Additive Manufacturing of 3D Ceramic Structures for Electronic Applications of $YBa_2Cu_3O_7$

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***Abstract* - Multichannel dc SQUID systems have to be mounted inside a cryostat to be operated below the critical temperature T_c. SQUIDs have to be encapsulated to prevent aging of the high temperature superconducting (HTS) materials. Additive manufacturing offers the opportunity to develop arbitrary structures for sample holders and SQUID capsules to address problems of conventionally manufactured systems. To investigate the potential of additive manufacturing techniques for the use with superconductors for wiring purposes, we developed a 3D-printing process for the high-T_c superconductor $YBa_2Cu_3O_7$. For this purpose we built a 3D printer with a paste extruder to print different ceramics and printed with this setup substrates out of $SrTiO_3$ dispersed in water and polyethylene glycol. Furthermore, the option to print $YBa_2Cu_3O_7$ with the paste extruder was investigated. For this purpose $YBa_2Cu_3O_7$ was dispersed in different organic solvents and printed on the additive manufactured substrates. Measurements showed that superconducting properties emerged below a T_c of about 84 K. Currently the process is being optimized for larger sample sizes, arbitrary structures and higher current capacity of the superconducting structures.**

***Keywords (Index Terms)*– HTS, additive manufacturing, ceramics, YBCO, SQUID magnetometers**

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The content of this KRYO 2016 poster presentation is based on our work first presented at the ASC 2016 [1].

The fabrication of superconducting structures is a highly complex process. For the manufacturing of Superconducting Quantum Interference Devices (SQUIDs), processes like pulsed laser deposition of $YBa_2Cu_3O_7$ on $SrTiO_3$ bicrystal substrates, optical and e-beam lithography and argon ion etching are used at our institute. An easier and more flexible fabrication method would offer the possibility to design new types of superconducting sensors without being limited to two dimensions. With this new method it would be possible to design, e.g., new concepts of 3D pickup loops for SQUID sensors.

SQUIDs can be destroyed by humidity. Therefore, capsules are used to protect the sensors from environmental influences. To check the water tightness of different capsules the humidity sensor SHT11 from Sensirion AG, Switzerland was used. The sensor was mounted in SQUID capsules made of Pertinax®, PLA, GFK, PETG, PEEK, PTFE and PPS. These capsules were placed in a climatic chamber at a humidity of 95 % and temperature of 25 °C for 70 hours. Relative changes of humidity compared to environmental values are depicted in Figure 1 of our poster. For some of these capsule materials low noise operation of sensitive dc SQUID magnetometers was already demonstrated [2, 3]. A corresponding noise spectrum for a dc SQUID in a capsule made of Pertinax® is depicted in Figure 2. There, a noise level $\sqrt{S_B}$(77 K, 10 Hz) of 70 fT/√Hz is reached and the corresponding magnetic gradient noise at 7 cm baseline of the electronic gradiometer is 10 fT/(cm√Hz).

Plastic materials from PLA and PETG were 3D-printed with the 3D-printer RF1000 from Renkforce GmbH, Germany. The extruder of this printer is shown in Figure 3(a). The 3D-printing of ceramic materials was performed with the 3D-printer RepRap Mendel and an in-house developed ceramic paste extruder which is depicted in Figure 3(b). Subtractively and additively manufactured electronic gradiometer arrangements for SQUIDs to be mounted in different planes are depicted in Figure 4[1]. Additive manufacturing allows arbitrary structures to reduce heat conduction by thin rod arrangements. Capsules for humidity protection of the HTS SQUID magnetometers, which are also manufactured subtractively and additively, are depicted in Figure 5. Water tight and pressure resistant 3D-printed containers have already been made from Nylon® filament [4]. Very versatile and inexpensive SQUID modules for gradiometer arrangements can be achieved with additive manufacturing.

3D-printed ceramic holders for SQUID capsules provide higher rigidity, better thermal insulation and water tightness with suitable materials compared to our conventional holders. As a substrate for $YBa_2Cu_3O_7$ we chose $SrTiO_3$ which assures very good matching of lattice constants, thermal expansion coefficients and negligible interdiffusion.

The $SrTiO_3$ stoichiometric powder 99+% (metal basis) is dispersed in polyethylene glycol 200 (both Alfa Aesar). Our $YBa_2Cu_3O_7$ is prepared by milling of the stoichiometric compounds and by dispersing the powder in 1,2 Propandiol (Henry Lamotte) or in polyethylene glycol 200 (Alfa Aesar). The ceramic pastes are processed with the ceramic paste extruder. The printing and drying processes are succeeded by mandatory sintering in an oxygen atmosphere to restore oxygen stoichiometry. The $SrTiO_3$ is sintered for 3.5 h at 1300 °C while $YBa_2Cu_3O_7$ is sintered for 12 h at 950 °C.

The electrical properties of 3D-printed $YBa_2Cu_3O_7$ lines are measured on a cubic and a planar structure (Figure 6). On the cubic structure the $YBa_2Cu_3O_7$ lines are printed around the edges which cannot be achieved by other manufacturing methods. The critical temperature of the 3D-printed ceramics was found to be $T_c \approx 84$ K. The critical current I_c was measured as 10 μA with a critical current density j_c(77 K) below 1 A/cm^2. The superconducting transition temperature T_c is determined from temperature dependent resistance measurements. Structural properties are investigated by scanning electron microscopy (Figure 7). Further optimizations are necessary to increase the density of the 3D-printed $YBa_2Cu_3O_7$ and to achieve better electrical properties.

Gradiometer modules and capsules for dc-SQUIDs were manufactured with additive manufacturing. With the produced capsules water tightness measurements were performed. A 3D-printer for ceramic pastes was used to build ceramic structures out of $SrTiO_3$ and $YBa_2Cu_3O_7$. These structures developed superconducting properties below a T_c of about 84 K.

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[1] By subtractive manufacturing we mean conventional machining of objects or parts.

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