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Approaches for additive manufacturing of 3D electronic applications

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Abstract

Additive manufacturing processes typically used for mechanical parts can be combined with enhanced technologies for electronics production to enable a highly flexible manufacturing of personalized 3D electronic devices. To illustrate different approaches for implementing electrical and electronic functionality, conductive paths and electronic components were embedded in a powder bed printed substrate using an enhanced 3D printer. In addition, a modified Aerosol Jet printing process and assembly technologies adapted from the technology of Molded Interconnect Devices were applied to print circuit patterns and to electrically interconnect components on the surface of the 3D substrates.

Keywords: Additive manufacturing; Integration; 3D electronic devices; Printed electronics; Powder bed-based printing; Aerosol Jet printing

1. Introduction

The growing request for products manufactured in batch size one does not only affect mechanical functional components. This trend becomes more and more visible in electronics production as well. On the one hand, the electronic functionality has to be adapted to customer requirements more and more often. On the other hand, the electronic devices have to provide additionally integrated mechanical, geometrical, and optical functions due to the demand for miniaturization and smart systems. This is indicated by the growing market for 3D Molded Interconnect Devices, for example [1]. However, most of the processes and production chains in electronics production are focused on planar processes as well as on assembly and interconnection techniques for high volume. To enable a cost-efficient and sustainable manufacturing of customized and personalized electronics, one approach is to completely redesign established process chains and to combine additive processes for electronics production with additive manufacturing technologies (AM). In addition to the almost non-restrictive scope of design, AM processes for creating mechanical parts offer the opportunity to produce complex 3D structures. [2][3][4]

Due to the enormous progress within the last years these technologies made their way from prototyping towards manufacturing. To integrate electronic functionality these AM processes can be complemented by enhanced assembly processes and digital printing technologies used within the field of organic and printed electronics [5].

2. Options of functionalized 3D substrates

Principally, AM is based on layer-by-layer building of the parts and embedding of functional elements in every single layer. Thereby conductive circuit tracks for electronic applications can be integrated (Figure 1 feature 1). In this way multi-layer circuit carriers can be generated. Additionally, the available space allows the manufacturing of circuit tracks with a high cross-sectional area for enhanced ampacity. Moreover, electronic components or even small subsystems

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can be embedded to increase the level of integration (Figure 1 feature 2). Embedded components are additionally protected from environmental influences.

For the functionalization of the surface fine circuit patterns are created on the 3D substrate by printing processes (Figure 1 feature 3). The conductive pattern interconnects the electronic components in Surface Mount Technology (SMT) that are attached on the part's surface (Figure 1 feature 4). This enables a 3D orientation of the components which is particularly relevant for sensors or light emitting/sensitive elements. Finally, printed electronic components can be created by employing printing processes to substitute process steps for assembling and mounting of SMT components (Figure 1 feature 5).

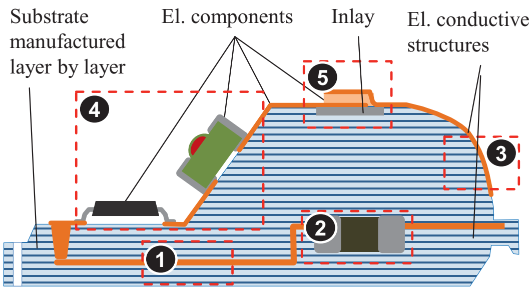

Figure 1. Opportunities for the electronic functionalization of additive manufactured 3D parts; (1) embedded conductive track; (2) embedded el. component/subsystem; (3) printed 3D circuit track; (4) mounted SMT components; (5) printed electronic component on inlay.

To illustrate the specific opportunities and challenges for AM of these 3D electronic devices, the combination of a powder bed based 3D printing and an Aerosol Jet printing process is described below.

3. Enhanced building process for 3D devices

3.1. Powder bed based printing

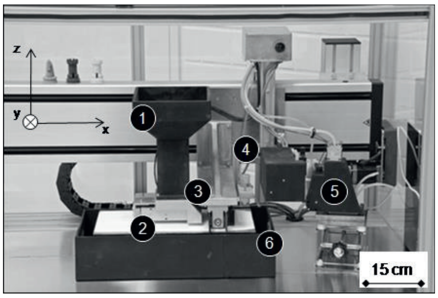

Figure 2: 3D printing test rig; powder reservoir (1), platform (2), powder feeder (3), mechanism for application of suspensions (4), printing head (5), powder overflow (6).

For the investigations presented in this paper, a flexible powder bed-based 3D-printer (Voxeljet AG) was used, see Figure 2. The process chamber has a dimension of 110 mm by 250 mm by 95 mm. The material is deposited by a powder feeder (volume of 2 l) and planed by a cylindrical recoater, rotating opposed to the moving direction of the x-axis. For the application of binder material a Spectra SL128 printing head (FUJIFILM Dimatix) was applied.

The process cycle of the powder bed based printing process is presented in Figure 3 (step 1-3). Depending on the purpose, the created parts can be post-treated by infiltrating the component for example by an epoxy resin to improve the mechanical properties. To create electronic applications in an AM part, additional methods for integrating electronic components (Figure 3 step 4), creating conductive paths during the building process (Figure 3 step 5) and generating a connection between both (Figure 3 step 6) have to be developed.

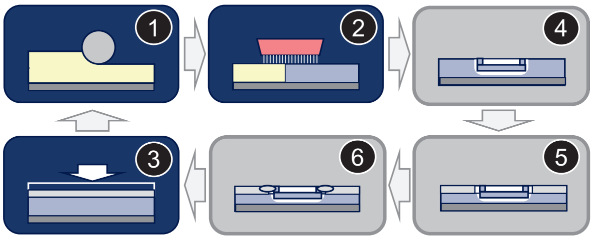

Figure 3: Enhanced process of 3D-printing; (4) embedding electrical components; (5) creating conductive paths; (6) connecting a component to the conductive path.

3.2. Embedding of electronic components (Figure 1 feature 2)

For the preliminary studies a chip resistor in SMT was regarded for integrating it into a part. For the majority of electronic SMT-components the height is considered to be higher than one powder layer. As a result, the components collide with the powder feeder during recoating (Figure 4 left side) which causes a destruction of the printed object or the powder bed. Thus, a system to create cavities during the process was integrated into the 3D printing test rig to bury the components in the powder bed (Figure 4 right side).

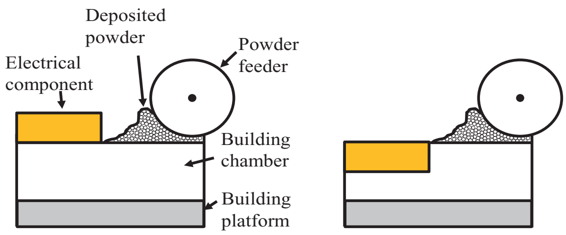

Figure 4: Chart of the problem when depositing an electronic component on the powder layer; left: components placed on the layer; right: pursued method to bury the component.

The exhausting module consists of an exhausting tool (needle), a negative pressure system and an additional axis, where both components are fixed. Based on the field of application, the needle and thereby the needle diameter can be changed. For transporting the selected SMT-components (weight of 0,45 g), a diameter of 1.6 mm was necessary to achieve a sufficient holding force for the calculated movement forces. By using the control software of the printer, the device can be moved to any position on the powder layer. Using the integrated axis, the exhausting needle can be lowered to the powder bed. The maximal range of the axis is 50 mm with a repeat accuracy of +/- 0.1 mm. Several investigations were performed to improve the accuracy and the quality of the cavities.

With the help of the new system and the adapted exhausting parameters, precise cavities can be generated during the building process. Furthermore, electronic components can be transported by the same system and can be inserted into the cavities. To avoid a destruction of the powder bed while depositing the electronic component, the generated cavities are also wider than the component. For detecting the necessary oversize of the cavities, a series of experiments with changing offsets were performed. The best results could be reached by enlarging the cavities for 0.7 mm to each side. The depth of the cavities has to be increased by 0.8 mm to enable a placed SMT-component at the same level as the powder layer. Figure 5 (step 1-3) illustrates the process of implementing electronic components during the 3D-printing process. The processed exhausting strategy is presented on the right side (Figure 5 step 1 a-b). After exhausting the powder at the corners and the midpoint of the non-printed area, the exhausting needle starts at one corner and moves to the next corner in horizontal or vertical direction. Due to this movement, the remained powder gets scraped of the walls and fell to the bottom of the cavity, where the negative pressure removes the powder. A series of experiments, where the negative pressure was modified (200 mbar to 900 mbar) pointed out, that the level of negative pressure is not relevant for the precision of the cavities.

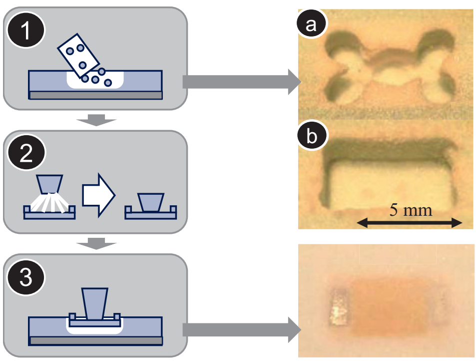

Figure 5: Burying of components; (1) approach of creating cavities; (2) sucking and transporting electronic components; (3) inserting them in the cavity and recoating with powder

3.3. Creating conductive paths (Figure 1 feature 1)

To create conductive paths during the building process of a plastic part, an additional material has to be added during the printing process. There are a few different conductive materials which differ in their state of aggregation (fluid or solid) as well as in the conductive element (silver, gold, copper etc.) and their percent by volume. A high load of conductive material often includes an increase of the viscosity, but also complicates the handling of this material [6]. Conductive materials with a viscosity below 20 cP can be handled by an inkjet printing module that is additionally integrated into the test rig. High viscous materials require have to be processed by a dispensing system.

To select a suitable conductive material, the environmental process conditions are captured and used as boundary conditions for a CFD-simulation (Computational Fluid Dynamics). The modeling includes building the geometric design of the powder followed by setting up a multiphase simulation involving the three fluids: air, binder and an electrically conductive fluid. As displayed in Figure 6, an isotropic conductive adhesive (ICA) with a viscosity of $\eta = 300$ cP and a nanosilver ink with a viscosity of $\eta = 20$ cP were investigated.

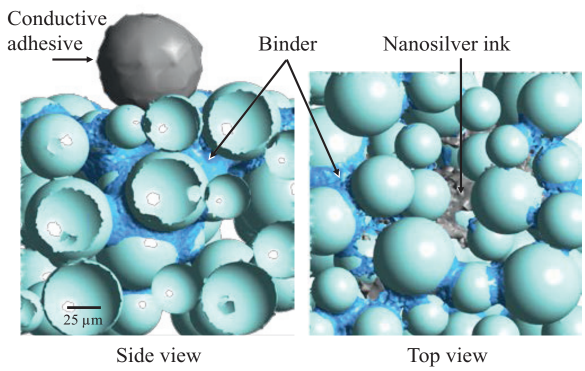

Figure 6: Results of CFD-simulated conductive materials on a powder sample; left: an isotropic conductive adhesive; right: a silver nano ink.

As a result of the simulation the suitability of a fluid to be printed on a powder-based substrate can be evaluated by the dynamic viscosity. Deposited high-viscous fluids, like the ICA, remain on the surface of the powder bed (Figure 6 left side). Low-viscous fluids get drawn into the powder and form an incoherent conductive structure (Figure 6 right side).

Based on the simulation, first investigations were made with a conductive adhesive deposited by a compressed air dispenser with a 400 µm needle on the powder bed. Applied lines with a width of 400 µm and a height of 300 µm result in a resistance of approx. 0.1 Ω/m.

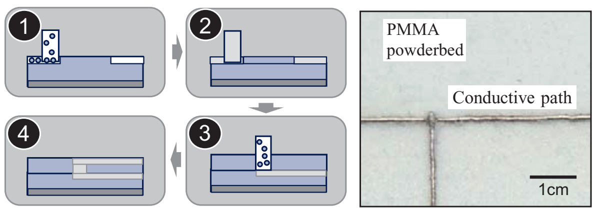

Figure 7: Approach of creating conductive paths during the building process; left: (1) creating channels; (2) filling the channels with ICA; (3) creating a cavity with the exhausting tool; (4) filling the cavity and creating another conductive path; right: conductive path on a PMMA powder bed

Due to the size of the used needle, the current paths are actually higher than a single powder layer. As a result, according to the integrated electronic components, continuing

the process without affecting the conductive path is not possible. Therefore, the already implemented exhausting system was used to create channels in the powder bed (Figure 7 step 1), which get filled with conductive material in a second step (Figure 7 step 2). By adapting the needle size and geometry of the exhausting system, the width of the channels can be reduced. The minimal feasible channel depth is 0.15 mm.
This method also enables the possibility to create three-dimensional conductive paths. By creating a cavity between different layers, which gets filled with conductive material afterwards, a via-connection between conductive paths can be achieved.

3.4. Connecting the conductive paths to the electronic components (Figure 1 feature 1+2)

To complete the electrical circuit, a connection between the conductive path and the electronic components must be generated. Due to the fact that the created cavities are wider than the integrated electrical parts, a gap between the terminal of the SMD and the created conductive line exists. To realize an electrical connection, the gap has to be bridged (Figure 8 step 1). For this the process continues as usual and the new deposited powder fills the gap (Figure 8 step 2). By using the integrated exhausting system again, the powder can be removed locally until the conductive path and the electronic component are laid open (Figure 8 step 3). The created channels can be filled with conductive adhesive by the dispenser system (Figure 8 step 4), which ensures a permanent interconnection between the conductive line and the electrical part.

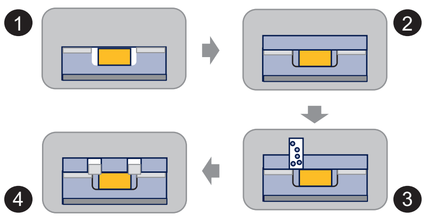

Figure 8: Approach of connecting the electronic component to the conductive path; (1) inserted SMD and conductive paths; (2) filling the gaps with PMMA; (3) removing the powder; (4) filling with ICA.

The following powder layer will fill up the created holes and the building process can be continued by depositing the binder on the powder layer, which solidifies the material and encloses the created electrical circuit.

4. Functionalization of 3D surfaces

4.1. Aerosol Jet printing

The Aerosol Jet technology developed by Optomec is a maskless and contactless direct writing technology [7]. One of the main advantages is the wide range of materials that can be processed. This enables to manufacture a variety of electronic functions by printing conductive, semi-conductive and dielectric inks. The ink is pneumatically atomized inside the printhead and the generated aerosol is carried to the virtual impactor. There it is densified and afterwards guided to the printing nozzle, see Figure 9. Inside the compact nozzle the aerosol is aerodynamically focused by an added sheath gas and is finally sprayed onto the substrate's surface. Depending on the process parameters and the nozzle geometry a line width of < 100 µm up to 10 mm of the deposited ink layers can be printed. In addition, a focal length of the aerosol beam and a high nozzle stand-off enable printing on complex 3D surfaces. [8]

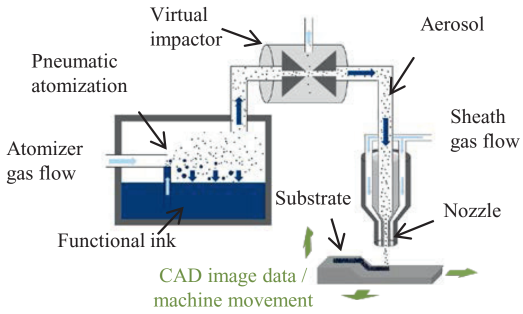

Figure 9: Schematic representation of the Aerosol Jet printing process.

For printing patterns on the additively manufactured 3D substrates, a 5-axis NC handling system provided by Neotech Services MTP was employed to place and move the substrate underneath the integrated printing nozzle.

4.2. Printing of 3D conductive patterns (Figure 1 feature 3)

For the electronic functionalization of the surface of the powder bed substrates the electrical conductive pattern has to be merged with the 3D CAD model of the part. A CAD projection step can be performed for simple layouts. For complex circuitries, software tools like Nextra [9] or MIDCAD [10] used for designing Molded Interconnect Devices were utilized.

After preparing the layout, printing parameters have to be assigned to the redesigned 3D features of the circuit pattern and the NC code for the movement of the handling system can be generated automatically.

As mentioned above, one of the main challenges for printing fine circuit patterns on the outside of the powder bed based substrates is the high surface roughness compared to substrate materials commonly used in printed electronics. This can cause serious seeping of the applied (and still wet) functional ink. In addition, capillary effects result in small cracks and grooves. However, the investigations have shown that the application of conductive layers on the part's surface using silver nanoparticle inks is possible. This is due to the fact that the Aerosol Jet printer can process high-viscous inks. Silver inks with a viscosity η = 50-100 cP were used for the functionalization of the surface. Furthermore, the pattern can be printed on dry powder bed substrates after the chemical reaction between binder and powder is finished. This is not possible during the building process of the part.

Yet the experiments showed that the printing speed has to be reduced to print conductor lines on the powder bed substrates dependably. This correlates with increased line widths of 400 µm on not infiltrated PMMA powder substrates and 250 µm on infiltrated substrates at layer thicknesses up to 10 µm.

After depositing, the nanoparticle inks require a thermal post-treatment to enable the solvent to evaporate and to achieve good electrical conductivity by initializing a sintering of the particles [11]. Oven sintering is mainly used for this process in printed electronics. However, this can hardly be integrated into the building/printing systems. A thermal processing of the entire device additionally results in shrinking and warping due to the thermally sensitive PMMA substrate material. Thus, selective sintering methods have to be employed with regard to subsequent processes for the application of electronic components. A variety of sintering techniques are generally available [12]. However, for sintering inks on surfaces of 3D printed parts, photonic sintering by laser or light respectively seems to be most appropriate with regard to integration in the printer. For the experiments, a light beam soldering system and a diode laser (λ = 940 nm) respectively were used. Both systems can be applied to cure conductive adhesives used for the interconnection of electronic components as well.

4.3. Assembly and interconnection of SMT-components (Figure 1 feature 4)

From the view of electronics production, SMT-components are usually assembled on printed circuit boards by placing electronic components onto previously applied solder paste depots, followed by a soldering process in a reflow oven. The solder joints enable a reliable electrical as well as mechanical interconnection.

For AM parts, pick-and-place units integrated into the 3D system, as illustrated above, can be used to place SMT-components. Alternatively, solutions for Molded Interconnect Devices like adapted multi-axis robots or intelligent workpiece carriers for standard pick-and-place systems are applicable. [1] [13]

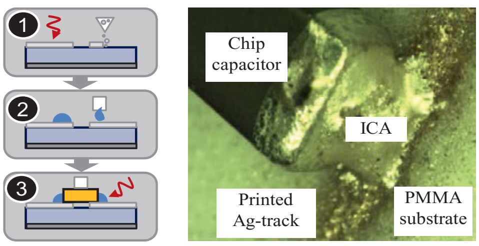

Figure 10: Interconnection of SMT components by ICA; left: (1) printing of the circuit pattern; (2) dispensing binder; (3) component placement and ICA curing; right: chip capacitor interconnected by light beam cured ICA.

In contrast, soldering techniques for interconnecting SMT-components on AM parts cannot be applied due to the low thermal stability of the substrates. As described above, one approach is to use isotropic conductive adhesives instead of solder. There are adhesives available featuring low curing temperatures and no significant thermal impact to the substrates if oven cured. Alternatively, the conductive adhesive can be cured using the integrated selective sintering systems, see Figure 10.

Two limitations occur when using adhesives on PMMA powder bed substrates. On the one hand, the mechanical bond strength of the component on the substrate is very low. For this reason, an additional adhesive has to be dispensed to fix the components mechanically. On the other hand, the reproducible application of very small volumes of ICA, which are essential for mounting highly integrated fine pitch SMT-components, requires complex dispensing technologies.

An alternative approach is to utilize cavities in the substrate's surface, see Figure 11. After dispensing adhesive filler material, the SMT-components can be placed in the cavity. Applied PMMA powder or squeezed up adhesive is bridging the gap between component and AM part.

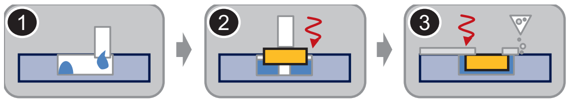

Figure 11: Interconnecting embedded components by Aerosol Jet printing; (1) filler dispensing; (2) component placement and filler curing; (3) interconnecting by ink printing and curing.

Afterwards conductive tracks for interconnecting component and circuit tracks can be printed according to [14]. For the tests, a flipped QFN packaged component with 24 leads with a pitch of 800 µm was embedded and interconnected by light beam sintered nanoparticle silver tracks, see Figure 12. In this context, the Aerosol Jet process enables printing on small beads/trenches formed by the adhesive. Thus, an automated processing is enabled due to increased tolerances for dispensing and component placement.

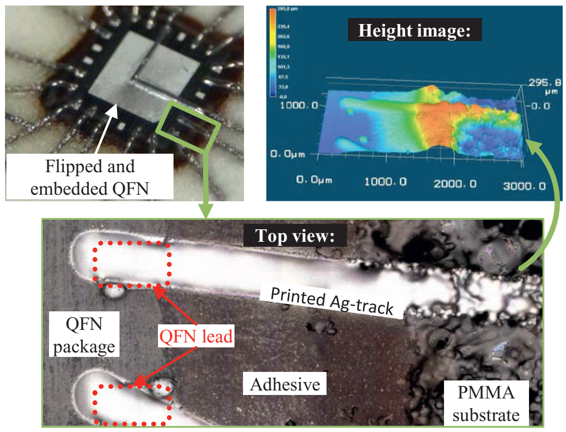

Figure 12: Aerosol Jet printed interconnection of a flipped and embedded QFN-component.

4.4. Printing of components (Figure 1 feature 5)

As an emerging technology, printed electronic components are an alternative to SMT-components. Electronic functionality like capacitors, inductors or even active components, e. g. transistors and OLEDs, can be created by printing functional materials layer by layer [5] [15].

However, the performance of the components strongly interferes with the dimensional precision (space, thickness) of the deposited layers. In this context, the investigated system setup enables the insertion of inlays with defined surface characteristics into the substrate, similar to the placement of SMT-components mentioned above. Current research focuses on printing components on glass and plastic inlays. Capacitors with a top and bottom electrode (electrode area 5-50 mm²) and an intermediate dielectric layer up to 100 pF have been fabricated. To customize the characteristic electronic properties of the capacitor a simple adaption of the component's dimension can be performed. For example, the size of electrodes or the thickness of the dielectric layers can be adapted by changing the printing layout in the CAD model only. As a result, no variety of SMT components has to be stored and managed to enable a broad range of electronic functionality.

5. Conclusion and Outlook

Combining additive manufacturing technologies used for building mechanical parts as well as for printed electronics provides a good base to deal with the challenge of variety in manufacturing of 3D electronic devices. However, both technologies cannot be merged without adaptions.

The layer-by-layer building process by means of powder bed based 3D printing enables embedding of electronics inside the part. For this purpose, an additional axis with a dispensing unit and an exhausting system was implemented into a 3D printer. Conductive paths were generated by continuously dispensing isotropic conductive adhesive. Electronic components were automatically embedded in created cavities. SMT-components embedded at the part's surface were interconnected by means of Aerosol Jet printed silver nanoparticle inks. The experiments showed, that the mix of materials and the surface characteristics are challenging the application of the printed structures in high resolution and with very thin layers. Printing parameters have to be adapted and deposited nanoparticle inks for conductive layers have to be cured by an integrated light beam soldering or laser system. The utilization of digital printing technologies additionally offers new opportunities for generating fully additive manufactured electronic components. In this context, repeatable printing of active components in the environmental conditions of the AM printer will be in the focus of further research and will enable even shorter process chains. In this context, appropriate databases and software tools for printed components have to be developed and merged with existing CAx tools for electronics design.

For further enhancement of the part's functionality, multi-material modules have to be integrated into the 3D printing system. With regard to the entire process chain, this will challenge existing technologies for process and product control as a result. Optical measurement methods, commonly used in electronics production, will not be applicable for integrated circuit patterns and embedded components. For example, one approach might be the development of enhanced X-ray techniques towards mass production.

Acknowledgements

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