400°C, the parts were successfully sintered, undergoing a measured shrinkage of ~18%. Testing of the manufactured substrates was undertaken to determine the density of the manufactured substrates, surface roughness and mechanical bend strength. Density and associated porosity was calculated using the Archimedean approach using a 0.1mg accuracy micro-balance (Sartorius, Germany) [4]. Surface roughness measurements were obtained using 3-dimensional focus-variation measurements (InfiniteFocus, Alicona, Austria). Mechanical bend strength was determined by 3-point bend testing of samples measuring 5mm x 5mm x 50mm. The test parameters were derived from the standard tests used by Morgan Advanced Materials (Z005, Zwick/Roell, Germany). Analysis of sectioned components using SEM confirms the production of monolithic ceramic components. Figure 2A illustrates the hybrid manufacturing process and Figure 2B and Figure 2C shows components fabricated using this method.



(A)

(B)

(C

Figure 2 - A: Process flow for the hybrid manufacturing of precision engineered ceramic substrates. B: Comparison of hollow hemispheres manufactured using additive manufacturing only (left) and hybrid manufacturing using in-situ post process machining (right) C: Comparison of pyramids manufactured using the hybrid approach (left) and additive manufacturing only (right)

Electronic circuitry was produced using silver-based LTCC conductor (Heraeus TC0306, Germany) dispensed using a digitally-driven, direct-write system with topographical compensation. Conductive tracks were produced planar and conformal substrates, demonstrating the capability of the manufacturing process. Sintering of the dispensed conductor required a secondary firing cycle that peaks at 865°C. Dispensing of Type-5, Sn96.5Ag0.5Cu3.0 solder paste and placement of surface mount components was achieved using a commercially available dispensing/pick and place system. The solder was reflowed using a reflow oven following the recommended thermal cycle. Continuity of the dispensed tracks were determined using a digital multimeter (Keithley, US). Track profile and dimensions were measured using 3-dimensional focus-variation measurements (In-finiteFocus, Alicona, Austria).

555-timer circuits were designed for both planar and 3D substrates to demonstrate the flexibility and capability of the proposed manufacturing process. A planar circuit consisting of 9 passive components and 1 IC and 3D circuit consisting of 5 passive components and 1 IC were used.

III. RESULTS AND DISCUSSION

The development of a bespoke hybrid manufacturing process has enabled the production of precision engineered ceramic substrates. Using this digitally-driven hybrid manufacturing approach a variety of planar and 3D substrates were fabricated using alumina and LTCC material. Rheological testing of the ceramic precursor material confirmed the paste exhibited non-Newtonian properties by sheer thinning and thixotropic response. Thermal processing resulted in measured shrinkages of ~18% of the ceramic substrates. Analysis of the manufactured substrates has confirmed the production of full-density ceramic parts with part densities of ~99.8%. Surface roughness measurements of post machined parts exhibit a measured R_a of 1.11µm compared to measured R_a value of 8.09µm for non-machined parts. Mechanical bend strength was determined to be 218MPa. Inspection of part cross-sections using SEM has confirmed the production of fully dense, monolithic ceramic parts. Figure 3 shows SEM imagery of an interlayer region on a sample.

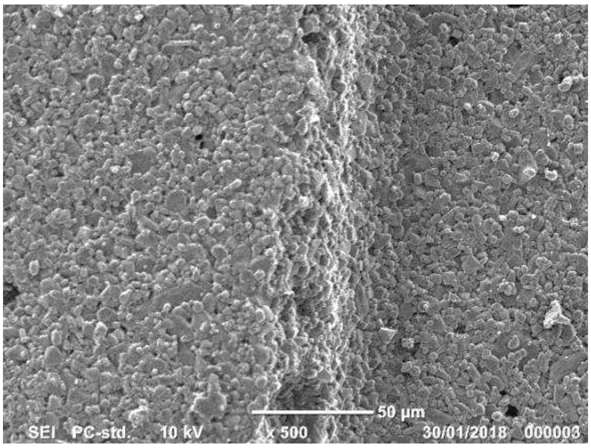
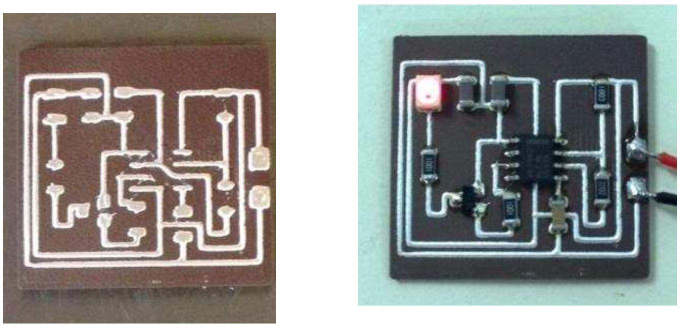


Figure 3 - SEM image of the interlayer region of a sectioned component

Deposition and subsequent sintering of LTCC silver conductor material onto the fired ceramic substrates has resulted in the production of electronic circuitry in the form of a 555-timer. Circuits were produced on both planar and 3D substrates using a free-form direct-write process, demonstrating the flexibility of the manufacturing process. The track dimensions and profile were measured to be between 200-250µm. Continuity of the circuits was validated prior to the deposition of solder and placement of components. Figure 4A shows the LTCC conductor following the secondary thermal process. Figure 4B shows the circuit with the 9 surface mount components and 1 surface mount IC package.



(A) (B)

Figure 4 – A: 2.5D planar substrate with LTCC conductor tracks. B: Functioning 555-timer circuit produced using digitally-driven, additive manufacturing

To the authors knowledge, this is the first example of a thick film ceramic substrate and circuit produced solely by digitally-driven, additive manufacturing.

Further development of the process, was demonstrated by the creation of non-planar circuitry over a 3D substrate. Free-form deposition of the LTCC conductor was used in conjunction with topographical compensation to create the circuitry on the 3D geometry. Deposition of Type-5, Sn96.5Ag0.5Cu3.0 and placement of surface mount components as small as 0603 (1608 metric) was achieved. Figure 5 shows the production of a 555-timer circuit on a 3D substrate produced using this digitally-driven hybrid manufacturing approach.

(A) (B)

Figure 5 - A: 3D substrate with LTCC conductive tracks. B: 3D substrate with working 555-timer circuit produced using the digitally-driven, hybrid manufacturing approach.

Figure 6 shows a LTCC substrate with LTCC conductor tracks. This preliminary work demonstrates the capability of the process to use co-fireable material for the creation of multilayer electronics.

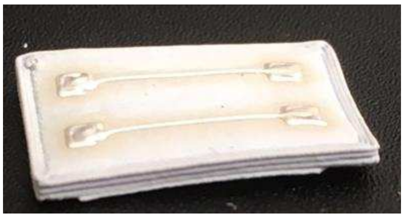


Figure 6 – Deposition of LTCC silver conductor onto a LTCC substrate

The production of an LTCC substrates confirms the capability of the manufacturing process to use a range of materials whilst providing proof-of-concept for multilayer electronic substrates and packaging.

IV. CONCLUSION

In conclusion, this paper has shown the development of a digitally-driven, hybrid manufacturing process for the agile and responsive production of ceramic thick-film substrates of arbitrary geometric complexity. The substrates exhibit densities in excess of ~99.8% with measured shrinkages of ~18%. Electronic circuits have been produced using LTCC conductor and a digitally-driven direct-write process on both planar and 3D substrate. The use of components as small as 0603 (1608 metric) have been demonstrated. Substrates fabricated using alumina and LTCC materials has cofirmed the capability of the process to use a range of materials.

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