Journal of Electroceramics, 13, 409–412, 2004

Solid Freeform Fabrication of Piezoelectric Actuators by a Micro-Casting Method

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Submitted February 4, 2003; Revised March 9, 2004; Accepted May 17, 2004

Abstract. In recent years, there has been much interest in the manufacturing of piezoceramic actuators by Solid Freeform Fabrication (SFF) methods, following developments in polymer and metal shaping. With these methods, actuator shapes can be realized that are impossible or very difficult to obtain by traditional ceramic shaping techniques. At TNO, research is currently performed on the development of technology to use SFF methods to develop multi-material components, i.e. combining polymers, ceramics and metals in one production process. One SFF-technique, which is investigated in this study, is micro-casting. In this process, a highly loaded ceramic suspension is deposited by a nozzle, attached to a computer-controlled positioning system. With this process, it is possible to make 3D components directly from CAD files, or to fill volumes using wider nozzles. As a case study, such a casting process was used to produce a piezo-electric bender and an ultrasonic transducer element.

Keywords: SFF, actuator, multi-material, PZT, casting

Introduction

While most electroceramic components are currently still manufactured by traditional techniques such as extrusion, die pressing or tape casting, it is widely realised that these techniques have important limitations in e.g. shape capability and size range. In response to this, increased attention is paid to solid freeform fabrication methods, which allow the manufacturing of components of complex shapes directly from a CAD-file [e.g. 1, 2 and references therein]. These SFF methods have mostly been developed in the past for prototyping purposes and used in polymer systems, but have recently been extended to ceramic materials. Examples of these methods include ink jet printing [3], Robocasting [4], Fused Deposition of Ceramics [5] and other related methods (see [1, 2] for a more complete overview). All these methods have clear advantages in terms of ease of production of complex shapes. Nevertheless, these methods have the drawback that they are limited in production speed, and therefore only of commercial interest for ceramic shapes that cannot easily be produced in any other way.

At TNO TPD, research is currently performed on the development of fast, cheap and reliable SFF technology in order to develop multi-material components, i.e., combining polymers, ceramics and metals in one production process. This work presents a step in this process, namely the development of PZT actuators by a micro-casting method. In this method, a computer-controlled dispensing system is used to deposit ceramic and metal suspensions. In all suspension-based SFF-methods, suspension properties are crucial for the quality (functional and mechanical) of the eventual product. Careful control of powder dispersion, rheology, suspension-substrate interaction and drying behavior are crucial to obtaining a good end result. This paper reports on development of piezoelectric actuators, describing the manufacturing of a PZT bimorph bender and a PZT ultrasonic actuator. The bender is used as a simple first case to study effects of suspension formulation, apparatus parameters, deposition and drying behaviour on a simple component type, for which a reference component for comparison purposes can easily be made by regular methods (tape casting and

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cutting). Next, more complex shaped piezoelectric ultrasonic actuators were produced. This work only reports on the shaping of PZT elements for the actuators. The work on depositing metal electrodes is currently in progress.

Experimental Procedure

Suspension Development

The PZT powder was kindly supplied by Morgan ElectroCeramics. It is a morphotropic composition PZT with an average particle size of 0.60 μm. The powder was suspended in distilled water by milling in a ball mill for 1 hour together with a dispersant (Dispex A40). To control the viscosity, a varied amount of methyl cellulose solution was added. In some suspension, Triethylene Glycol (TEG) was used as a plasticizer. The suspensions were stored on a roller bank, to prevent sedimentation. Rheological measurements were carried out using a Physica Rheometer equipped with a Z1 double gap or a Z2 single gap DIN cup for measuring viscosity using the coaxial cylinder method The sintered samples were inspected by Scanning Electron Microscopy (SEM).

Experimental Apparatus

The apparatus used for the casting process is a commercially available pressure-driven dispensing unit (EFD 1500XL) equipped with interchangeable nozzles. Nozzle sizes range from 100–900 μm. The dispensing unit is connected to an in-house built xy positioning system, and material is deposited on a substrate table moving in the z-direction. The suspensions used required an operating pressure of ~1 bar. The pressure was fine-tuned with a precision valve, to ensure a constant, steady flow. Constant monitoring of the pressure proved necessary.

Results and Discussion

Suspension Development

The rheological behaviour of the suspension produced is illustrated in Fig. 1, which shows viscosity as a function of solids content, referring to the viscosity of the water- 2% methyl cellulose mixture, the viscosity of which was measured for reference.

The measured shear stress as a function of shear rate is shown in Fig. 2. The data show the desired thixotropic behaviour. The expected shear rates in the nozzle of the casting apparatus (see below) are expected to be somewhat higher than the maximum measured value, but since the viscosity curve is almost at a constant level at 1000 s^{-1} the value at this shear rate is taken to be relevant.

The rheological data shown in Fig. 1 are fitted to a relation for the viscosity of highly loaded suspensions, commonly known as the Krieger-Dougherty viscosity

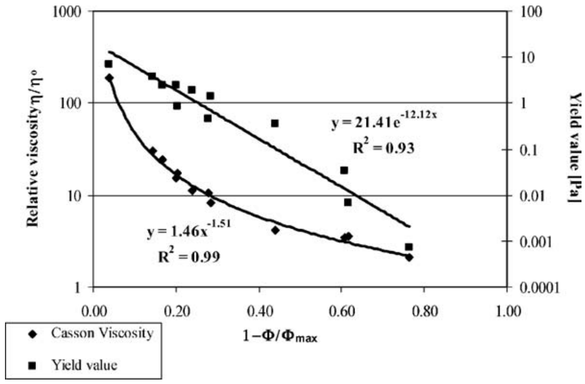

Fig. 1. Rheological behaviour of PZT suspensions in 2% methocel solution as a function of solids loading. η_0 is the viscosity of the fluid (water + methyl cellulose), which is given in Fig. 2. Φ is solids loading (volume percent), whereas Φ_{max} is the maximum solids content as determined by fitting to the Krieger-Dougherty model.

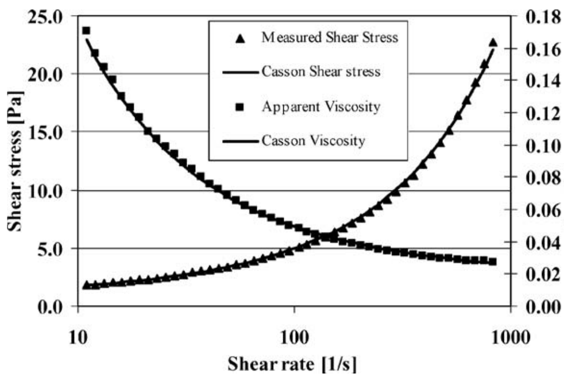

Fig. 2. Rheological behaviour of PZT suspension at a solids loading of 50 vol% PZT.

model [6], i.e.

$$(\eta/\eta_s) = \mathrm{A} \cdot (1 - \Phi/\Phi_{max})^n,$$

where A is a constant (−1.46 for our data), Φ is the solids content of slurry, Φ_{max} is the maximum solids content, where the closest packing is reached ($\Phi_{max} = 0.625$ for this case), and $n = -K_H$. Φ_{max}, where K_H is the hydrodynamic shape factor. For spherical particles $K_H = 2.5$. The calculated value of $K = 2.42$ for the PZT slurry indicates that the particles are slightly non-spherical. As shown in Fig. 1, the yield value decreases exponentially as the amount of liquid in the fluid increases (fluid = liquid + PZT powder).

In principle, a highest possible solids loading is desirable to reduce stress build-up during shrinkage. However, the suspensions with highest solids loading proved difficult to process in the casting apparatus, and after some trial experiments the casting tests were done with a suspension of 40 vol% PZT.

Casting Experiments

The prepared suspensions were used to manufacture $10 \times 4 \times 0.4$ mm PZT benders, in order to study deposition and drying effects. Since speed is a critical parameter for use of SFF techniques beyond the laboratory realm, it was attempted to deposit the suspension as fast as possible. As the casting process deposits lines of suspension, areas were produced by depositing multiple lines and adjusting the space between the deposited lines so that the top surface becomes as flat as possible. The maximum line speed used was 30 mm/s. Typical deposition time for a bender unit was ∼30 seconds. Examples are shown in Fig. 3.

Experiments were done on flexible substrates, in order to detect the development of stresses during drying (which show as bending of the substrate after deposition). Different substrates were used, including porous alumina tape (wet and dry), glass, dense alumina, and silicone rubber foil. The matching of substrate and suspension proved critical for obtaining stress-free samples. Typically, it is critical that the drying rate of the top and bottom of the deposited layer is roughly equal. Drying effects are less important in small thin-walled structures, but are a critical point in (relatively) voluminous structures such as the ones made here. Straight and flat PZT bender elements that easily detached from the substrate could be produced by using a silicone foil substrate.

Next to the bimorph bender elements, PZT ultrasonic transducer elements were produced with a shape specially designed to control the waveform of the ultrasonic wave emitted. These are shown in Fig. 4. The thickness of these elements is 60 μm. The casting method proved to have insufficient resolution to obtain the desired shape exactly, so the final shape was produced by a laser cutting process.

The produced samples were sintered at 1100°C in oxygen atmosphere, after slow heating for binder burnout. Sintered samples were inspected in the SEM.

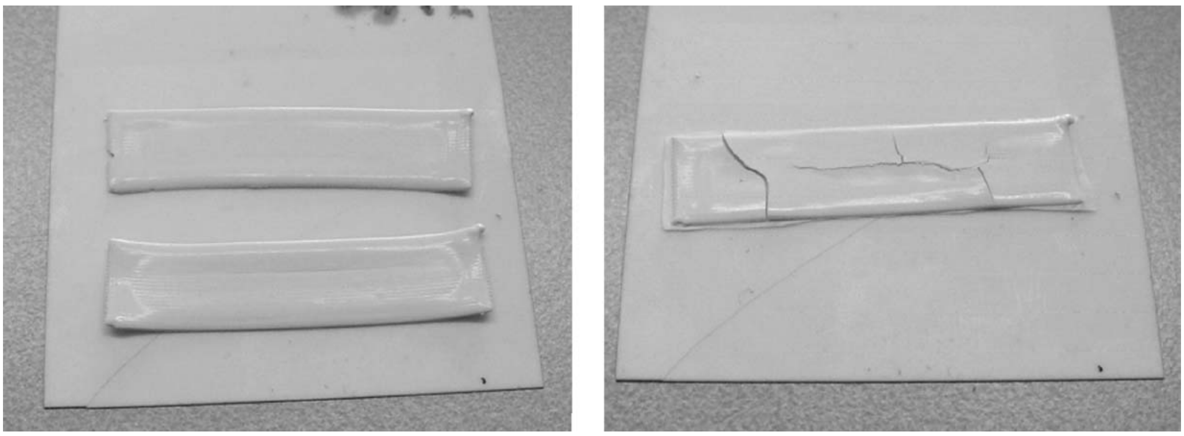

Fig. 3. Examples of bimorph bender elements produced by casting. Shown left are successful, crack-free samples, whereas the samples on the right show cracks due to shrinkage stress. The length of the shapes is 1 cm.

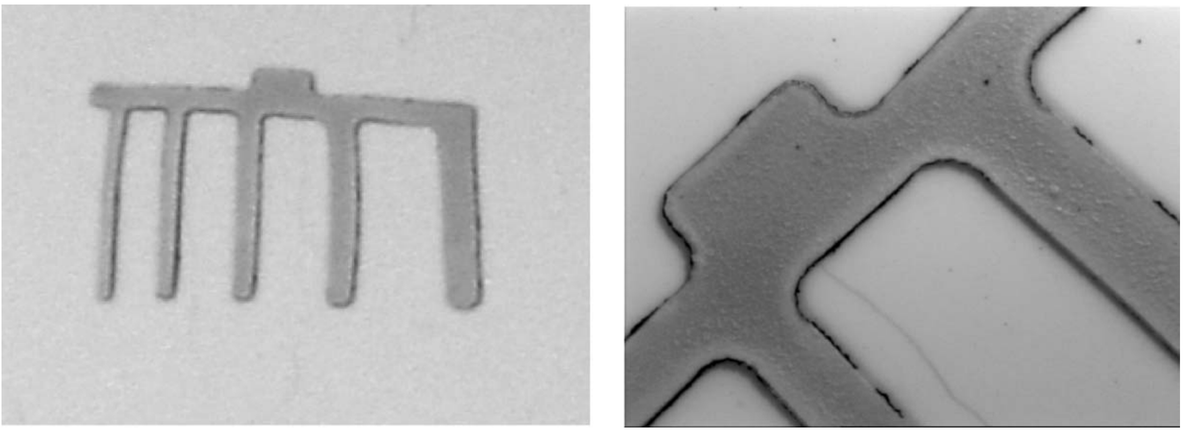

Fig. 4. PZT ultrasonic actuators made casting process. The width of the total sample in the left picture is 20 mm.

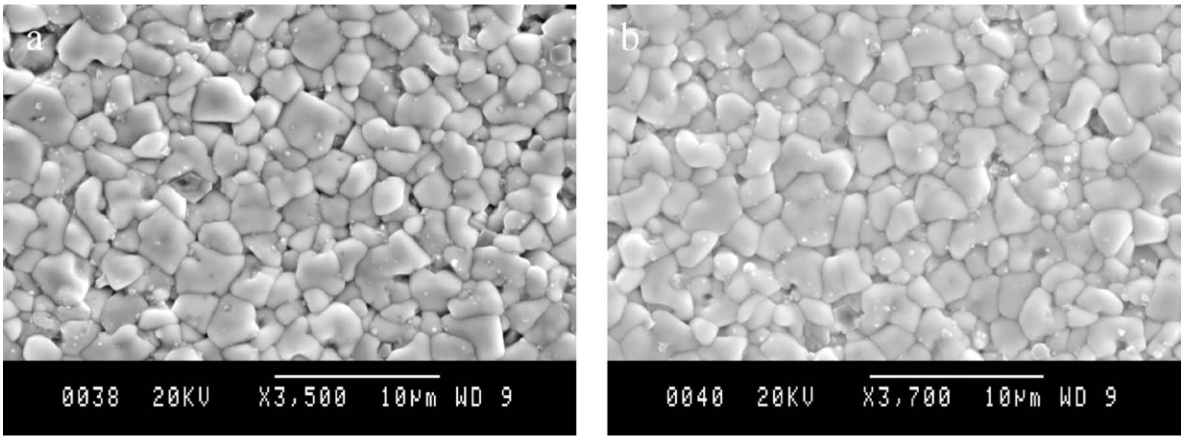

Fig. 5. SEM micrographs of the microstructure of (a) the PZT bender and (b) the PZT ultrasonic transducer.

Typical microstructures are shown in Fig. 5. It can be seen that the samples have high density, although still some pores are left.

Summary

In this paper we report on the manufacturing of PZT actuator elements by a simple micro casting method. Crack-free elements of cm-dimensions were produced rapidly from a PZT suspension in water and methyl cellulose. Drying turned out to be a critical step in the process, and is strongly influenced by substrate type.

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