

## Inkjet printing of multifilamentary YBCO for low AC loss coated conductors

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**Abstract.** Considerable progress has been made with the development of REBCO coated conductors in recent years, and high performance conductors are available commercially. For many applications, however, the cost remains prohibitive, and AC losses discourage their selection for higher frequency applications. Chemical solution deposition (CSD) methods are attractive for low-cost, scalable preparation of buffer and superconductor layers, and in many respects inkjet printing is the method of choice, permitting non-contact deposition with minimal materials wastage and excellent control of coating thickness. Highly textured coatings of YBCO and Gd-doped CeO<sub>2</sub> have previously been reported on buffered metal substrates. Inkjet printing also introduces the possibility of patterning – directly depositing two and three dimensional structures without subtractive processing – offering a low-cost route to coated conductors with reduced AC losses. In this contribution, the inkjet deposition of superconducting YBCO tracks is reported on industrially relevant buffered metal substrates both by direct printing and an inverse patterning approach. In the latter approach, ceria tracks were printed reported, which are a candidate both for resistive filament spacers and buffer layers. TFA-based precursor solutions have been printed on SS/ABAD-YSZ/CeO<sub>2</sub> and Ni-W/LZO/CeO<sub>2</sub> RABiTS substrates, and the resulting multifilamentary samples characterised by microscopy and scanning Hall probe measurements. The prospects for future inkjet-printed low AC loss coated conductors are discussed, including control of interfilamentary resistivity and bridging, transposed filamentary structures and stabilisation material.

### 1. Introduction

Whilst YBCO and related rare earth (REBCO) coated conductors with high  $J_c$  are now available commercially, high cost and AC losses prevent their use in many applications. Hysteresis losses scale linearly with width [1], so for AC applications there is a strong motivation to divide the REBCO layer into filaments. This is often accomplished by laser striation or chemical etching, which adds an additional processing step and is intrinsically wasteful. Striation alone is not sufficient to maximize performance because of electrical and magnetic coupling losses. The former can be addressed by increasing the interfilamentary resistance, encouraging stabilization striation and the use of resistive



filament spacers. Ideally, however, full transposition of filaments is also required [2]. As twisting is impractical for coated conductors, this is often addressed at the cabling stage, e.g. with the CORC or Roebel architectures, but a tape-level solution would clearly be beneficial [3].

Chemical solution deposition (CSD) methods are attractive for low-cost, scalable preparation of the buffer and superconductor layers of REBCO coated conductors; and inkjet printing is a particularly versatile approach. Drop-on-demand inkjet printing offers excellent coating thickness control and uniformity, reduced materials wastage and, by virtue of a sealed ink reservoir, fewer issues with solution purity and solvent vapour containment than alternatives such as dip and slot die coating. Furthermore, the high resolution patterning capability exploited for graphics printing could allow superconducting patterns and structures to be deposited directly without subtractive processing [3,4].

Piezoelectric printheads are widely used for both graphics and industrial applications. The small nozzle (10–60  $\mu\text{m}$ ) through which ink is ejected is uncapped, so the ink is kept under negative pressure. Very small drops can be produced (1–100 pL) at rates up to 50 kHz, and printheads are available with more than 1000 nozzles, so this technology is suited to high throughput, high resolution deposition. In the low resolution limit, electromagnetic printheads based on solenoid valves is also available. The jetting rate (<1 kHz) and nozzle count are much lower, but the drop volume is larger (>1 nL), so similar throughputs can be achieved. The large (~100  $\mu\text{m}$ ) orifice size and positive ink pressure can increase the robustness and maintainable lifetime of the printheads.

The TFA MOD approach has been very widely investigated for YBCO, and it has been successfully implemented by inkjet printing for both continuous and multifilamentary patterns [3-5]. Oxides suitable for resistive spacers and buffer layers have also been printed, including Gd-doped ceria by the present authors, both as highly textured films [6] and randomly-oriented thicker films.

This article demonstrates two inkjet approaches to producing multifilamentary YBCO coatings on industrially relevant substrates. Firstly, initial tests with direct printing of YBCO filaments on ABAD substrates are reported. Secondly, an inverse approach (based on a previous patent by some of the present authors [7]) is demonstrated on RABiTS, in which untextured  $\text{CeO}_2$  filaments are used to template an over-printed YBCO film. The future prospects are then discussed.

## 2. Methods

### 2.1. Directly printed YBCO filaments

For direct YBCO printing, a 4 mm wide stainless steel/ABAD YSZ/PLD  $\text{CeO}_2$  tape (Bruker) was used. TFA solutions in methanol with a total metal ion concentration of  $0.5 \text{ mol dm}^{-3}$  (ICMAB) were printed in Cambridge using a 60  $\mu\text{m}$  piezoelectric dispenser (MJ-AT, Microfab). A bipolar drive waveform was designed using quantitative drop visualisation system (Cambridge) to achieve optimal drop formation. Samples were printed on the ABAD substrate after cleaning with acetone and methanol. The printed coatings were processed immediately using a two-stage heat treatment.

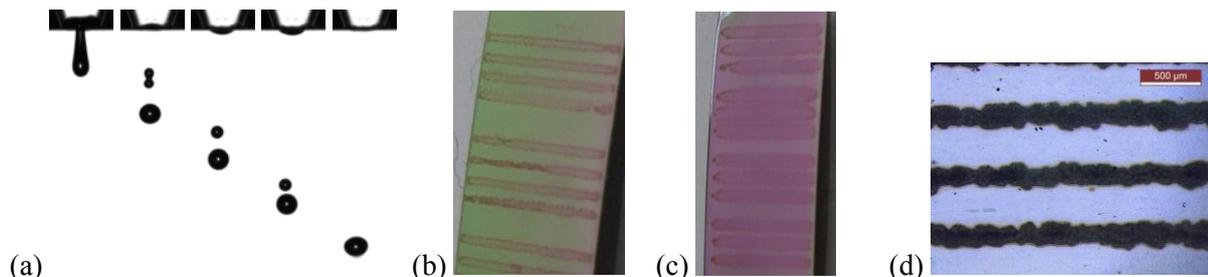
### 2.2. Inverse printing of YBCO filaments

For the inverse printing approach, a 10 mm wide Ni-W/LZO/ $\text{CeO}_2$  RABiTS tape was used (Deutsche Nanoschicht).  $\text{CeO}_2$  was chosen as the templating material, and a propionic acid and acetate based ink ( $0.5 \text{ mol dm}^{-3}$ ) was prepared in Cambridge [6]. The same Microfab dispenser was used to print longitudinal tracks on the substrate following ultrasonic cleaning. A short low temperature heat treatment (1 h, 650  $^\circ\text{C}$ ) was applied in pure Ar to dry and convert the filaments without crystallising well-textured  $\text{CeO}_2$ , which is expected to require a higher temperature [6]. Another TFA solution (~0.9  $\text{mol dm}^{-3}$ , Deutsche Nanoschicht) was then printed using a 100  $\mu\text{m}$  electromagnetic nozzle (SMLD 300, Gyger). The substrate was fully coated, including the  $\text{CeO}_2$  filaments. A two-stage heat treatment was applied, and the resulting sample was characterised by scanning Hall probe microscopy.

### 3. Results and discussion

#### 3.1. Directly printed YBCO filaments

Optimisation of the Microfab drive waveform for the YBCO ink produced a single drop 97 pL in volume with a velocity of  $1.5 \text{ m s}^{-1}$  within 0.5 mm of the orifice (figure 1(a)). Track widths varied significantly between substrates cleaned by wiping and ultrasound, figure 1(b) and (c); and tracks one drop wide could be as thin as 20 nm after heat treatment. Multiple depositions (5–10) were necessary for an acceptable thickness, and straight tracks  $\sim 200 \mu\text{m}$  wide could then be achieved, figure 1(d), although occasional breaks along the filament length occurred due to variations in substrate wetting.



**Figure 1.** (a) Drop visualisation showing the formation of a single drop of YBCO precursor ink ( $80 \mu\text{s}$  intervals); transverse tracks with various drop spacings after (b) wiping and (c) ultrasonic cleaning; and (d) longitudinal tracks with 5 superimposed depositions.

#### 3.2. Inverse printed YBCO filaments

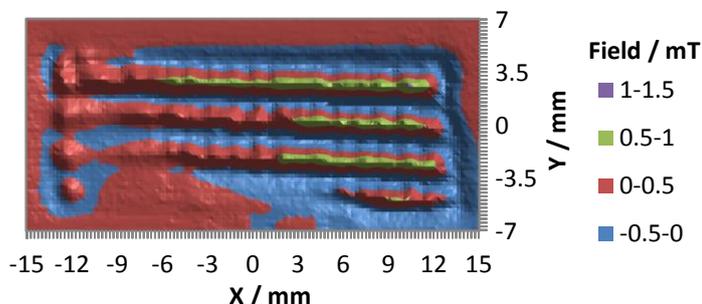
Optimisation of the Microfab drive waveform for the  $\text{CeO}_2$  precursor ink resulted in a drop volume of 80 pL and a velocity of  $2 \text{ m s}^{-1}$ . On the ultrasonically cleaned substrate, the average drop deposited in isolation reached a diameter of  $0.25 \pm 0.02 \text{ mm}$ . Six tracks were printed with a drop spacing of 0.1 mm, producing straight-edged uniform filaments approximately 1.3 mm in width (figure 2).



**Figure 2.** Photograph of inkjet printed  $\text{CeO}_2$  filaments on a RABiTS substrate.

After heat treatment of the  $\text{CeO}_2$  precursor filaments, the sample was over-printed with YBCO precursor ink. The electromagnetic jetting parameters were optimised at 400 mbar and  $400 \mu\text{s}$ , producing  $\sim 15 \text{ nL}$  drops, and a continuous coating was produced with a 1 mm drop spacing. Assuming a dense coating of uniform thickness, the expected thickness after heat treatment is  $\sim 230 \text{ nm}$ .

A Hall probe scan clearly showed distinct superconducting filaments (figure 3), correlating in position with the channels between  $\text{CeO}_2$  filaments, with an approximate width of 0.5 mm.



**Figure 3.** Hall probe scan of an inverse printed YBCO sample showing clearly resolved superconducting filaments.

Estimating the critical current density,  $J_c$ , assuming a uniform thickness of 230 nm, yields a value of  $0.6 \text{ MA cm}^{-2}$  [8]. There are also spatial variations in performance, but in one filament a continuous length of 18 mm exceeds 50% of the maximum  $J_c$  for this sample. Whilst the maximum  $J_c$  and spatial variations are not yet acceptable for applications, this is a promising result for an initial study.

### 3.3. Discussion and future prospects

It has been demonstrated that continuous filaments in an acceptable width and thickness range can be produced on ABAD substrates by direct printing of YBCO precursor inks. The large number of deposition stages required is problematic, so future studies should target a higher ink concentration:  $1.5 \text{ mol dm}^{-3}$  should be attainable. The sensitivity to substrate preparation indicates that further wetting optimisation is required. Crystallographic and superconducting characterisation is now in progress.

The inverse printing approach is promising and versatile. A detailed crystallographic study of the YBCO and  $\text{CeO}_2$  regions is required, but the results suggest that locally inhibiting the growth and/or texturing of subsequently deposited YBCO is sufficient to achieve a filamentary superconducting structure. An ink could therefore be selected for templating solely based on rheological and jetting properties.  $\text{CeO}_2$  printing is particularly interesting because of the prospect of adjusting texture locally through heat treatment variations and/or selective Gd substitution. Deposited on either the substrate or YBCO, this could form part of the production process for filament transposition structures, and/or for local interfilamentary bridges for reliability in long conductors (at the expense of increased losses) [9]. Electrical transport measurements are in progress for the present samples, but there is clearly potential for tailoring the electrical and/or magnetic properties of inkjet-printed filamentary spacers.

In an all-inkjet RABiTS coated conductor, textured filamentary  $\text{CeO}_2$  could also be printed as part of the buffer stack, essentially the inverse of the present approach and analogous to previous reports of striating the buffer stack [10]. Widespread activities in printed electronics also suggest that inkjet printing should be readily applicable to producing filamentary silver stabilisation layers.

## 4. Conclusions

Filamentary YBCO structures have been prepared by inkjet printing on ABAD and RABiTS substrates. Direct printing on ABAD substrates can produce fine filaments with multiple depositions, but more uniform wetting and an increased ink concentration are required. The feasibility of the inverse printing approach has been demonstrated using printed  $\text{CeO}_2$  filaments, and Hall probe characterization has confirmed the production of superconducting YBCO filaments. Both methods could form part of an inkjet route to low AC loss coated conductors and merit further investigation.

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## References

- [1] Brandt E H and Indenbom M 1993 *Phys. Rev. B* **48** 12893
- [2] Mawatari Y 1996 *Phys. Rev. B* **54** 13215
- [3] Glowacki B A and Mosiadz M 2009 *J. Sol-Gel Sci. Technol.* **51** 335-347
- [4] Van Driessche I, Feys J, Hopkins S C, Lommens P, Granados X, Glowacki B A, Ricart S, Holzapfel B, Vilardell M, Kirchner A, Baecker M 2012 *Supercond. Sci. Technol.* **25** 065017
- [5] Duckworth R C, Paranthaman M P, Bhuiyan M S, List F A and Gouge M J 2007 *IEEE Trans. Appl. Supercond.* **17** 3159
- [6] Mosiadz M, Tomov R I, Hopkins S C, Martin G, Hardeman D, Holzapfel B and Glowacki B A 2010 *J. Sol-Gel Sci. Technol.* **54** 154
- [7] Bäcker M, Glowacki B A, Falter M and Engell J, Patent DE102006030787A1
- [8] Vandaele K, Mosiadz M, Hopkins S C, Patel A, Van Driessche I, Glowacki B A 2012 *Mater. Res. Bull.* **47** 2032
- [9] Takacs S 2013 *Supercond. Sci. Technol.* **26** 055022
- [10] Majkic G, Kesgin I, Zhang Y, Qiao Y, Schmidt R and Selvamanickam V 2011 *IEEE Trans. Appl. Supercond.* **21** 3297