Technical Memorandum

Ambature TM # 2016-01

To: Ron Kelly, CEO, Ambature Inc.

Cc: Michael Lebby, Ketan Patel

From: Davis H. Hartman

Date: 03/03/2016

Re: **On Materials for Superconductor-Filled Coatings and Formings**

Ron,

We have looked at the potential of fabricating superconducting coatings and forms from HTS powder material, embedded in polymer matrix materials. In particular, we have considered the application of thick film coatings on irregular largely shaped objects (for Meissner magnetic field expulsion) and molded, drawn or extruded wires. Because these two applications are different, the materials requirements are different as well. In both cases, the cryogenic environmental conditions drive materials synthesis.

This memo outlines our current state of knowledge of the composite materials design trades and performance constraints. We have engaged the help of Mr. Robert Denton, a polymer scientist with considerable experience on design and synthesis of complex organic structures. Mr. Denton has been able to bound the problem for these two application genres and to identify candidate materials for synthesis.

In the text that follows, I have blended Mr. Denton's notes with my own comments. To maintain a record of Mr. Denton's notes, I have inserted them in blue font, while my own inserted comments are in black.

Consideration of the Polymer Matrix

Surface Coating

For surface coatings, the most desirable polymeric matrix-phase materials would be thermoset resins; such as epoxies, acrylates, urethanes, silicones, polyimides or other monomers, that can be cured using either chemical catalysts or by photo-initiation (visible or UV range) catalysts. They can function over a wide range of temperatures, but nearly all of them are glassy, amorphous and brittle solids at liquid nitrogen temperatures. Inorganic filler loadings as high as 70% by volume and >90% by weight have been achieved using thermosetting resins. Thicker coatings may be more vulnerable to stress-induced fracturing under cryogenic immersion.

Wire or formed material

For wires or materials that can be shaped at room temperature or above, thermoplastic polymers would be the matrix-phase material of choice. However, they have limitations as to how much inorganic filler can be loaded into them. Practical inorganic filler loadings in thermoplastics seldom can exceed 40% by volume depending of course on the particle size and surface area of the filler. The thermoplastics which are known for maintaining high strengths and reliability at low (liquid nitrogen) temperatures are Nylon™ (polyamide), polypropylene, PTFE (polytetrafluoroethylene, "Teflon™") and UHMWPE (ultra high-molecular weight polyethylene).

Powdered Superconducting Filler Properties

For our stated application, the principle dispersed-phase ("filler") is $YBa_2Cu_3O_7$ (hereinafter referred to as "YBCO") for ease of discussion. The density of YBCO is approximately 6.3 g/cc, much heavier than the silicate materials I am used to working with. However, we can assume that the volume loadings would be similar to what we got with our barium glass fillers in the dental composites (i.e. 60 to 70% by volume). At these filler levels the dispersed phase is very closely packed (i.e. < 1 micron).

Figure 1 is a picture of the polished surface of a (cured) ≤5 micron particulate-filled thermosetting composite (PFTC). Notice how closely packed the particles are. Also keep in mind that in the black matrix (resin) phase there is colloidal silica, which is too small to be visible at this magnification.

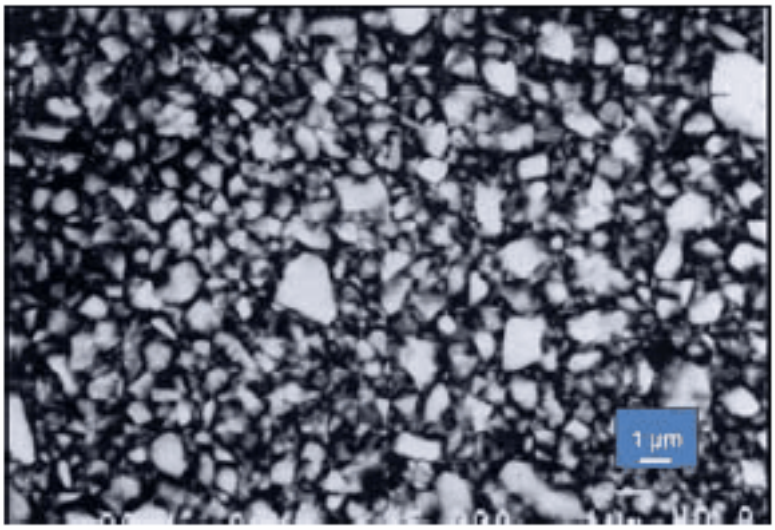

Figure 1: Polished surface of a (cured) ≤5 micron particulate-filled thermosetting composite (PFTC).

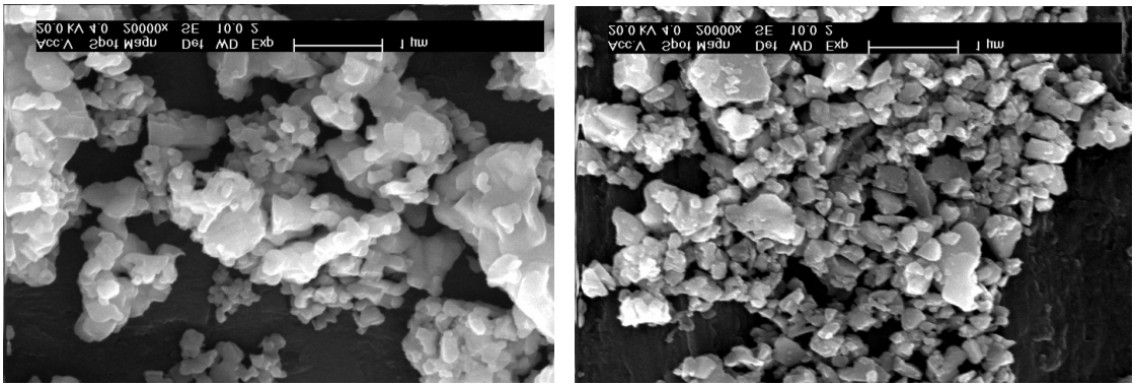

Figure 2: YBCO powder unmilled (left) and milled to submicron size (right).The particles are angular to sub-angular, and slightly "platy".

The biggest problem with fabricating most PFTCs is that the raw, untreated fillers are angular to sub-angular in shape, and have relatively polar surfaces. Thus, the resin monomers don't wet the surface very efficiently, and when sheared, the uncured material tends to be highly dilatant (i.e., one in which viscosity increases with the rate of shear strain). This has been overcome by using coupling agents and/or surfactants that modify the surface of the particle. For silicates, we used silanes (double-ended molecules with a siloxane end group that would bind to the silicate particle's surface, and an organic end group that would bond with the monomer resin). However, YBCOs do not have the siloxane bridge (Si-O-Si) or the pendant hydroxyls needed to form a hydrogen bond with the silanes, so a different type of surface modification is required. It has been found that the surface of YBCO can be successfully treated with alkylamines, arylamines, thiols, disulfides and selenols; however for acting as coupling agents for YBCO use in polymer composites the alkylamines hold the greatest promise. (see Feng Xu, et al., 1998).

Figure 2 shows a picture of YBCO powder unmilled (left) and milled to submicron size (right). The particles are angular to sub-angular, and slightly "platy". I would imagine that the Sigma-Aldrich < 5 micron powder is similar to the left photo. Here's an article about the effect of milling on the properties of the powders:

http://www.aptis.be/application-notes/chemical-applications/milling-effect/?lang=en

Sintered YBCO

When the YBCO is produced by a sintering process, the particles are much more rounded, which would allow for a higher packing and better control of viscosity. Notice how different the shape of the particles is here than in the previous two photos above. This is powder from an outfit called SCI (Science Engineered Materials): www.sciengineeredmaterials.com

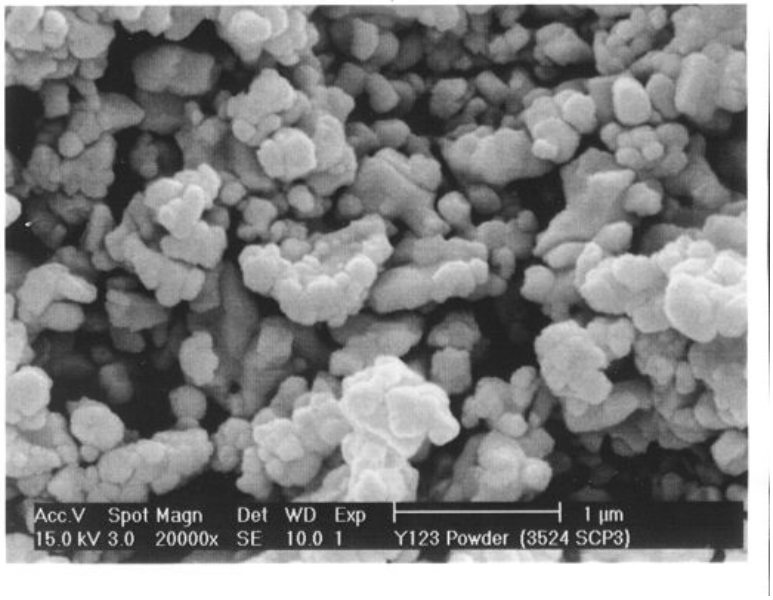

Figure 3: Photo of YBCO is produced by a sintering process, the particles are much more rounded, which would allow for a higher packing and better control of viscosity.

Next Steps

We are now ready to select, from a short list of candidate resin materials, a family of test fixtures to make up a design of experiment that seeks out the optimum configuration of fill density, resin viscosity, curing properties, glass transition dynamics and cryogenic properties, to name a few. We intend to build simple structures on ceramic microwave substrates and simple four-point probe measurement of material resistivity versus temperature as well as I-V characteristics a or below the material's superconducting transition temperature. These measurements should establish reduction to practice of the basic concepts. More elaborate measurements are possible, but they will involve significant time and expense. Therefore, strategic decisions will be needed to determine plans moving forward at that time.

Davis H. Hartman

Robert K. Denton Jr., CPG, LPSS