Superconducting YBCO Foams

Subjects: Others

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Superconducting foams of $YBa_2Cu_3O_y$ (YBCO) are proposed as trapped field magnets or supermagnets. The foams with an open-porous structure are light-weight, mechanically strong and can be prepared in large sample sizes. The trapped field distributions were measured using a scanning Hall probe on various sides of an YBCO foam sample after field-cooling in a magnetic field of 0.5 T produced by a square Nd-Fe-B permanent magnet. The maximum trapped field (TF) measured is about 400 G (77 K) at the bottom of the sample. Several details of the TF distribution, the current flow and possible applicatons of such superconducting foam samples in space applications, e.g., as active elements in flux-pinning docking interfaces (FPDI) or as portable strong magnets to collect debris in space, are outlined.

Keywords: High-Tc superconductors ; YBCO ; foam ; trapped fields ; current flow ; superconductivity ; ceramics

1. Introduction

Today, high-T_c superconductor samples are mainly fabricated in three different shapes: wires/tapes, thin films and bulk materials [1][2][3]. The wires and tapes serve the purpose of energy transport or building of large electromagnets, the thin films cover the needs of superconducting electronics and sensors, and the bulk materials are employed for levitation, in electric motors and generators or as trapped field magnets (superconducting permanent magnets), which can be much stronger as any permanent magnet material. For most applications operating at liquid nitrogen temperature (77 K), $YBa_2Cu_3O_y$ (YBCO) is the material of choice due to its superior properties at elevated temperatures [4]].

For building superconducting trapped field (TF) magnets or “supermagnets”, a large sample size of the superconducting material is required as the maximum trapped field depends on the sample size in contrast to permanent magnets [5][6]. However, obtaining large sample sizes is a difficult task as a good texture is essential to enable the flow of strong supercurrents. The necessary oxygenation step when preparing YBCO leads to a phase transformation from a tetragonal phase ($YBa_2Cu_3O_{6...6.5}$) to an orthorhombic phase ($YBa_2Cu_3O_{6.6...7}$). In this step, internal cracking may occur which limits the possible sample size [7]. Furthermore, the oxygenation time required to fully oxygenate a large, bulk sample increases tremendously; so necessary oxygenation times of 14 days and more are quite common. Therefore, superconducting samples prepared in this way are costly, and difficult to be handled. Furthermore, magnetostriction plays an important role when trapping large magnetic fields [6]. Due to the forces involved, the superconductor sample may break up, and the aforementioned internal cracks strongly contribute to this. Therefore, a reinforcement by steel rings and additional polymer impregnation is required to withstand the forces [8][9][10]. In this way, a record trapped field of 17.6 T at 26 K was reached in the literature, measured in between a stack of two melt-textured superconductor samples with 25 mm diameter.

An alternative preparation route for bulk superconductors would be very interesting to solve the problems mentioned. Porous superconducting materials, which were recently reviewed in [11], may solve several of the points mentioned above. A possible way out was attempted several years ago with the preparation of superconducting foams. Polymer, metallic or ceramic foams as nature-inspired bionic materials mimicing the construction elements of biologic load-bearing structures like wood or bones are nowadays used in many places in industry for various tasks, e.g., as energy absorbers in aeronautics or in car industry, as light-weight structural damping material, as filter materials, and others. These uses were recently reviewed in References [12][13][14]. The open-porous structure of foams enables the addition of metallic layers by, e.g., electrodeposition to further improve the mechanical strength [15], and the pores may be filled up with resins. Such treatment could be very important for future TF magnets based on superconducting foams, which are presented in Fig. 1. Furthermore, the foam-type material enables an easy shaping of the samples and upscaling of the sample size [16], being only limited by the furnace dimensions.

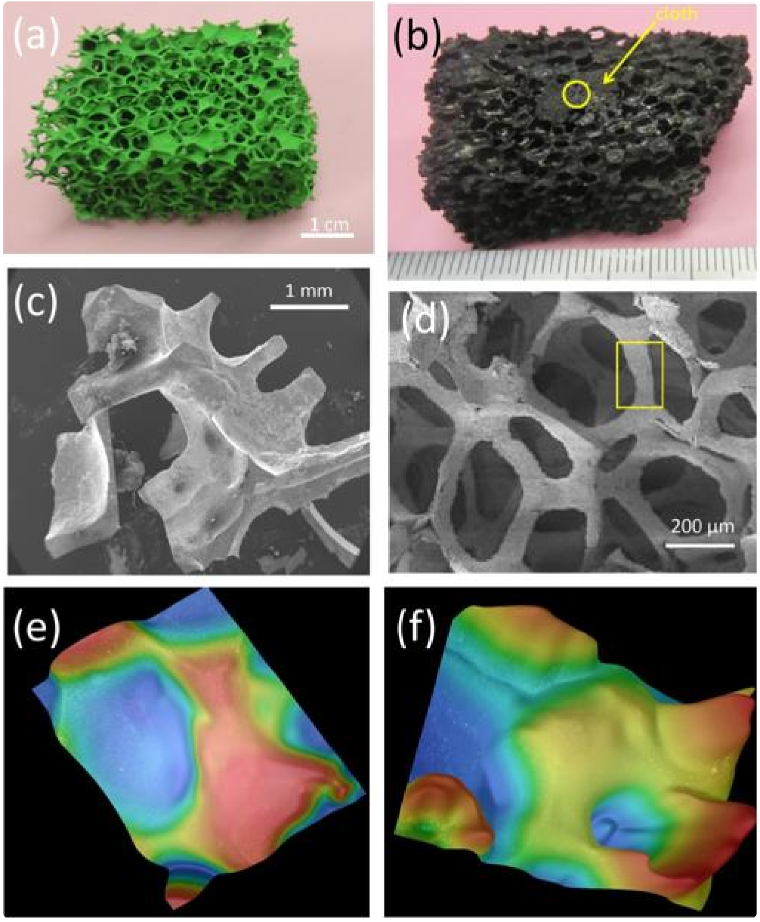

Figure 1. (a) Image of the preform stage: A green 211 foam. (b) presents the fully reacted, superconducting foam. On the top side, the remains of the seed crystal (yellow circle) and a YBCO cloth (yellow arrow) are still visible. (c), (d) SEM images of the 3D structure of the 211 foam with different magnification. In (c), broken off struts of the foam are presented, in (d) the struts around the pores are shown. The yellow rectangle marks the central piece of a strut as analyzed by magnetic measurements and for the microstructure investigation. (e) and (f) present 3D idepth profiles of the foam struts and pores, obtained by 3D-light microscopy (Keyence optical microscope VHX-3000 series).

The preparation technique to obtain superconducting YBCO foams with an induced texture makes use of the infiltration growth (IG) process. A polyurethane foam serves as base, and is coated in a first step with a slurry of Y_2BaCuO_5 (211) particles in polyvinylpyrrolidone (PVP). This foam is then heated treated to burn off the polyurethane and form a stable 211 foam. Using the IG process, this green foam is then converted into a superconducting YBCO foam. For more details of the fabrication procedure, see Refs. [17][18][19].

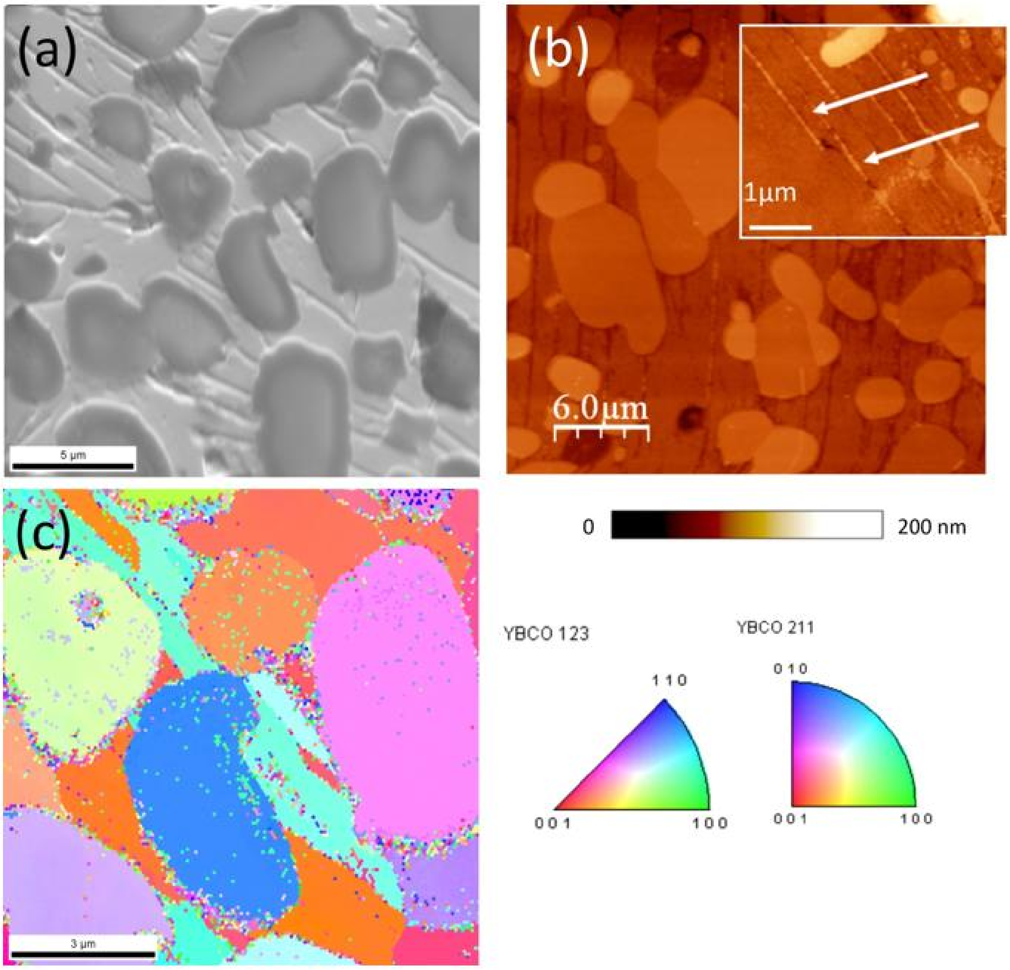

Figure 2. Microstructure of a cross section of a foam strut, investigated by SEM (a), AFM topography showing the YBCO matrix, the characteristic stripes and the embedded 211 particles (b). The inset shows the tiny 211 particles typical for the foams (arrows). (c) shows an EBSD orientation map in [001]-direction (perpedicular to the sample surface). The color code is given in the stereographic triangles on the right side. The YBCO matrix shows two dominating orientations, whereas the 211 particles (both large and tiny ones) are randomly oriented.

This IG-processing leads to an unique microstructure with many extremely small 211 particles, which is investigated by optical microscopy (3D depth profiles), SEM, AFM, TEM and electron backscatter diffraction (EBSD) as described in Ref. [19]. This information serves as valuable input for modelling of the superconducting foams, concerning the superconducting and the mechanical properties [20][21]. Some experimental results are shown in Fig. 2.

The YBCO foams were originally intended to be used as fault current limiters [17][18], as the open porous structure of the foam materials enables a very effective cooling process. Liquid nitrogen or any other coolant in form of liquid or gas can directly be sent through the sample. Therefore, possible hotspots in the material can be effectively cooled down again [12]. This very effective cooling can be easily demonstrated when cooling a foam sample in liquid nitrogen to perform, e.g., levitation experiments as shown in the Supplementary Materials of Ref. [19]. The superconducting foams can be applied as trapped field magnets, as the easy upscaling enables to create foam samples of larger dimensions as the conventional bulk samples, avoiding the extremely long oxygenation times required. Furthermore, the foams have much less weight as compared to the bulks, and less material is required reducing the costs of a sample further. These advantages make the superconducting foams ideal candidates for applications in space. This may comprise the flux-pinning docking interfaces (FPDI) discussed in the literature [22][23] and portable high-magnetic field units which can be mounted in satellites to magnetically collect waste debris [24][25][26]. The present status of the foam samples as trapped field magnets is discussed in detail in Ref. [19]. A typical measurement at 77 K is presented in Figs. 3 (a) and (b).

2. Applications of Superconducting Foam Samples

The superconducting YBCO foams could see many different applications making use of the efficient cooling process, e.g., for fault current limiters. This was already proposed in the first publications on foams [17][18]. Cooling of superconducting foam structures from room temperature to 77 K proceeds about ten times faster compared to respective bulk materials of the same mass and composition [12]. This can directly be demonstrated when cooling a foam sample in liquid nitrogen, e.g., to test the levitation properties on a magnetic rail consisting of 3 Nd–Fe–B magnets in a row (S–N–S configuration,

[27]) as shown in Figs. 3 (c), (d) and in the video sequence in the Supplementary Materials. When operating on such a magnetic rail, the foam sample is cooled so well that it takes ~5 min to warm up again. Furthermore, the lift height of the foam sample is much higher than that of an YBCO bulk sample due to the reduced weight. Another interesting possibility would be to turn around the situation of the levitation experiment: Using long pieces of foam would create an easily coolable superconducting rail, where magnetic objects can levitate upon. Such a superconducting rail system could be cooled very effectively by any gaseous or liquid coolant being pumped through.

Trapped field magnets can be sources of magnetic fields in places where the standard technology to generate large magnetic fields will not work. Such examples are:

- TF magnets can be applied as static or rotating elements in electric motors and generators (see, e.g., the review in Reference [28]). Here, the reduced weight of the foam samples is very promising. This also applies to magnetic coupling elements in the power line, which is employed to transmit power into a container with different atmospheric conditions. Such lightweight machinery and coupling elements may be useful for space applications.
- TF magnets are portable systems. As long as the system is kept below superconducting transition temperature T_c, the magnetic field stays in the sample. Using persistent current mode, there is no need for any power supply.
- Combined with pulsed magnetic fields (PMF) [29][30], superconducting samples could be activated as TF magnets when needed, or serve as field receptors only when being cooled.

The points presented here set the possible uses for light-weight TF magnets, but are not yet all application possibilities for superconducting foam samples. Superconducting foams with small open porosity can easily be continuously reinforced, e.g., with resins, to improve their mechanical properties and, thus, to overcome the forces encountered in levitation and quasi-permanent magnet applications [8]. Also an electroplating process to further improve the mechanical strength as done for metallic Al foams [15] could be carried out here. This will avoid the cracking problems of bulk superconductor samples prevailing when trapping large magnetic fields at low temperatures. All these improvements can be applied to the YBCO foam samples, contributing to bring these applications to reality.

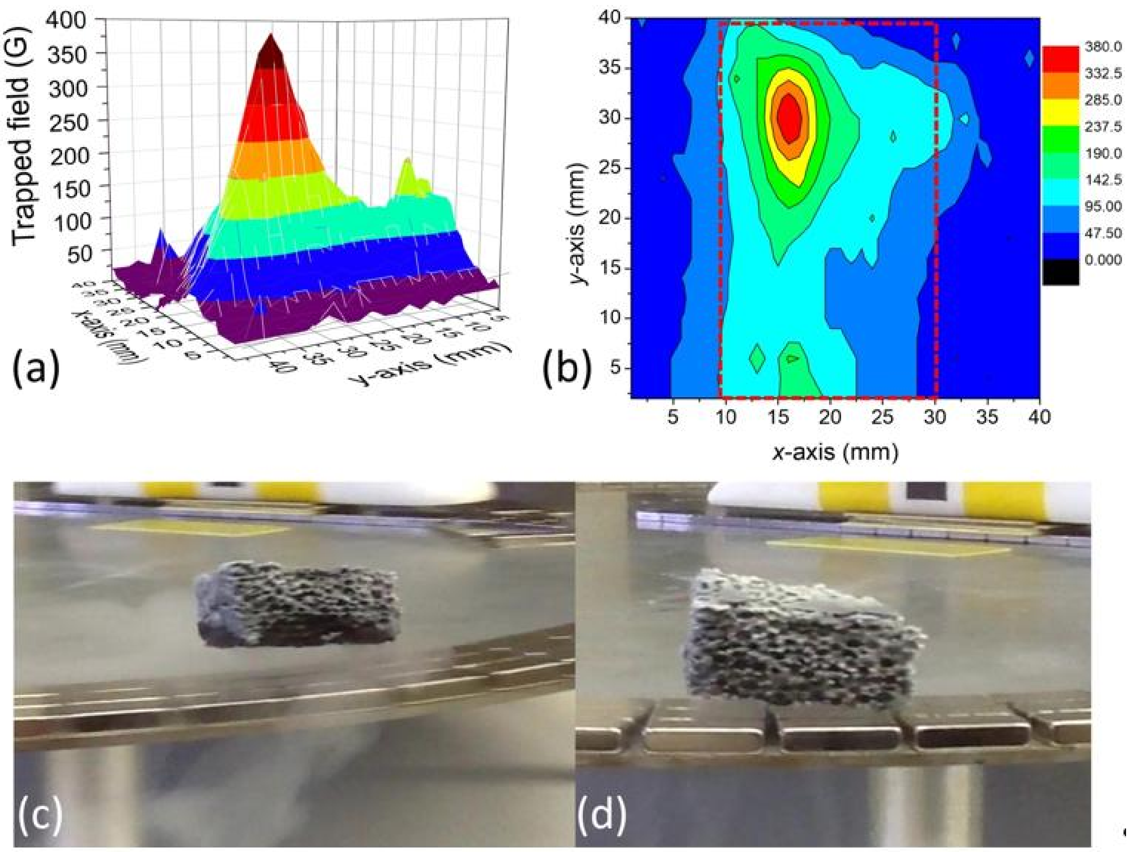

Figure 3. Trapped field measurements on a foam sample. Distribution of B_z measured by scanning Hall probe on different sample sides of the foam as surface plots (a,c) and contour plots (b,d). The sample position is marked in the contour plots by a dotted red line. Superconducting foam levitating above a magnetic rail. (a) shows the foam sample at full speed running on the rail, and (b) gives the foam sample when being close to warm up.

Two main applications of superconducting foam samples in space engineering can be envisaged: The foam samples may play an important role for the pinning force docking interfaces (FPDI) discussed in Refs. [22][23]. The supercoducting material required in this application needs to be of large size, i.e., several centimeters in diameter. This size is still out-of-reach for conventional bulk samples, and the weight of such a sample will be considerable, and cracking of the sample may be an important issue. The FPDI system makes use of the stiff field-trapping capability of the superconducting material. One satellite would be equipped with a permanent magnet, and the other one with a superconducting element including a cryocooler. This approach will clearly simplify the docking process between two spacecrafts.

The other space application would be the collection of waste debris in space [24][25][26] using a large magnetic field. The required system could be integrated in a satellite when using a superconducting TF magnet. A cryocooler would keep the superconducting sample at the required temperature to maintain the magnetic field. If not needed anymore, the sample may warm up above Tc and the system is demagnetized. To switch on again, a PFM pulse may be employed. In this way, the system is capable to be swtiched on and off on demand.

The large amount of possible applications of foam samples suggest that further development of this sample type is an important task for the future. Combining the latest developments concerning the IG-processing of HTSc materials, the newly developed large seed crystals, the optimization of the sample shape for the given task and improved understanding of the open porous structure via extensive modelling of the 3D structure [31][32] can lead to unique types of superconducting samples to fulfill different demands of applications.

3. Conclusions

To conclude, porous high-T_c superconductors are very promising materials for applications wherever the sample weight or the cooling efficiency counts. This is given, e.g., in space experiments, for fault current limiters, and trapped field applications in rotating machinery. The achieved trapped field values are still small, but promising and the cooling efficiency can be demonstrated in simple levitation experiments. The future work will require also a deeper understanding of the current flow in such samples, combining already existing modelling approaches of mechanical properties of metallic foams with modelling of the superconducting current flow. Thus, the superconducting foams may be a handy way to generate large magnetic fields in space.

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