Ceramic Based Structural Health Monitoring (SHM) Modules for Rough Environment

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Abstract:
Structural Health Monitoring (SHM) systems enable to permanently monitor the health of structural components. We introduce a new concept of SHM transducers based on ceramic multilayers. This approach allows for a tremendous improvement of robustness against environmental influences as well as integration of electronic components for signal processing. The so-called LTCC/PZT modules (LPM) are prepared by laminating fired PZT ceramic discs with LTCC green layers and subsequent sintering. Experimental results on transducer properties will be presented and compared to results of FEM modeling.

Keywords: LTCC/PZT Module, Structural Health Monitoring (SHM)

Introduction

Structural health monitoring (SHM) of functional and safety components used in technical constructions is required in many industrial fields and is pushed by legally clauses and competition situations on the market. SHM systems enable to permanently monitor the health and condition of structural components e.g. of aircraft, rotorcraft, pipelines, bridges, wind turbines and automobiles. Innovative technology for non-destructive inspection uses acoustic waves. Transmission and receiving of these waves are generally realized by piezoelectric transducers. They act as ultrasound transmitter and receiver. Most SHM systems are based on piezoceramic-polymer composites for transducer function. They are very flexible but show low temperature and chemical stability. Moreover integration of electronic control and signal processing are not solved yet.
We introduce a new concept of SHM transducers based on fully ceramic multilayers, so-called LTCC/PZT modules (LPM). The advantage of that approach is, that electronic circuits can be integrated into the LTCC multilayer sheets and are connected to signal processing units which are soldered at the top of the device. This paper gives an overview on technological challenges and their solution. FEM modeling has been carried out to simulate transmitting and receiving behavior of LPM transducer and will be compared to experimental results. Therein transducer lay-up and package shape are investigated in detail.

Design & Fabrication

The basic design idea in building robust fully inorganic piezoelectric SHM modules is to integrate an already sintered and metallized PZT part into passive ceramic green tapes. The package is subsequently fired. The principle has been already published in detail in [1]. The approach combines multilayer- and piezo-technology and is ideal to produce robust ultrasound transducer for SHM in a rough environment.

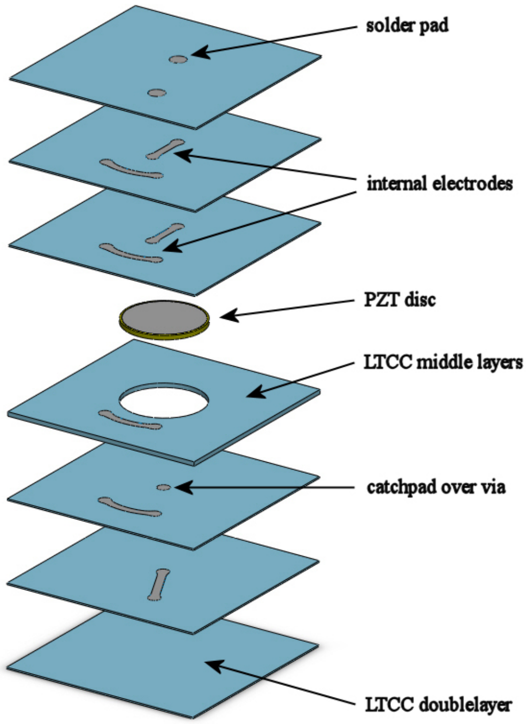

Fig. 1: LPM designed as an Acoustic Multilayer Module (AML) – schematic explosion image –

The schematic setup of an Acoustic Multilayer Transducer (AML transducer) is shown in Fig. 1. For fabrication Heraeus “HeraLock® Tape HL2000” green sheets were used. The setup used 3 double layers of LTCC above the PZT disc, 2.5 double layers in the middle, where the PZT disc is integrated and both 2 and 3 double layers beyond the

disc. The green thicknesses of the middle layers were fitted to reach a sintered thickness of about 0.54 mm which is the sintered PZT disc thickness. The cavities in the LTCC middle layers for the PZT disc where machined by laser cutting. For piezoceramic material an already sintered and electroded PZT disc of PIC 255 (Ø = 9.97 mm, t = 0.54 mm) from PI Ceramics GmbH. Reliable electrical termination of the PZT disc from the transducer surface to the outside was achieved by filling of vias as well as screen printing of internal electrodes and catch pads with conductor paste. LTCC layers were laminated one upon the other and were isostatically pressed. Subsequent sintering took place in a sintering press "PEO 603" from ATV Technologie GmbH with binder burnout at T_{burn} = 450 °C for t_{burn} = 2 h. Firing was carried out at T_{sint} = 865 °C for t_{sint} = 30 min and a pressure of 0.05 MPa.
In order to get design rules for a precise setup and effective transmitting and receiving of acoustic waves, the number of LTCC layers and geometrical size of the AML transducers were varied. For batch production 9 identical AML transducer were produced from one (100 x 100) mm panel. Separating was done via wafer saw for square and laser machining for round shapes. Always 18 AML transducer with geometries: (20 x 20) mm, (25 x 25) mm, Ø 20 mm and Ø 25 mm were produced for experimental evaluation and comparison to FEM simulation.

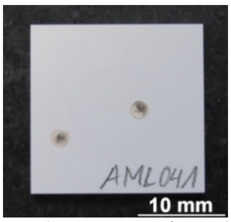

Fig. 2: AML transducer (20 x 20) mm

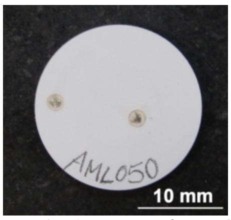

Fig. 3: AML transducer Ø 20 mm

FEM Simulation & Measurements

Different application and damage detection methods demand the knowledge about the radiation pattern of the used transducers. Therefore the measurements for the characterization of the AML transducers were carried out on a 600 mm x 300 mm aluminum plate with 2 mm thickness. The AML transducers were glued with Automix Rapid 03 (Delo) epoxy adhesive. Measurements with laser vibrometer were carried out to characterize the angular radiation pattern of two different shaped transducers. The setup is shown in Fig. 4. A sinc-function was used as excitation waveform for AML ultrasonic wave actuation (Fig. 5).

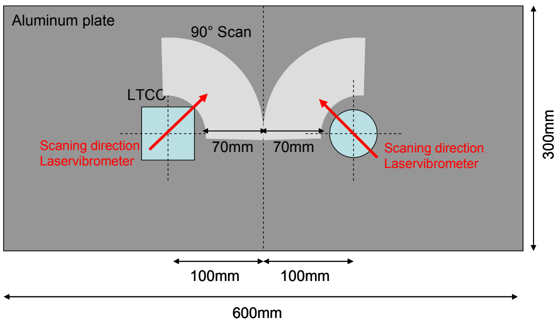

Fig. 4: Measurement Setup

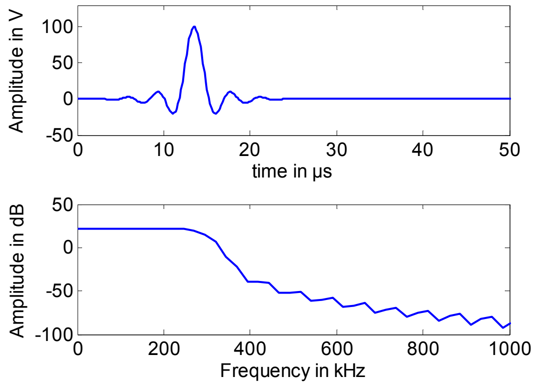

Fig. 5: Excitation Waveform

The FEM simulation was carried out with ANSYS Multiphysics. The simulated specimen was identical to the shown measurement setup. For symmetry reasons only the upper half of the plate was simulated. The material properties are listed in Table 1.

Table 1: Material properties for FEM simulation

PZT: PI Ceramic (PIC255)		
ρ	7.80E+03	kg/m^3
e_{31}	-7.10	N/Vm
e_{33}	13.70	N/Vm
e_{15}	33178	N/Vm
c^E_{11}	1.230E+11	N/m²
c^E_{33}	9.711E+10	N/m²
c^E_{12}	7.670E+10	N/m²
c^E_{13}	7.025E+10	N/m²
c^E_{44}	2.226E+10	N/m²
c^E_{66}	2.315E+10	N/m²
$\varepsilon^S_{11}/\varepsilon_o$	930	(unitless)
$\varepsilon^S_{33}/\varepsilon_o$	857	(unitless)
Aluminum (AW 5754)		
E	70E+09	Pa
ρ	2700	kg/m³
ν	0.34	
LTCC: Heraeus (HeraLock® Tape HL2000)		
E	120E+09	Pa
ρ	2900	kg/m³
ν	0.24	

Adhesive: Delo (Automix 03 Rapid)		
E	2E+09	Pa
ρ	1160	kg/m³
ν	0.34	

LTCC and adhesive are assumed to have linear elastic and isotropic behavior due to small strains of ultrasonic waves. The actual FE Model and the cross section of the AML transducer are shown in fig. 6.

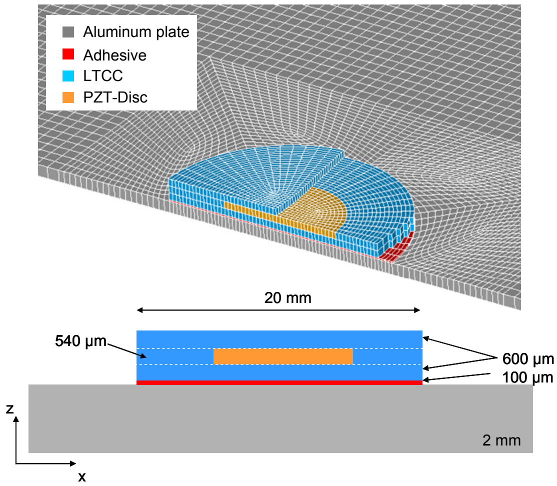

Fig. 6: FE Mesh and cross section of FE-Model for AML transducer Ø 20 mm

Results

In preliminary tests delamination between LTCC and PZT during sintering was an issue. We sustainably optimized process by the above introduced setup and technology chain. This resulted in LPMs without crack formation, warping and delamination. The proof of reliable electrical termination of the PZT disc was carried out by low signal measurements (capacity, dielectric constant, loss factor). For that AMLs were poled with E = 2 kV/mm, t = 5 min at room temperature. After polarization (24 h) a dielectric constant of $\varepsilon_{33}^T/\varepsilon_0 = 800$ ($\tan\delta = 0.013$) was measured. This value was lower compared to values measured on single PZT discs showing a dielectric constant of $\varepsilon_{33}^T/\varepsilon_0 = 1609$ ($\tan\delta = 0.019$). This tendency was already observed in [1] and we assume that there are two main reasons for that behavior. First, mechanical clamping of PZT disc by the surrounding LTCC material may cause changes of low signal and high signal properties of LPM. FEM simulation for verify that approval is in progress. Second, lead diffusion from PZT disc to LTCC could be detected as previously shown in [2]. This leads to an altered stoichiometry in PZT materials which causes to a shifting of low signal data. Further works are in progress to figure out the dominant influence. However this decrease is not tremendous for ultrasound transducer application as shown in the results of acoustic wave measurements below.

The laser vibrometer measurements (Fig. 7 and Fig. 8) show the different radiation pattern for square and round shaped AML transducer, although the embedded PZT disc was of the same size and shape. The LTCC mainly determines the radiation pattern of the transmitted acoustic waves.

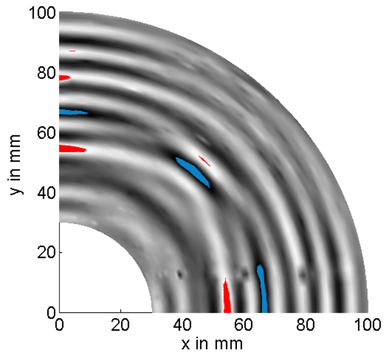

Fig. 7: Radiation pattern of square AML transducer (25 x 25) mm, snapshot at 50µs

Fig. 7 shows 90° of the radiation pattern of the square AML transducer (25 x 25) mm. The 0° and 90° direction is different to the 45° direction caused by the preferred excitation of ultrasonic waves whose wavelength is a multiple of λ/2 of the AML size in the actual direction. This λ/2 resonance was preliminary observed in [3].

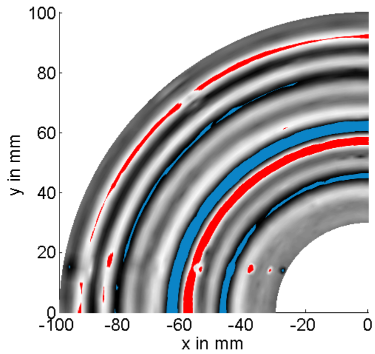

Fig. 8: Radiation pattern of round AML transducer Ø 20 mm, snapshot at 50µs

Fig. 8 shows a uniform radiation pattern of the round AML transducer (Ø 20 mm).

In Fig. 9 the measurement and simulation results for the square AML transducer (25 x 25) mm is shown.

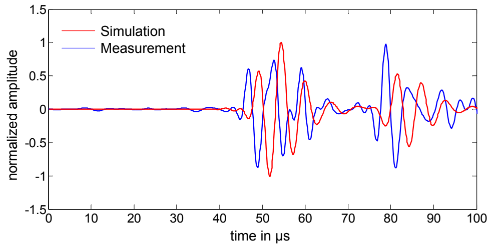

Fig. 9: Comparism of simulated and measured signals for AML transducer (25 x 25) mm, 0° direction

The distance between the transducers was 200 mm during a pitch-catch measurement scenario, which means one AML transducer acts as actuator and the second AML transducers acts as receiver. A time shift between simulated and measured signals was observed. Basically the signal shapes of both wave packages are qualitatively comparable, only amplitudes differ by some amount, which will be further studied by adjusting damping coefficients to fit the measured results. The simulated radiation pattern for round and square AML transducer are presented in Fig. 10.

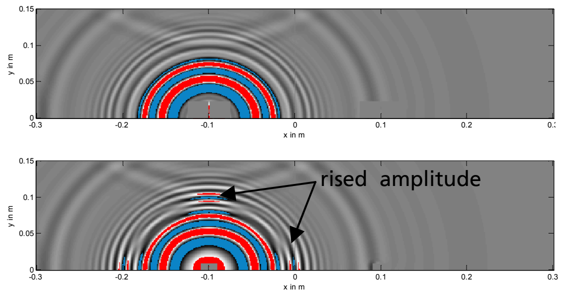

Fig. 10: Radiation pattern of round AML transducer Ø 25 mm (upper), square AML transducer 25 x 25 mm (lower), snapshot at 50µs

The angular radiation pattern shows a uniform shape in the case of the round AML transducer. The square AML transducer has a non uniform angular radiation pattern. There is a rise in certain wave package at 0° and 90° directions that. This behavior is also in good agreement with the measurement results of the laser vibrometer.

Conclusion

The main aim of producing robust AML transducer for SHM in rough environments was successfully achieved by combination of piezoelectric- and multilayer technology. Advantages of these fully inorganic modules with integrated PZT discs are seen in withstanding of the high requirements of thermal and chemical consistency but also integration of additional electronic components by reliable 3D wiring.

Measurements of dielectric properties as well as examination of ultrasound receiving capabilities proof excellent actuator and sensor behavior of this AML transducer.
Further studies will aim at the improvement of the FE Model in terms of damping coefficients and adjustment of material properties for the presented AML transducer to achieve an improved match of measured and simulated signal results.

Acknowledgement

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