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Development of a Novel Sensor-Actuator-Module with Ceramic Multilayer Technology

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Abstract

There is a need for low-profile piezoelectric modules directly integrated into structural components like lightweight metals to control the vibration and noise of thin-walled structures and components.

This paper reports on a new module design based on LTCC/PZT multilayers. The newly developed packaging technology entails the lamination of sintered PZT ceramic plates with LTCC green layers and subsequent sintering. This module design has the advantage of complete encasement of the PZT by the insulating carrier material. The approach combines LTCC microsystems technology and piezo technology and allows for tremendous consolidation of functional integration, e.g. sensing, actuation and electronic control. Ferroelectric hysteresis loops and deflection of LTCC/PZT modules glued onto steel plates were measured and compared with reference steel plates based on PZT plates. LTCC/PZT modules showed a maximum deflection of around 130 µm in the static mode and above 550 µm in the dynamic mode with a resonance frequency of 19.7 Hz. Single LTCC/PZT modules with optimum design were integrated into an aluminium matrix prepared by metal die casting in cooperation with the University of Erlangen-Nuremberg. X-ray analysis was performed to show that the LTCC/PZT modules survived this manufacturing step without cracks, confirming the vision of adaptive metal structures in the automotive and machine engineering industries.

Keywords: LTCC, PZT, sensor, actuator, multilayer technology, aluminium die casting

I. Introduction

In adaptronics a passive structural component is combined with piezoceramic actuators and sensors as well as controlling electronics[1-6]. The actuators and sensors are mainly attached to the structural part by assembling techniques like gluing or bonding, which has crucial restrictions, for example in view of robustness, reliability, positioning possibilities, environmental influences and productivity.

It is of great advantage to directly integrate piezoelectric modules during fabrication of lightweight structures. This reduces processing steps and opens up new design possibilities. The route considered here was to integrate a functional module during aluminium die casting, which entails high thermal and mechanical loads. The temperature of the aluminium melt is T = 700°C and the die filling time t = 50 ms. During the die casting process, the pressure p = 100 MPa. Polymer-packaged piezoelectric modules like Macro Fiber Composites (MFC, Smart Material Corp., Germany) or DuraAct™ (Invent Corp., Germany) exist, but their use for die casting integration is limited with an aluminium wall thicknesses of > 4.5 mm owing to low temperature stability and low coupling rigidity of the polymer[7-10]. Thus, there is an essential need for the development of robust, fully inorganic piezoelectric modules. The present paper reports on the design, fabrication and performance of novel packaged LTCC/PZT modules, which can be used as integrated sensors and actuators, with the following specifications: frictional connection to metal matrix, electrical insulation, robustness to withstand high mechanical and thermal loads during aluminium die casting and electrical termination of the piezoceramic material.

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II. Experimental

(1) Design

The main focus of this work was the development of a fully inorganic piezoelectric module, referred to as an LTCC/PZT module, by multilayer technology for integration into die-cast aluminium matrices. We started with a pre-sintered and electroded PZT plate based on a PZT-PMN formulation. As a carrier material for mechanical stabilization and insulation against the aluminium matrix, an LTCC material (Low-Temperature Cofired Ceramic) was chosen. Beside its advantage of enabling 3D structures and electrical termination, a good chemical adhesion to aluminium metal was expected because of the alumosilicates contained[11,12].

The PZT plate was integrated into LTCC green tapes by lamination techniques. Therefore, the complete packaging and internal electrical wiring had to be developed. The schematic design of the LTCC/PZT module is shown as an explosion image in fig. 1. The module was based on 3-ply LTCC laminates with a sintered size of 45 mm × 20 mm × 1 mm. A cavity with a size of the PZT plate – 25 mm × 10 mm – was cut into the middle LTCC layer by laser machining. The PZT plate was fixed into this cavity.

For electrical termination of the PZT plate, an Ag electrode was applied at the top and bottom LTCC layer by screen printing, which can also be seen in fig. 1. Vias filled with Ag conductor were included for internal connection to two outer solder pads.

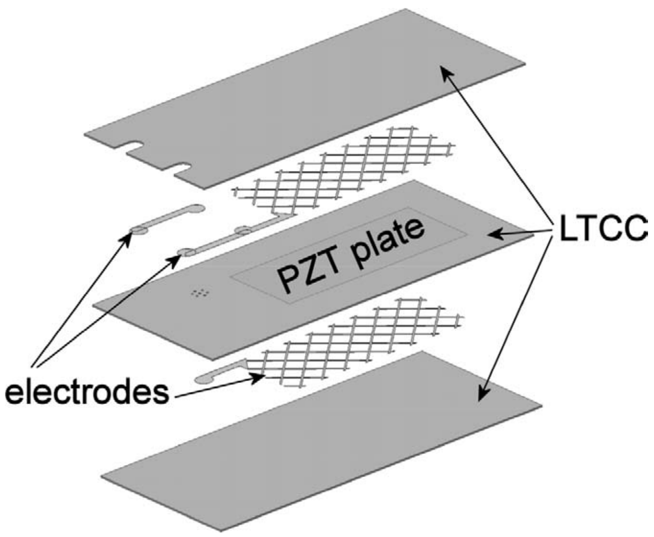

Fig. 1: LTCC/PZT module (enhanced schematic explosion image).

(2) Fabrication

For fabrication of the modules a 3-ply LTCC laminate setup was chosen. Two types of LTCC green tapes – DuPont 951 Green Tape™ and Heraeus HeraLock® Tape-HL2000 – were used. Before being laminated, the LTCC green tapes had to be preconditioned in a convection oven at T_{pre} = 80°C for t_{pre} = 10 min.

For the LTCC/PZT module, a cavity with a size of the PZT plate – 25 mm × 10 mm – was cut into the middle LTCC layer by laser machining. The green thickness of the middle LTCC layer was adjusted to reach a sintered thickness of 0.2 mm, which corresponds to the pre-sintered PZT plate thickness. For the internal wiring, mesh-like Ag electrodes were applied to the top and bottom LTCC layers by screen printing. A mesh electrode was used to ascertain electrical connection with redundant wiring paths. Vias filled with Ag conductor were included for internal connection to outer solder pads. PZT plates were metallized on the top and bottom with a conductive Ti/Pt electrode by sputtering.

The LTCC/PZT modules were laminated in an isostatic lamination system (IL 4008) with recommended parameters of p_{DP951} = 21 MPa at T_{DP951} = 70°C, t = 10 min for LTCC DuPont 951 and p_{HL2000} = 17 MPa at T_{HL2000} = 75°C, t = 10 min for LTCC HeraLock® Tape-HL2000, respectively.

The laminated LTCC/PZT modules were sintered in a muffle furnace RHF 15/3 (Carbolite) with a special burnout and firing profile. Burnout was performed at T_{burn} = 450°C for t_{burn} = 2 h. The modules were fired at T_{fire1} = 850°C for the DuPont 951 Green Tape™ and T_{fire2} = 865°C for the HeraLock® Tape-HL2000, respectively.

Aluminium die casting was performed at the University of Erlangen-Nuremburg, in the Institute of Science and Technology of Metals. An industrial-scale "Frech" die casting machine for serial production was used. The temperature of the aluminium melt was T_{melt} = 700°C with a filling time t_{fill} = 50 ms. A pressure of p_{cast} = 100 MPa was applied.

(3) Measurements

For characterization of the LTCC/PZT modules, their dielectric (dielectric constant $\varepsilon_{33}{}^T/\varepsilon_0$ and dielectric loss angle tan δ) and electromechanical properties (deflection and ferroelectric hysteresis loops) were measured. For comparison, a reference system consisting of a non-embedded PZT plate was characterized.

The PZT plates in the LTCC/PZT laminates as well as the PZT plates for the reference system were polarized at room temperature with E_{pol} = 2 kV/mm for t_{pol} = 5 min.

A Hewlett Packard 4149A Impedance Analyzer was used to measure the dielectric constants at f_{di} = 1 kHz, at least 24 h after polarization.

Ferroelectric hysteresis loops were determined with E_{hys} = 2 kV/mm, f_{hys} = 10 Hz with a Sawyer-Tower circuit and proprietary developed software.

For deflection measurements, LTCC/PZT modules and the reference system were glued onto steel plates with a length l = 265 mm and a width w = 30 mm, which were clamped in a fixture. Deflection was measured by means of the laser triangulation method with "Micro-Epsilon". Measurements were performed in the static mode with an electric field strength of E_{stat} = 2 kV/mm and in the dynamic mode with E_{dyna} = 0.05 kV/mm.

(4) Microstructure evaluation after aluminium die casting

For evaluation of damage during aluminium die casting and adhesion of LTCC/PZT modules to the metal matrix, X-ray analysis was performed. X-ray images were captured with a "Procon X-Ray CT-Compact" device with an acceleration voltage of U_{acc} = 130 kV, current of I_{acc} = 100 µA and the analysis software "XRay-Office". Furthermore cross-sections were prepared for microscopic inspection of the metal/LTCC interface.

III. Results and Discussion

(1) Module fabrication

The substrate material for the LTCC/PZT modules was selected with provision being made for the aluminium die casting step. From a multitude of tested carrier materials, in previous research[13], two types of LTCC materials – DuPont 951 Green Tape™ and Heraeus HeraLock® Tape-HL2000 – were investigated. These materials were expected to ensure good chemical bonding to the aluminium matrix, because of the alumosilicates contained in them.

Initial lamination and sintering tests with encased PZT plates in LTCC DuPont 951 showed crack formation on the edges or warping after sintering. This was caused by the 13-% shrinkage in the x-y plane of the LTCC. Increasing the number of LTCC green layers and/or additional loads on modules during sintering did not prevent crack formation.

Essential progress in avoiding cracks and warping was achieved by using LTCC HeraLock® Tape-HL2000. Thanks to the special fabrication of the self-constrained LTCC HeraLock® Tape-HL2000 as described by Rabe[14], shrinkage appears almost exclusively in the z-direction and not in the lateral plane. With this material, LTCC/PZT modules could be successfully prepared. A further advantage of this LTCC material is the avoidance of fitting steps, which are usually needed in multilayer technology.

(2) Functional characterization

After polarization, non-embedded PZT plates showed a dielectric constant of $\varepsilon_{33}{}^T/\varepsilon_0 = 2800$ ($\tan\delta = 0.0174$) and LTCC/PZT modules of $\varepsilon_{33}{}^T/\varepsilon_0 = 2070$ ($\tan\delta = 0.0173$).

Examination of the PZT plates integrated in the LTCC/PZT modules by X-ray analysis and destructive testing, which will be described in more detail in section 3.3, showed no crack formation or electrode degradation. That is why we assume that clamping of the PZT plate by the surrounding LTCC and the so induced mechanical stress cause a reduction in the dielectric constants. Evaluation of the stress conditions will be the focus of future experiments.

The same tendency could be observed in measurement of the ferroelectric hysteresis loops.

Here remnant polarization of the LTCC/PZT module was decreased down to $Pr_{LTCC/PZT} = 12.5\ \mu C/cm^2$ compared to the non-embedded PZT plate with $Pr_{ref} = 32.3\ \mu C/cm^2$, as shown in fig. 2. Maximum polarization could not be achieved by mechanical clamping of the PZT material. An interpretation of this behaviour will be the subject of in-depth investigations in future work.

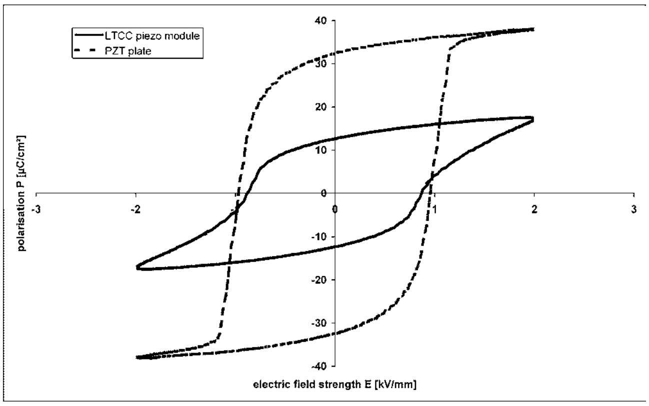

Fig. 2: Ferroelectric hysteresis loop of LTCC/PZT module and single PZT plate (E_{hys} = 2 kV/mm, f_{hys} = 10 Hz).

For deflection measurements, LTCC/PZT modules as well as non-embedded PZT plates were glued onto steel plates as described in section 2.3. The deflection of the steel plates with glued-on LTCC/PZT modules was in the static mode $\Delta l = 129\ \mu m$ and in the dynamic mode at a resonance frequency of $f_R = 19.70$ Hz, $\Delta l = 550\ \mu m$. Steel plates with the reference system glued on showed a deflection of $\Delta l = 256\ \mu m$ in the static mode and $\Delta l = 865\ \mu m$ in the dynamic mode at a resonance frequency of 15.8 Hz, as shown in figs. 3 and 4. There is a shift in the resonance frequency of $\Delta f = 4$ Hz of the system based on LTCC/PZT modules compared to the reference system, which can be explained by a change in stiffness. Because of the additional LTCC layers, the modules exhibit higher stiffness than non-embedded PZT plates. The lower deflection of 50 % compared with the reference system leads to an offset of the working point.

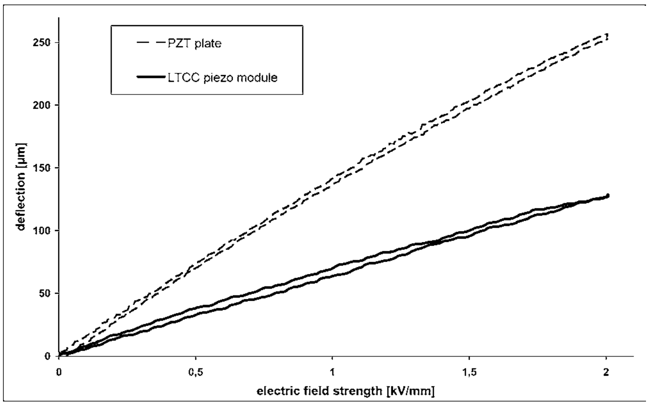

Fig. 3: Deflection of a steel plate with applied LTCC/PZT module in comparison with a steel plate with single PZT plate in static mode (up to E_{stat} = 2 kV/mm).

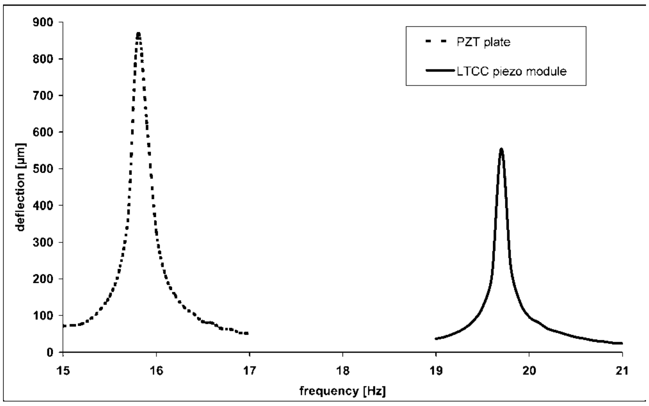

Fig. 4: Deflection of a steel plate with applied LTCC/PZT module in comparison with a steel plate with single PZT plate in dynamic mode (E_{dyna} = 0.05 kV/mm).

(3) Metal die casting experiments

LTCC/PZT modules were integrated into metal matrices at the University of Erlangen-Nuremberg in an aluminium (Al) die casting process. After die casting, Al plates with encapsulated LTCC/PZT modules were analyzed by X-ray and optical microscopy. X-ray analysis showed excellent integration of the LTCC/PZT modules in the Al matrix. The modules survived the die casting process without crack formation and exhibited good adhesion to the Al matrix. The latter has been also confirmed by optical cross-sections, as shown in fig. 5.

To prevent damage to the LTCC/PZT modules during the die casting process, the samples had been fixed in a supporting structure made of metal networks as described in the literature references 1 and 2. The network structure was completely infiltrated by the hot melt and is still visible in the cross-sections.

No trapped air bubbles or delamination has so far been detected. Quantitative characterization of the interface adhesion of the LTCC/PZT module to the Al matrix is still under investigation.

The die casting experiments proved that the developed LTCC/PZT modules can withstand high-temperature and pressure conditions and are thus well suited for integration in die-cast metal matrix composites.

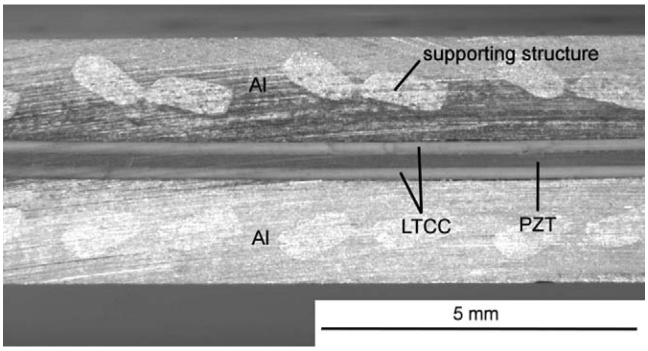

Fig. 5: Cross-section of an Al die-cast plate with integrated LTCC/PZT module and supporting structure.

IV. Conclusion & Outlook

A fully ceramic-based LTCC/PZT module has been developed successfully based on a new packaging technology. The technology entails lamination of pre-sintered PZT ceramic plates with LTCC Heraeus HeraLock® Tape-HL2000 green tapes and subsequent sintering to obtain sensor/actuator modules.

The functionality of the LTCC/PZT modules was shown by dielectric and deflection measurements as well as by recording hysteresis loops. The LTCC/PZT modules were integrated into Al metal matrix in die casting experiments. The modules survived this manufacturing step without damage, confirming the idea of adaptive metal structures for the automotive and machine engineering industries. The advantage of the LTCC/PZT modules is the complete encasement of PZT in the carrier material. This approach combines LTCC microsystems technology and piezoelectric technology and enables tremendous improvement in functional integration, e.g. sensing, actuation and electronic control.

Further examinations will be focused on Al die-cast LTCC/PZT modules with full electrical termination as well as interpretation of the clamping mechanism within the LTCC/PZT modules.

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