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Rapid prototyping of electrically conductive components using 3D printing technology

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ABSTRACT

A method of rapid prototyping of electrically conductive components is described. The method is based on 3D printing technology. The prototyped model is made of plaster-based powder bound layer-by-layer by an inkjet printing of a liquid binder. The resulting model is highly porous and can be impregnated by various liquids. In a standard prototyping process, the model is impregnated by epoxy or polyurethane resin, wax solution, etc. In the test described in this paper, to obtain the electric conductivity, the model has been impregnated by a dispersion of carbon nanofibers (CNF) in epoxy resin. Surface resistivity of the model below 800 Ω/sq has been obtained when impregnated by a mixture containing less than 4 wt.% CNF. Volume resistivity of the molded and hardened CNF dispersion used for model impregnation have also been measured and a value less than 200 Ω cm has been obtained at 3 wt.% CNF content. Unexpectedly, the onset of electric conductivity (percolation threshold) occurred at lower mass fraction of CNF for a dispersion containing CNF agglomerates, when compared to the mixture with well uniformly dispersed fibers. This happened both for the impregnated model and for the molded CNF dispersion itself. An explanation of this phenomenon, based on percolation theory is given.

1. Introduction

Rapid prototyping techniques are nowadays broadly used in product development process. They allow for fast and low-cost manufacturing a small series of components directly from the component geometry parameterization stored in a 3-dimensional CAD model. The physical prototype allows for assessment of many aspects of functionality of the prototyped component in the developed product. For a review of various methods of rapid prototyping see Venuvinod and Ma (2004).

One of the limitations of the common rapid prototyping techniques is the narrow choice of materials the prototype can be made of, thus limiting the scope of the material properties assigned to the prototype. This limits the extent of tests which can be made with the component in the prototype product. The example of the area in which the applicability of a prototype component cannot be tested without the adequate material properties is the medium- and high-voltage product engineering (products operating at 3–50 kV and >50 kV voltage, respectively). In such applications, the shape of a component together with the electric properties of the material determines the distribution of electric fields which is critical for operation of the device. Electric conductivity of the component is of primary importance in such a case.

A number of techniques are available to prototype electrically conductive components. For example, significant amount of work has been done towards application of the rapid prototyping methods to manufacture electric discharge machining (EDM) metal electrodes. The selective laser sintering (SLS) described by Dürr et al. (1999) and later by Tang et al. (2003) is one of the promising technologies, being currently the virtually unique commercial technology allowing for prototyping in metals. For the EDM application, SLS can also be followed by additional metal infiltration as proposed by Tay and Haider (2001) or metal plating process as described by Zhao et al. (2003) which improves the performance of the electrodes. Another example of technology which allows for direct metal prototyping is plasma deposition manufacturing reported by Zhang et al. (2003), a technology under development. These technologies offer very high conductivity of the components and resistance to wear related to the EDM process but require sophisticated, costly equipment.

In this paper we report on a test of a simple method to manufacture an electrically conductive prototype. The method has been developed to prototype conductive components which in the final product have been expected to be made of an electrically conductive, carbon-black-filled thermoplastic polymer compound, of moderate conductivity. The volume resistivity of such compounds

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is typically of 10^1–10^3 Ω cm and the typical surface resistivity is of 10^2–10^4 Ω/sq. The aim was to reproduce these values in the rapid prototype model.

3D printing technology has been chosen for the task. It consists of two steps. First, a model is made of powder deposited layer-by-layer and bound by an inkjet printed liquid binding agent. As a result a relatively weakly bound, fragile, porous, and permeable structure is formed. In the second step, the structure is impregnated by a hardenable infiltrant, e.g. based on epoxy resin, which, after curing makes the prototype stiff and durable enough to be handled.

The electric conductivity can be added to the model in that second step by adding an electrically conductive filler to the infiltrant. However, using common conductive fillers such as carbon-black or metal powders increases the viscosity of the infiltrant so that it is not able to impregnate the 3D model structure.

One of the alternative fillers which can be used is carbon nanofibers (CNF). The very small diameter of the fibers allows them to penetrate together with the infiltrant deeply into the structure of the 3D model. In the same time, due to a low concentration of CNF needed to achieve the required conductivity, the viscosity of the resin—CNF mixture can be low enough to effectively impregnate the structure. A test of application of the CNF filled epoxy resin as the infiltrant of a model in the 3D printing process is the subject of this paper.

2. Procedure of manufacturing samples

For all the tests, prototypes have been made by 3D printing technology using a printer from Z Corporation. Plaster-based powder has been used as the model building material.

Prototypes have been impregnated by a dispersion of CNF in epoxy-based infiltrant being a mixture of EPOLAM 5015 resin and EPOLAM 5015 hardener by Axson Technologies. CNF used was Pyrograf-III PR-24 XT-LHT by Pyrograf Products Inc. As reported by the manufacturer, the average diameter of the fibers is 100 nm and typical length is 50–200 μm. The fibers are heat-treated at 1500 °C by the manufacturer to convert any chemically vapor deposited carbon present on the surface of the fiber to a short range ordered structure and to increase the electric conductivity. The fibers are also processed with an improved debulking method so that the fibers require less energy to achieve dispersion (Pyrograf Products Inc., 2007).

The mixing procedure to achieve the CNF dispersion has been as follows:

- preparing a required amount of CNF to obtain the desired CNF mass fraction;
- adding 15 ml of resin and stirring;
- long ultrasonic mixing;
- adding 5.5 ml of hardener;
- short ultrasonic mixing.

Two versions of the procedure have been applied:

- long ultrasonic mixing in sonication bath, 30 min time;
- long ultrasonic mixing using a probe sonicator, 40 min time with a 50% duty cycle and external water cooling of the container with the mixture.

The procedure no. 1 resulted in the dispersion containing CNF mostly in form of aggregates and will be referred to further in the text as “aggregated-CNF”. The procedure no. 2 resulted in a highly dispersed mixture and will be referred to as “dispersed-CNF”.

Fig. 1 shows a typical CNF aggregate present in the dispersion prepared according the procedure no. 1 and Fig. 2 shows the dispersed-CNF mixture. The length of the fibers is in both cases shorter than that reported by the manufacturer. In particular, the dispersed-CNF mixture consists of fibers of length around 3–10 μm. Shortening of the length of the fibers is most probably the result of the ultrasonic mixing.

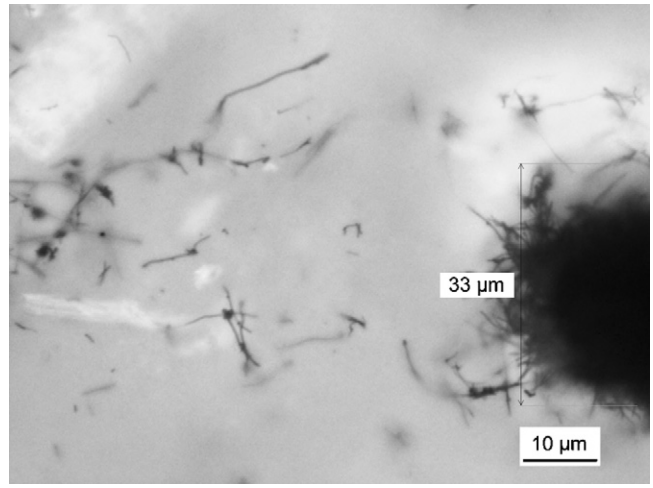

Fig. 1. Microscopic picture of the aggregated-CNF mixture; the measured diameter of the CNF aggregate is marked.

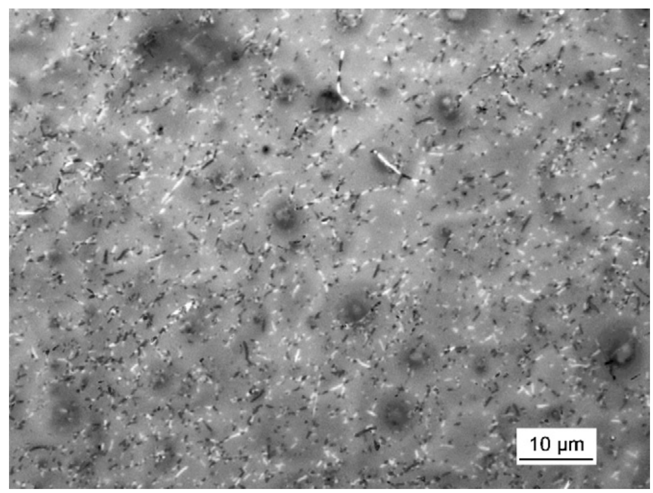

Fig. 2. Microscopic picture of the dispersed-CNF mixture.

For each CNF dispersion obtained, a number of 3D printing samples impregnated by the dispersion have been manufactured, being plates of 2 mm thickness, 20 mm width and 50 mm length. The samples have been cured at 80 °C during 1 h. Additionally, samples made of the dispersion itself have been molded and cured in the same conditions to be able to measure the volume resistivity of the obtained epoxy resin–CNF compound. Examples of the samples are shown in Figs. 3 and 4, respectively. For measurements of the resistivities, contacts have been applied on the samples using electrically conductive, silver-filled epoxy-resin-based adhesive, CW2400 Circuit Works by ITW Chemtronics, as is shown in Figs. 3 and 4.

3. Results of resistivity measurements

The results of the measurements of the volume resistivity of the CNF-resin compound are shown in Fig. 5. The onset of conductivity occurs at lower CNF mass fraction for the aggregated-CNF mixture than for the dispersed-CNF one. This effect was originally not expected by the authors, as usually it is believed that higher