SUMMARY

"Application of Additive Manufacturing in Ceramic-Polymer Microsystems"

The aim of this dissertation was to provide an insight into new technological approaches and evaluate the possibility of applying the additive manufacturing approach to produce ceramic and ceramic-polymer microsystems. The first part of this work provided a comprehensive introduction to the topic. In the chapter 2, the benchmark multilayer LTCC technology was described - its strengths and weaknesses. It was indicated how additive manufacturing can extend the capabilities of the technology and - in a longer perspective - provide an alternative for the current processes. In the chapter 3, methods of additive manufacturing were categorised and analysed, strengths and weaknesses of each were discussed with a particular focus on ceramic processing. Stereolithography was indicated as currently the most suitable for manufacturing of ceramic microsystems.

The part two described an original research into application of additive manufacturing for ceramic and ceramic-polymer microsystems. The chapter 4 was focused on assessment of the structuring capabilities in ceramic processing. The lower threshold of structurability was evaluated, primarily for microfluidic channels and high aspect ratio posts. Several new processes were proposed, allowing to decrease the size of obtainable features:

- open channel manufacturing,
- hybrid additive-subtractive structuring,
- bonding using a glaze layer,
- bonding using a ceramic photosensitive resin,
- preserving small features using SVM.

The influence of process parameters on the structuring capabilities and the properties of the commercial materials were evaluated:

- how the printing orientation affects resolution, fidelity, and internal structure
- how the object position in the device affects overcuring,
- how the sintering peak temperature affects porosity and dielectric properties,
- how the glass phase affects porosity and dielectric properties.

The porosity of the obtained structures was closely studied, the amount of open and closed pores in developed structures was analysed. Crucially, it was shown that the ceramic stereolithography allows to manufacture complex spatial shapes, which are unobtainable in the widely used multilayer LTCC technology:

- vast unsupported shapes,
- thin layers below 50 μm,
- small separated cross-sections,
- high ratio external features.

Nevertheless, the properties of the commercially available materials, compatible with inexpensive SL devices were unsatisfactory. In order to meet the expectations for the advanced ceramic microsystem development, especially regarding porosity and the resulting dielectric properties, an original photosensitive composition was developed, based on ceramic-glass composite material as in LTCC. The material was designed to be compatible with inexpensive SL devices and provide a high performance in the sintered form. Therefore, the composition had to be balanced between several factors:

- high ceramic load,
- suitable rheology,
- precisely adjusted light sensitivity,
- sufficient mechanical strength in the green state.

Only a carefully adjusted composition allows to obtain complex spatial structures with fine features. Such a material was successfully developed, matching the small process window. Examples of geometries unobtainable in the benchmark multilayer LTCC technology were demonstrated. A compatible thermal process was developed as well, in order to obtain the full properties of the ceramic part. A very high relative density was obtained with no deformation or cracks. The manufactured structures had a very smooth surface and dielectric performance matching the benchmark multilayer LTCC technology. It is considered as the major achievement of this dissertation. The results were compared to the recently reported similar solutions developed in parallel to the original research, highlighting the advantages of the original composition.

In the chapter 5, originally developed methods, aiming to expand the capabilities of ceramic microsystems through combination with polymer materials, were described. Such an approach can provide synergy and allow to develop advanced optoelectronic packages and sensors. Furthermore, it allows to embed temperature-sensitive materials. Two original methods are described:

- selective plasma bonding with PDMS,
- direct polymer AM on structured ceramic substrates.

Both methods were thoroughly analysed and optimised through a series of analyses, proving that:

- bonding with polymers allows for safe embedding of temperature- sensitive materials,
- polymer materials can provide high optical transparency,
- advanced polymer structures can be formed on ceramic substrates,
- bonded materials can form a durable system.

Examples of application were described, particularly in microfluidic optical biosensors with detection of fluorescence, in order to demonstrate the potential of the developed methods. The novelty of the approach and potential advantages of combining the capabilities of ceramic and polymer structures are considered as an important achievement of this dissertation.

Crucially, the developed methods and processes allow to obtain advanced spatial ceramic structures in both ceramic and polymer structures and efficiently combine them to obtain tailored solutions without complex processing. All of them are based on inexpensive, widely popular equipment and materials. The only exception is the original proprietary material developed in this work. Therefore, its further development is planned, in order to enhance the technology readiness level and obtain a product which could be introduced to the market.
Since the developed methods provide an ease of manufacturing and do not require any advanced, expensive equipment for simple structures, it can be possible for non-technologists to adapt the processes. It can enable experts in other areas (chemists, pharmacists, biologists) to apply the additive manufacturing as a tool in their workflow. A particularly promising solution is the direct polymer on ceramics printing. Universal ceramic substrates with an array of electrodes can be provided to print the desired microfluidic device on top. This can reduce the idea-to-sample time to just hours and enable a rapid experimenting concept. It can also change how teams cooperate, allowing to send digital files instead of fragile samples. During this research, the same model of SL device was used at both WUST and TU Ilmenau. Both of them allowed to manufacture structures with high repeatability, validating the concept.

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