Fabrication and Characterization of a Form- and Force-Locked Piezo-Metal Sensor Module

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Abstract

The direct integration of piezoceramics in sheet metal is a novel approach for production of adaptronic structural metal parts. In this paper the manufacturing process and characterization results of the first piezo-metal sensor module are described. The processes include high precision generation of micro-cavities in sheet metal, microscopic piezoceramic rods, PECVD insulating layers with high dielectric strength, micro-assembly and non-positive joining by forming. For the characterization of the module measurements of surface roughness, geometric parameters, and electrical properties were performed on the rods, the micro-structured sheet, and the insulation layer. Finally, the sensor function has been proven by a mechanical excitation resulting in a proportional measured sensor signal.

1. Introduction

Integration of functions into structural metal parts is a key technology for numerous future products aiming for increased resource efficiency and performance. The functional integration of active materials in sheet metal provides both, a reduction of product weight and cost along with superior sensor and actuator performance compared to current products. Sheet metal with integrated piezoelectric elements for actuation and sensing can be used for various applications, including collision sensing and health monitoring of joint connections in automotive components or security-related components for aircrafts.

A novel concept for the functional integration of piezoceramics in aluminium sheets has been developed. Unlike current technologies where piezoelectric modules are applied to existing structural parts, a direct integration of piezoceramics without prior packaging is proposed. In order to achieve sensor and actuator functionality, the piezoceramics require mechanical coupling to the sheet metal while not significantly deteriorating the passive mechanical properties of the base material.

In the following, the design, fabrication methods, and characterization results of the first functional prototype of a piezo-metal sensor module are described.

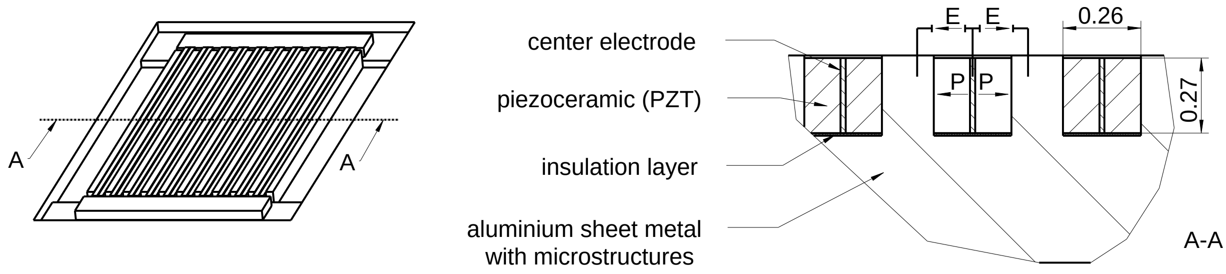

Fig. 1: *Design principle for the piezo-metal sensor module*

2. Fabrication of the piezo-metal sensor module

2.1 Design

The design principle chosen for the prototype is shown in figure 1. Piezoceramics are placed into micro cavities located on the surface of a sheet metal part. The depth of active area is less than 0.3 mm and the thickness of the sheet metal is 1.5 mm. The piezoceramic rods are therefore placed far-off the neutral axis of the sheet metal.

Within the prototype piezo-metal module ten piezoceramic rods with cross-sectional areas of $0.26 \times 0.27\ mm^2$ and 10 mm length have been applied. Each of the rods consists of two piezo-ceramic layers and a center electrode for electrical contact. The rods are integrated in micro cavities with nominal dimensions of $0.3 \times 0.3 \times 10\ mm^3$ resulting in a clearance between the piezoceramic rod and the cavity walls to ensure assemblability. The web between two cavities is 0.2 mm wide, which results in a pitch of 0.5 mm.

The piezoelectric d_{33} effect is used to provide for both maximum charges generated by strains resulting from deformations of the sheet metal and ease of manufacturing. Comparable to piezoelectric stack actuators, the piezoceramics are arranged in an electrical parallel circuit and mechanical series connection as it is depicted in figure 1. Thereby, the ground electrode is formed by the basis material and the signal is generated at the center electrode. Short circuits between the center electrode and the carrier sheet are prevented by the application of an insulating coating on the cavity grounds.

Mechanical and electrical coupling and therefore functional integration of the piezoceramic rods in the sheet metal is achieved by a subsequent forming process recently described in [1]. This forming process provides further an averaging of manufacturing tolerances [2] and the required pretension of the piezoceramic rods.

2.2 Aluminium Sheet Carrier

The ten micro cavities were fabricated by means of micro milling using a sheet of EN AW-5182 aluminium alloy (AlMg4.5Mn0.4), which is a common car body material. Figure 2 shows a scanning electron microscope (SEM) image of the micro-structured sheet.

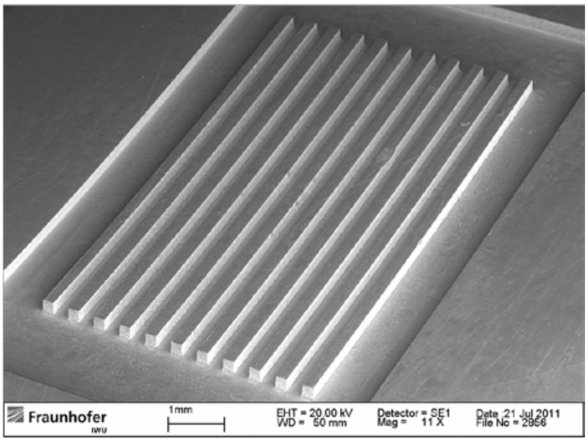

Fig. 2: *Micro-structured aluminium sheet metal*

Between the cavity sidewall and the piezo-ceramic rods a stiff mechanical coupling is necessary to transfer small strains within the sheet metal to the piezo-ceramic rods in order to sense small amplitude vibrations coupled into the carrier.

In order to allow for good transfer of the generated charges of the piezoceramics to the sheet metal, a close electrical contact is required. A prerequisite to achieve that close contact is a minimum surface roughness at the cavity walls. Figure 3 shows a close-up SEM image of the cavity walls where the surface roughness of these areas is observable. An average surface roughness of $R_a = 0.36$ µm and $R_z = 2.20$ µm has been measured on the cavity walls using a laser microscope.

The surface roughness of the cavity ground influences the properties of the subsequent insulating coating for preventing shorts and is therefore crucial for the function of the piezo-metal sensor module. The roughness of the cavity ground was determined to be in the range of $R_a = 0.22 - 0.31$ µm and $R_z = 0.29 - 0.40$ µm, which is expected to be sufficiently smooth.

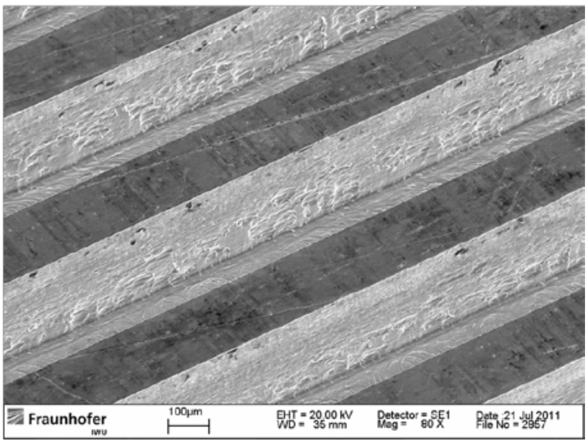

Fig. 3: *Magnification of micro cavity walls*

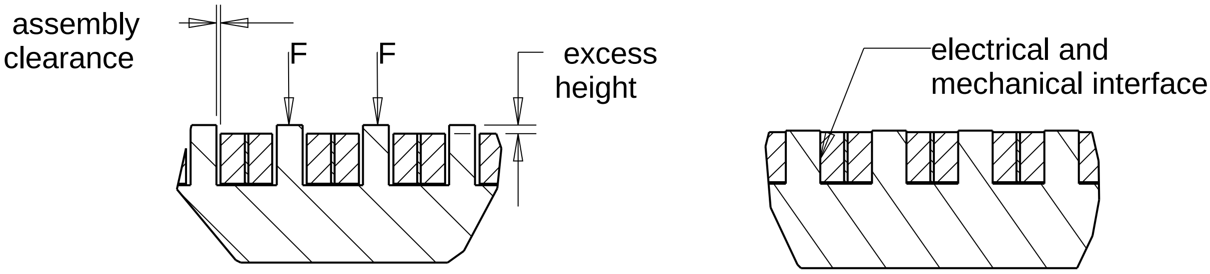

Fig. 4: *Principle of joining by forming for functional integration after assembly*

Another important parameter of the micro cavities is the depth. An average cavity depth of 312 µm with maximum deviations in the range of 3 µm has been determined from a cross-section of a sample sheet. The cavities depth therefore exceeds the 270 µm nominal height of the piezoceramic rods by more than 40 µm. This excess material is required for subsequent joining by forming.

2.3 Insulation of the Aluminium Sheet

The electrical insulation of the piezoceramic rods center electrodes against the micro-structured sheet metal is one of the most critical issues for the manufacturing of the piezo-metal sensor module. Its effectiveness depends on the chosen insulator material, the deposition parameters used [3] and the above described properties of the cavity ground.

Insulating layers were fabricated using a vacuum deposition system MicroSys400 (Roth & Rau). The insulating hydrogenated silicon carbonitride film SiCN:H was deposited in a PECVD process from trimethylsilane ($SiH(CH_3)_3$; "3MS") in mixture with nitrogen, hydrogen and argon using 13.56 MHz RF discharge.

The performance of the insulating layer is particularly defined by the dielectric strength. Breakdown voltage measurements were conducted for numerous samples by positioning a V-shaped electrode at the center of the cavity's ground and applying a variable voltage ranging from 0 to 1100 V in 5 V increments (voltage source Keithley 2410). Breakdown voltages in the range of 600 V have been measured at the cavity ground.

Significant differences comparing the layer thickness and resulting dielectric strength at the cavity ground and on flat areas away from the micro structure have been observed. On flat areas outside the micro cavities the insulator thickness is 4.5 µm and hence about 35 % larger than at the center of the ground of the micro cavities. Therefore, the breakdown voltage of the SiCN:H film exceeds values of 1.1 kV on flat areas.

However, a decreased dielectric strength was observed in assembled piezo-metal sensor modules. Breakdown voltages ranging from 170 to 280 V have been measured for modules with integrated piezoelectric rods. This deteriorated performance is likely to be caused by pinholes generated either due to roughness peaks in the micro cavities, inhomogeneous deposition of the insulating layer or defects resulting from the plastic deformation during the joining of the piezoceramic rods and the micro structured sheet metal by forming.

It should be noted that the measured dielectric strength is sufficient for sensor mode operation and would also be sufficient for small and large signal actuation.

2.4 Piezoceramic Rods width Center Electrodes

Piezoceramic rods with dimensions of 0.26 × 0.27 × 10 mm³ and center electrodes were cut from composite plates using a wafer dicing saw. The composite plates consist of two piezoceramic layers with an intermediate layer of Sn42Bi58 alloy. Those plates have been manufactured by joining metalized and polarized piezoceramic plates (M1100, Johnson Matthey Catalysts). Subsequent lapping and chemical mechanical polishing (CMP) of the composite plates produced the desired plate thickness of 260 µm and surface roughness of $R_a < 0.02$ µm and $R_q < 0.03$ µm.

2.5 Assembly of the Piezo-Metal Module

The piezoceramic rods were assembled into the micro cavities as shown in figure 4. The actual assembly clearances are influenced by the clearance fit and the deviations of the width of the rods and the micro cavities.

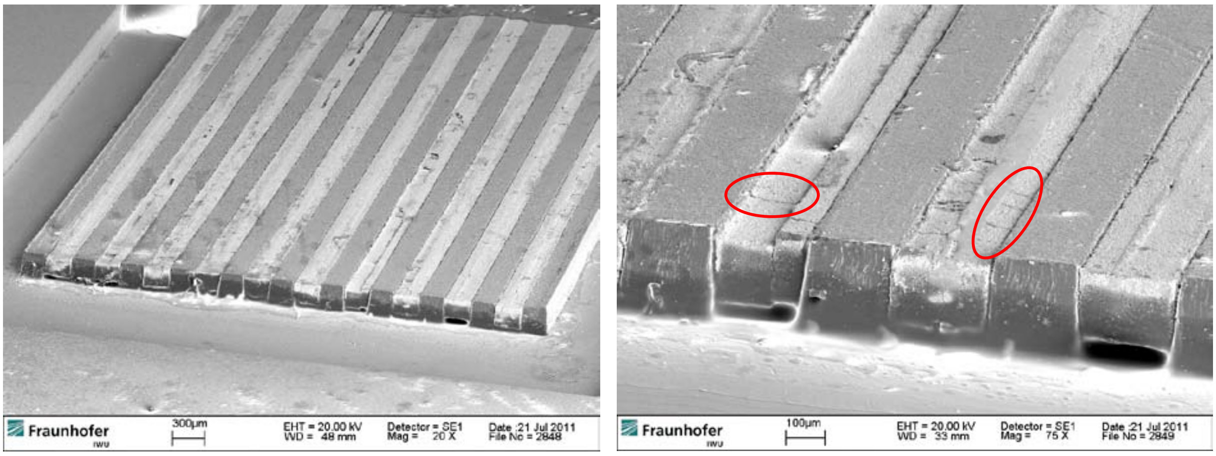

***Fig. 5:** Joined piezoceramic rods in a micro-structured aluminium sheet*

Figure 4 illustrates that a non-positive coupling is achieved by a forming process, where the webs are deformed using a planar die. This results in an electrical and mechanical interface between the piezoceramic and the sheet metal.

The joining by forming process was carried out in a hydraulic force-controlled press applying a maximum load of 12 kN. Figure 5 shows a SEM image of the joined piezo-metal module. The magnification on the right image shows that the high stress during the forming process caused small fractures (circles) within the piezoceramic rods, which have been described earlier in [4]. It should be noted that eccentricities of the center electrodes result from inaccuracies due to the manual manufacturing of the piezoceramic.

Further, it can be seen from figure 5 that piezoceramic rods are clamped by the deformed webs. The close contact between the piezo rods and the cavity sidewalls is more clearly observable from figure 6, which shows a microscope image of a polished section depicting the interface between piezoceramic and metal.

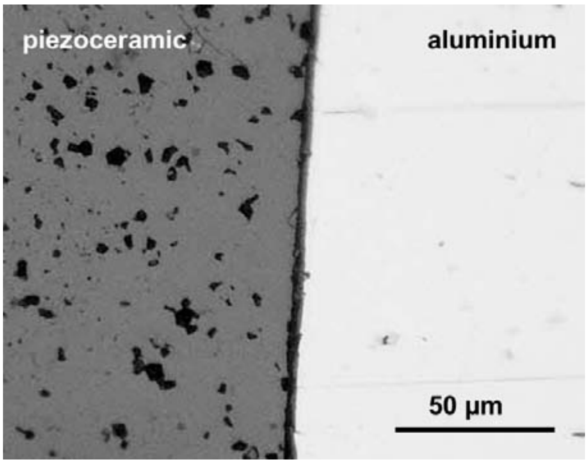

***Fig.: 6:** Interface between piezoceramic and metal*

The cavity widths have been measured before and after the joining by forming process using a Nikon MM400 measuring microscope. The results are shown in figure 7.

The average cavity width before joining was 312 µm and showed very little deviations in the range of 4 µm. After the joining by forming process, an average cavity width of 260 µm has been measured. Significant deviations of the cavity width occurred resulting from the varying width of the piezoceramic rods. This correlation proves the effect of averaging of dimensional errors since the variations of the width of the piezoceramic rods are reflected in the joined cavity width.

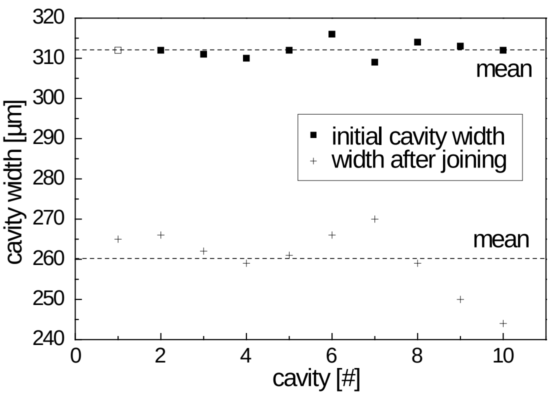

***Fig.: 7:** Cavity width before and after joining*

3. Characterization of the Piezo-Metal Sensor Module

In figure 8, the experimental setup for the characterization is depicted. The piezo-metal module is clamped on one side and bent on the other side by an excitation force resulting in a deflection *u* causing strains within the module.

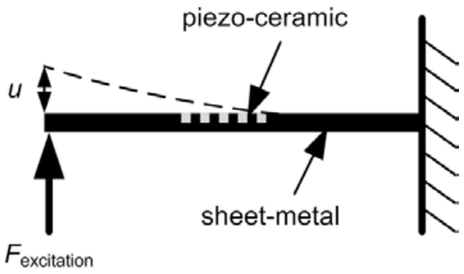

Fig. 8: *Schematic of the experimental setup*

Figure 9 is a photograph of the setup where the sheet-metal (1) and the piezoceramic rods (2) were electrically connected to a charge amplifier. The module was clamped on one side (3) and a piezo cube (PI P-611:3S Nano Cube) (4) driven by an amplified sinusoidal signal was mounted to perform periodic excitation on the other side.

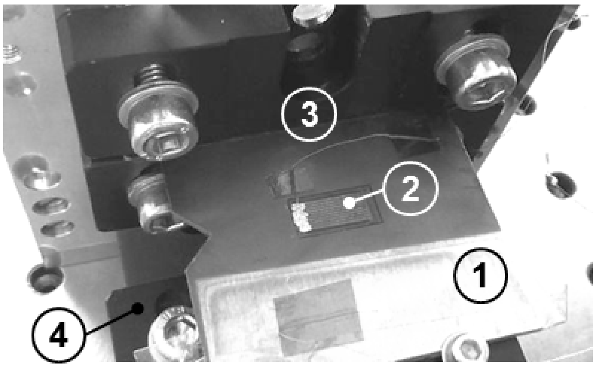

Fig. 9: *Experimental setup for characterization*

The deflection of the sheet metal causes strains in the direction of d_{33} within the piezoceramic rods and therefore generates charges due to the direct piezoelectric effect. In figure 10 the amplified charges generated by the piezo-metal sensor module are plotted in comparison to the exciting sinusoidal deflection measured by a high resolution laser triangulation sensor.

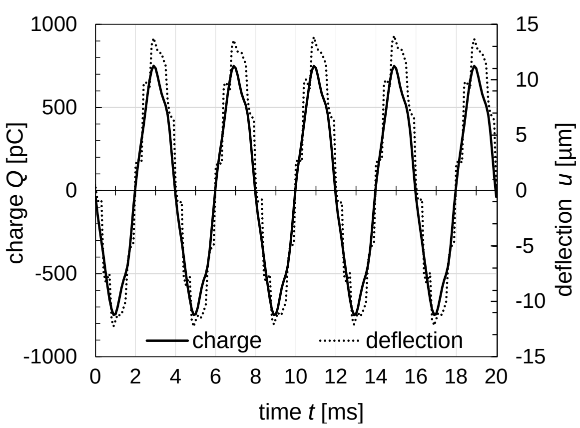

Fig. 10: *Deflection u (bending) of the piezo-metal sensor module and corresponding charge generated by the integrated piezoceramic rods (phase of signals was fitted for comparability)*

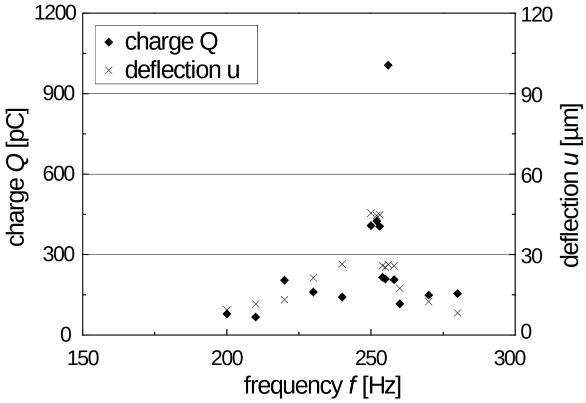

Fig. 11: *Generated charge by the piezo-metal sensor module and deflection of the piezo cube*

It can be seen from the graphs in figure 10 that the sensor signal is proportional to the mechanical excitation with high repeatability. This proves the effective electromechanical coupling of piezoceramic and sheet metal.

The charge generated by the piezo-metal sensor module is further a quantitative measure of the amplitude of the deflection *u* at the tip of the module (cf. figure 8). This was proven by measurements close to the mechanical resonance frequency (256 Hz) of the mechanical system consisting of clamped piezo-metal sensor module and exciting piezo cube.

In figure 11 the frequency response characteristics of both the generated charge and the deflection are plotted. Nearly congruent resonance responses have been observed. Therefore, the piezo-metal sensor module is capable of providing a quantitative measure of the mechanical deflection.

4. Conclusion

The feasibility of the direct functional integration of piezoceramics in micro-structured sheet metal has been demonstrated. It was shown that a configuration consisting of piezoceramic rods with center electrodes, where the sheet metal is used as ground electrode, allows for operation of piezo-metal modules as sensors.

The mechanical and electrical connection of the metal and the piezoceramic is solely achieved by a non-positive coupling generated by a forming process. This process is obviously capable of averaging dimensional errors of piezoceramic rods and micro cavities which are present due to tolerances in manufacturing. Piezoceramic rods with center electrodes can bear the mechanical stress induced by the forming process.

It was shown that the insulating coatings applied are sufficiently strong to endure assembly, joining by forming and generated electrical potentials in sensor operation in the range of 0 to 285 Hz excitation.

Further research aims for high-volume capable production technologies particularly for the manufacturing of micro cavities, the assembly and joining by forming processes. A significant reduction of the cycle times and increased repeatability and therefore reliability is expected by the use of micro impact extrusion to produce micro-formed cavities and automated micro-assembly of parallel batches of piezoceramic rods.

Further efforts are taken to increase the strength of the insulating coatings in order to increase the reliability of the piezo-metal sensor module and to enable in-situ polarization techniques and use of the module as actuator.

5. Acknowledgement

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