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Studies on the polarisation behaviour of novel piezoelectric sensor modules

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ABSTRACT

A novel approach to the manufacture of adaptive composite structures with integrated piezoelectric modules focusses on combining the previously separate production steps – production of the piezoceramic transducer, composite fabrication and integration of the transducers – into an efficient single-stage process. Based on the long fibre injection (LFI) technology, a novel multi fibre injection (MFI) method is developed. By integrating piezoceramic components like short fibres or pearls and suitable electrode structures into the composite, novel piezoelectric functional elements are created and embedded during the structure's manufacturing process. For the functionalisation of these elements, mainly to provide sensory properties, poling of the piezoceramic components during or after the production process is required. Based on initial simulations of electric field strength, poling process and resulting small signal properties, conclusions for an adapted poling strategy of these novel sensor modules are elaborated.

1. Introduction

Since the realisation of active structural components is gaining importance, the integration of piezoelectric modules into lightweight structures has been subject of numerous research activities [1,2]. Background of the presented investigations is the development of the technological basics for the high-volume production of active lightweight components with sensory properties using glass fibre-reinforced polyurethane composites with integrated piezoelectric functional modules [3]. Therefore, the specific advantages of the long fibre injection (LFI) spray coat method are used for the development of a novel multi fibre injection (MFI) technology, which is characterised in particular by the process-integrated generation and embedding of the piezoelectric module. Thus, the time and cost intensive process steps for manufacturing the sensor module and the composite as well as the joining process for the application of the sensor can be implemented in a single efficient overall process. The LFI basic technology is characterised by processing two-component polyurethane systems in combination with a long fibre reinforcement made of glass [4]. While the MFI technology itself is directly suitable for mass production, the generated piezoelectric composite layers are unstructured and the quality of the electric connection of the piezoceramic components uncertain. Both circumstances affect the necessary imprinting of a remanent polarisation and piezoelectric performance of the functional compound. Therefore, the polarisability of such piezoelectric layers is investigated within the present work. Based on linear-dielectric simulations as well as electromechanically coupled large signal simulations the effect of different scenarios of the electric connection is studied for poling. From the results of the large signal simulations, the piezoelectric performance of the functional compound is computed. Conclusions towards the enhancement of the polarisability are drawn.

2. Sample preparation and experimental studies

For the process integrated assembly and integration of the sensor modules, an MFI processing unit has been developed [5]. The automated procedure for the assembly of the sensor module is divided into three sub-steps. First, the lower electrode is placed on the mould surface. Onto that electrode, piezoceramic components like short fibres or pearls are deposited using a specially designed discharging unit, creating a piezoelectric functional layer. The piezoceramic components made of lead zirconate titanate (PZT) can be manufactured by an adapted polysulfone spinning process or even be obtained by production residues and are provided

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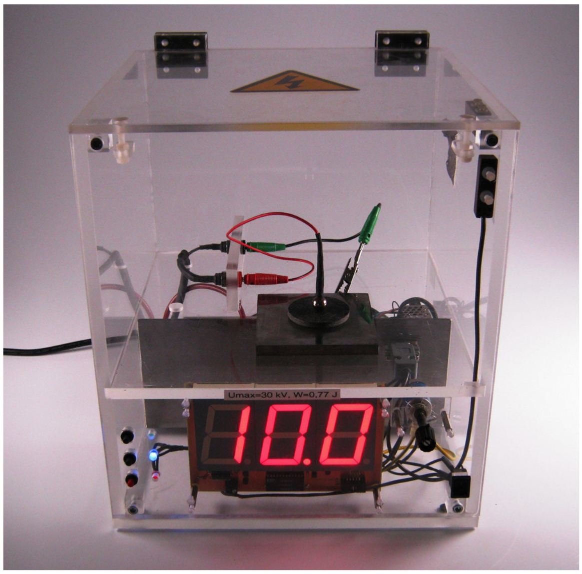

Fig. 1. High-voltage test bed and assembly for the determination of resistance against electrical breakdown.

by the Fraunhofer Institute for Ceramic Technologies and Systems IKTS, Germany [6]. By placing the upper electrode on the functional layer the assembly of the piezoelectric module is finished and the stack thus produced is subsequently back foamed with the glass fibre polyurethane mixture. Due to the characteristic of the MFI spray coat method, the sensor assembly has to be impregnated by the expanding matrix in thickness direction to be embedded completely into the composite. Therefore, porous electrode structures like metal wire meshes or carbon fibre semi-finished products are required. Investigations on the influence of the manufacturing process on integrated modules have shown that the expansion of the foaming matrix can induce a displacement of the upper electrode away from the piezoelectric functional layer. This as well as the sensor assembly with non-ideal uniform thickness of the piezoceramic layer can cause the formation of dielectric bilayers. Since the permittivity of the polyurethane matrix is small compared to that of piezoceramics, these layers impair the development of an electric field within the piezoelectric compound. Thus, high voltages are required to achieve sufficient electric field strengths for polarisation of the piezoceramic functional layer. Therefore, the resistance of the used glass fibre reinforced polyurethane matrix against electrical breakdown at high voltages was analysed. For this purpose, cylindrical specimens with a thickness of 2 and 4 mm and different densities (0.45 up to 1.0 g/cm^3) and fibre mass contents (10%, 20%, 30%) have been manufactured and tested in a specially designed high-voltage test bed that allows the charging of the specimens with voltages up to 30 kV (Fig. 1). In the experiments, however, no electrical breakdown of the matrix could be observed which means that the dielectric strength of the used composite specifications is at least 15 kV/mm.

Table 1
Specifications and parameters used for the simulation of electric field strengths.

Specification	1	2
Material	Metal wire mesh, CuSn6	
Mesh size [mm]	0.04	0.1
Wire diameter [mm]	0.032	0.065
Diameter (*d*) of PZT component [mm]	1.5	
Relative permittivity PZT	1000	
Relative permittivity PUR	4	
Applied voltage [kV]	10	

3. Effect of impairing polymer bilayer between electrode and piezoceramic compound

The usage of metal wire meshes as electrode structures and spherical PZT components or PZT fibres with circular cross section for creating piezoceramic functional layers results in specific geometric constraints. Together with the manufacturing effects, these constraints result in the formation of a polymer bilayer between electrode mesh and piezoelectric compounds. This circumstance becomes of utmost importance for the poling of the piezoceramic functional layer, which is required to functionalise the novel sensor elements. The effect of such bilayers on the polarisability is investigated in terms of the electric field induced inside the electric compound. Here, linear-dielectric behaviour is assumed for all constituents. As becomes clear below, it is sufficient to discuss the primary effects also for poling. Two individual compound arrangements for two chosen specifications have been modelled, resulting in different thicknesses of the polymer bilayers. In Table 1 the used parameters are summarised.

The arrangements represent the cross section of a PZT fibre. Further, the upper and lower electrodes are modelled as cross sections of wires that are aligned parallel to the longitudinal fibre axis. Due to the arrangement of electrodes and PZT components, there is no direct contact between them. For the following discussions, the electric field strength along two paths is considered. Path 1 passes exactly through the centre of the unit cell and the centre between two wire cross-sections (Fig. 2, left). Path 2 passes through the centre of the wire cross-sections and is offset from the centre of the PZT element to the amount of half the distance between two wires (Fig. 2, right). The electric field distribution is computed for an applied voltage of 10 kV between upper and lower electrode. Based on the effective distance of the electrodes this voltage causes an averaged electric field (nominal electric field) of 6.7 kV/mm.

In the following figures, the calculated field strength is shown along the paths between the electrodes. For specification 1, a maximum field strength of 3 kV/mm is determined along path 1, however, only in the edge region of the PZT cell. The desired field

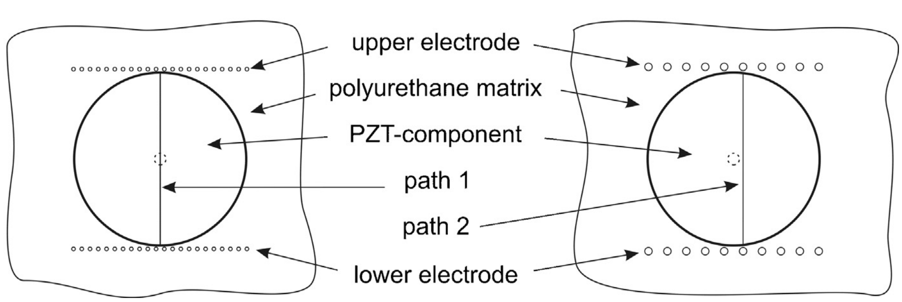

Fig. 2. Arrangement of specification 1 with path 1 (left) and specification 2 with path 2 (right).