Novel Packaged LTCC/PZT Modules for Actuator and Sensor Applications

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Abstract:
There is a need for low profile piezoelectric modules directly integrated into structural components like lightweight metals to control vibration and noise of thin-walled structures and components. In addition, condition monitoring of compound materials by the use of ultrasound waves is of great importance. Integrated transducers can help to overcome time-consuming maintenance rates with external, separate inspection systems e.g. in aerospace industry. Recently, we developed actuator/sensor modules based on LTCC/PZT multilayer which fulfill these requirements. Multilayer technology was used to package sintered PZT ceramic plates into green LTCC sheets forming a compound after laminating and sintering. Thin walled metal sheets with integrated LTCC/PZT modules were prepared by aluminum die casting in cooperation with the University of Erlangen-Nuremberg. They survived the manufacturing step without cracks and fortify the concept of adaptive metal structures in automotive and machine building industry. LTCC/PZT modules for transducer applications were build up in cooperation with the Fraunhofer IZFP Dresden, Germany. They have been successfully tested as impact sensors for structural health monitoring.

Keywords: LTCC, PZT, sensor, actuator, multilayer technology, structural health monitoring

Introduction

The concept of adaptive light weight constructions suffers from the lack of low profile piezoelectric modules, which can be directly integrated into the matrix material. Emerging applications are lightweight thin-walled metals with the ability to control vibration and noise. In addition, condition monitoring of compound materials by the use of ultrasound waves is of great importance. Integrated piezoelectric transducers can help to overcome time-consuming maintenance rates with external, separate inspection systems e.g. in aerospace industry.
Today, processing of active structures is divided into production of functional modules and passive structures and subsequent application or integration step. This approach has essential restrictions, as for example in view of positioning possibilities, exposure to environmental influences and productivity.
It is of great advantage to directly integrate piezoelectric modules during fabrication of light weight structures. This reduces processing steps and opens up new design possibilities. One addressed application concerns light weight metal structures with the challenge to integrate functional actuator/sensor modules during aluminum die casting. Another implementation concerns permanent structural health monitoring (SHM) in compound materials based on integrated ultrasound transducers replacing corrective maintenance. So far, no robust solution exists.
The present paper reports on the design, fabrication and performance of novel packaged LTCC/PZT modules, which can be exploited as integrated sensor, actuator and ultrasound transducer.

Design

Main focus of this work was the development of a fully inorganic piezoelectric module by multilayer technology for integration into die casted aluminum matrices.
The basic design idea is to cover already sintered and metallized PZT plates based on a PZT-PMN formulation with passive ceramic green tapes and subsequently firing the package to obtain the final multilayer module. As carrier material for mechanical stabilization, housing, and electrical insulation against the aluminum matrix a LTCC composition (Low Temperature Cofired Ceramics) was chosen. Beside its advantage of enabling 3D structures and electrical termination, a good chemical adhesion to aluminum metal was expected because of the containing alumosilicates [1].
Two different designs were developed.
Fig. 1 shows the schematic LTCC/PZT module variant for use as actuator and sensor in the low frequency range. A 3-ply LTCC laminate setup was chosen with screen printed wiring on the lower and upper LTCC layer und a cavity in the middle LTCC layer fitting the size of the PZT plate. The sintered

size of LTCC/PZT module was 45 mm x 20 mm x 1 mm.

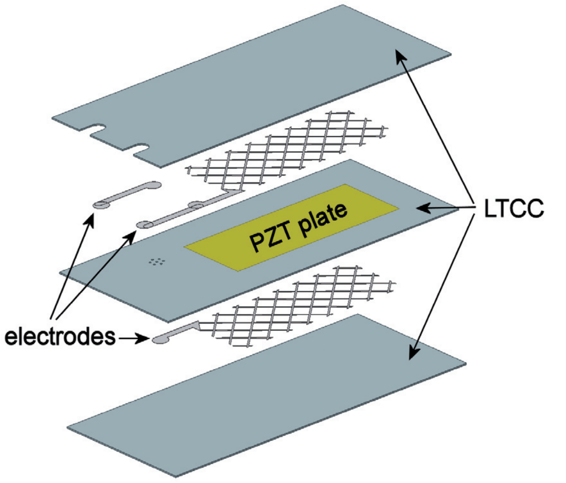

Fig. 1: Schematic layout of actuator LTCC/PZT module

Fig. 2 shows an alternative design of the LTCC/PZT module for use in the high frequency range. For this ultrasound transducer LTCC/PZT module a 4-ply LTCC laminate setup was used with a sintered size of 30 mm x 30 mm x 1.6 mm. Three PZT discs were used to allow vectored emission and detection of ultrasonic waves. They were also buried in the middle LTCC layer which was adjusted to a sintered thickness of the PZT discs. 3D-wiring was done with vias trough different LTCC layers and screen printed electrodes to connect the PZT discs. An additional layer was added as bottom LTCC layer to allow shielding to outer electronic components. The development of these modules was done in cooperation with the Fraunhofer IZFP Dresden, Germany [2].

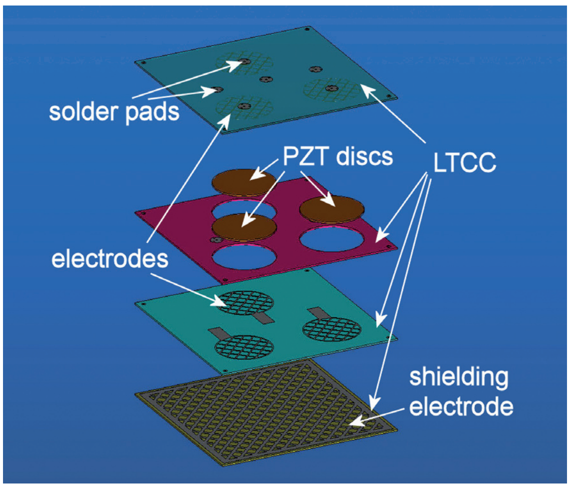

Fig. 2: Schematic layout of ultrasound transducer LTCC/PZT module

Fabrication

For fabrication of both module designs Heraeus HeraLock® Tape-HL2000 green sheets were used. The PZT plates and discs were integrated into LTCC green sheets by lamination techniques. Therefore, the complete packaging and internal electrical wiring had to be developed.

For the actuator LTCC/PZT module a cavity with a size of the PZT plate 25 mm x 10 mm x 0.2 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 sintered PZT plate thickness. For internal wiring mesh like Ag electrodes were applied on top and bottom LTCC layers by screen printing. Vias filled with Ag conductor were included for internal connection to outer solder pads. PZT plates were metallized on top and bottom with sputtered TiPt electrodes.

For the ultrasound transducer LTCC/PZT module three PZT discs with a thickness of t = 0.55 mm and a diameter d = 10 mm were buried in the middle LTCC layer which was adjusted to a sintered thickness. An additional layer was added as bottom layer to allow shielding to outer electronic components. Also Vias were filled for internal connection to the solder pads.

The LTCC/PZT modules were laminated and sintered in a muffle furnace with a special burnout and firing profile. Burnout was carried out at T = 450 °C for t = 2 h. Firing took place at T = 850 °C. Aluminum die casting was done at the university of Erlangen-Nuremburg at the Institute of Science and Technology of Metals. Therefore an industrial scale “Frech” die casting machine for serial production was used. The temperature of the aluminum melt was T_{melt} = 700 °C. The mold filling time was t = 50 ms. Thereby a pressure of up to p = 100 MPa occurred. Figures 3a and b show the two types of LTCC/PZT modules after sintering. Solderable Ag pads were screen printed on top of the modules for external wiring of the integrated PZT plates.

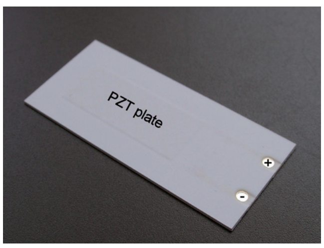

Fig. 3a: Sintered actuator LTCC/PZT module

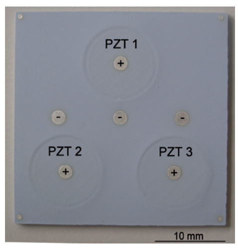

Fig. 3b: Sintered ultrasound transducer LTCC/PZT module

Results

The substrate material for the LTCC/PZT module was primarily selected in view of the aluminum die casting step. From a multiplicity of tested carrier materials Heraeus HeraLock® Tape-HL2000 turned out to fit demands on multilayer setup and further integration into structural components. Caused by the special fabrication of the self constrained HeraLock® Tape-HL2000 shrinkage appears almost exclusively in z-direction and is suppressed in x- and y-direction. Crack formation and warping could be prevented and LTCC/PZT modules could be prepared successfully on this material basis. PZT plates were poled with E_{pol} = 2 kV/mm, t_{pol} = 5 min at room temperature. After polarization of the actuator LTCC/PZT modules a dielectric constant of $\varepsilon_{33}^{T}/\varepsilon_0$ = 2070 (tan δ = 0.0173) was measured. This value was lower compared to values measured on unembedded PZT plates showing a dielectric constant of $\varepsilon_{33}^{T}/\varepsilon_0$ = 2800 (tan δ = 0.0174). Examination of the PZT plates integrated in the LTCC/PZT modules by X-ray analysis and destructive testing showed neither crack formation nor electrode degradation. That's why we assume that clamping of the PZT plate by surrounding LTCC causes reduction of dielectric constants. Evaluation of the stress conditions will be the focus of future experiments.

The data of ferroelectric hysteresis loops (f = 10 Hz with E = 2 kV/mm) showed the same tendency A reduced remnant polarization of the LTCC/PZT module was determined with $P_{r\ LTCC/PZT}$ = 12.5 µC/cm² compared to the unclamped PZT plate with $P_{r\ ref}$ = 32.3 µC/cm² as shown in fig. 4.

The interpretation of this behavior will be the topic of profound investigations in future works.

For deflection measurements actuator LTCC/PZT modules as well as single PZT plates were glued onto steel beams with a length l =265 mm and a width w = 30 mm which were clamped in a fixture. Deflection was measured by laser triangulation method. The deflection of the steel beam with LTCC/PZT module glued on was in the static mode Δl = 129 µm and in the dynamic mode at a resonance frequency of f_r = 19.70 Hz, Δl = 550 µm. Steel beams with the reference system glued on showed a deflection of Δl = 256 µm in the static mode and Δl = 865 µm in the dynamic mode at a resonance frequency of f_r = 15.8 Hz. There is a shift in resonance frequency of Δf_r = 4 Hz of the system based on LTCC/PZT modules compared to the system based on single PZT plates which can be explained by a change in stiffness. Because of the additional LTCC layers the modules exhibit a higher stiffness compared to single PZT plates. The lower deflection of about 50 % compared with the reference system leads to an offset of the working point.

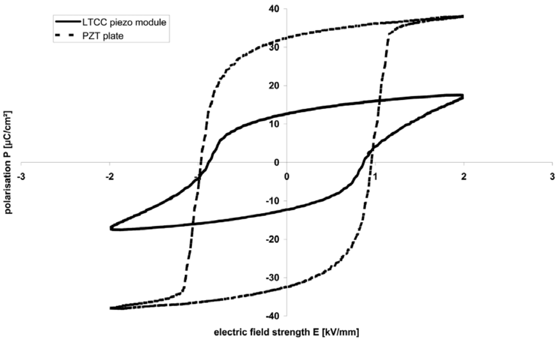

Fig. 4: *Ferroelectric hysteresis loop of actuator LTCC/PZT module compared to single PZT plate (E_{hys} = 2 kV/mm, f_{hys} = 10 Hz)*

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

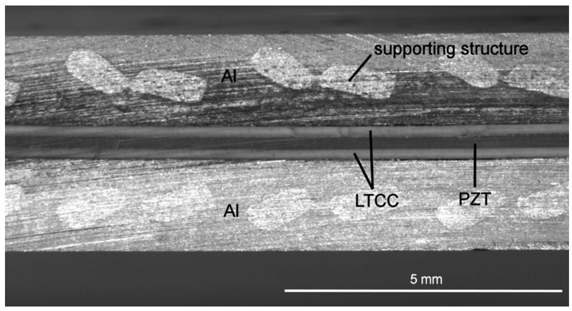

Fig. 5: *Cross section of an Al die casted plate with integrated actuator LTCC/PZT module and supporting structure*

To prevent LTCC/PZT modules for damage during die casting process samples were fixed in a supporting structure made of metal networks as described in [3]. The network structure was completely infiltrated by the hot melt and is still visible in cross sections. No trapped air bubbles or delamination were detected. A quantitative characterization of the interface adhesion of the LTCC/PZT module to the Al matrix is still under investigation. The die casting experiments proofed that the developed LTCC/PZT modules can withstand high temperature and pressure conditions.

They are well suited for integration in die casted metal matrix composites.
For structural health monitoring (SHM) of lightweight composite materials ultrasound LTCC/PZT modules based on three PZT discs were built as described before. To test ultrasound receiving properties the module was glued onto a carbon fibre reinforced plastic (CFRP) structure representing a typical composite material in aerospace industry. A PZT disc, which acted as an ultrasound generator, was glued in a distance of a = 180 mm from the module as shown in fig. 6.

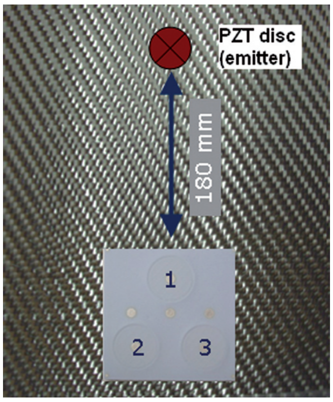

Fig. 6: *Ultrasound transducer LTCC/PZT module (receiver) and PZT disc (emitter) glued on CFRP plate*

Peak-to-peak values of emitted and received signals were measured in a frequency range f_{US} = 50-350 kHz. Figure 7 shows that all three discs integrated in the LTCC/PZT module received the emitted signal with almost the same peak-to-peak level.

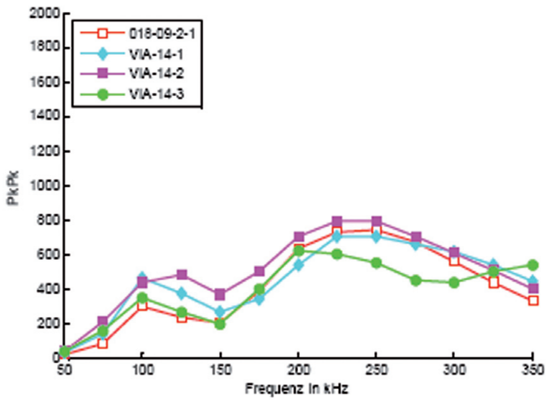

Fig. 7: *Peak-to-peak values of transmitted and received signal (reference: Fraunhofer IZFP) - embedded PZT disc 1: VIA-14-1, 2: VIA-14-2, 3: VIA-14-3); emitter signal: 018-09-2-1 (unfilled square*

Conclusion

A fully ceramic based piezoelectric module has been developed successfully by a new packaging technology. The technology uses lamination of already sintered PZT ceramic plates and discs with LTCC Heraeus HeraLock® Tape-HL2000 green tapes and subsequent sintering to obtain sensor/actuator modules.
Advantages of these modules with embedded PZT ceramic plates and discs are seen in reliable 3D wiring, mechanical stiffness, electrical insulation, shielding of external environmental influences and integration of additional electronic components.
Measurement of dielectric and electromechanical properties as well as examination of ultrasound receiving capabilities proof excellent actuator and sensor behavior of these so-called LTCC/PZT modules.
LTCC/PZT modules have been successfully integrated into Al metal matrix by die casting experiments. The modules survived this manufacturing step without damage confirming the idea of adaptive metal structures for automotive and machine building industry. 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 allows a tremendous improvement of functional integration, e.g. sensing, actuation and electronic control.

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