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Piezo-Metal-Composites as Smart Structures

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Abstract. In many applications vibration and noise are unwanted, but often inevitable. For instance in the field of automotive industry a reduction of comfort for the passenger is a result. In the range of high precision machine tooling negative influences on the quality of produced parts are possible by the appearance of unwanted vibrations. Adaptronic devices can help to improve the vibration and noise behaviour of structures. Today the production of adaptronic structures consists of two process chains: on the one hand the fabrication of structural parts, which occurs in a very efficient process with a low production time. On the other hand there is the functional integration step, which normally takes place under laboratory conditions and needs a lot of production time. For creating a smart structure the assembly of the structural part with the piezo-composite-module is performed. The authors propose a new process chain with material and functional integration in one process. Therefore a laminar piezo-module is integrated between two sheet metals by using an adhesive. After joining the compound, the semi-cured adhesive allows forming with a reduced generation of tensile loads due to friction between the blank and the piezo-module. As a last step of the process chain the adhesive fully cures and allows a coupling with a high stiffness. Experimental tests are used to characterize the functionality and to examine the process limits. Numerical studies allow the evaluation of stresses and strains in the piezo-module during forming.

Keywords: piezoceramic fibre, macro fibre composite, MFC, adhesive bonded sheets, piezo-metal-compound, deep-drawing, representative volume element, RVE, capacitance, measurement methods

1.1 Design and manufacturing of Piezo-Metal-Compounds

In order to create shaped intelligent structures the authors propose the integration of piezo-modules, especially macro-fibre-composites (MFC) between two metal sheets. The integration takes place by the use of a 2K-adhesive, which surrounds the MFC and connects the sheets. To obtain the desired shape forming takes place when the adhesive has still a low viscosity. During the forming process the strains resulting from the friction between the different layers can be reduced significantly. Hardening of the adhesive finishes after the forming operation has been performed. Because of that forming is possible without a destruction of the brittle piezoceramic fibres. The described method allows the production of intelligent, shaped multilayer-compounds in one process chain. More details of the manufacturing are presented in [1] and [2].

1.2 Forming operations with different MFC positions

To get information about tolerable MFC loads during forming, studies with different geometries and a variation of MFC position were applied. Furthermore different punch and die geometries allow an increasing amount of possible forming loads. The production of rectangular cups offers the possibility to place the MFC in regions with higher or lower forming loads. Two rectangular punches, with a width of 120 mm x 80 mm and a double curvature of 100 mm respectively 250 mm on the top of the punch are used. Fig. 1.1 shows the tool system and the geometries of formed parts with both types of punch. The MFC are integrated in the cup bottom as well as in the upper and the lower radii on the long vertical side of the cup. The aim is to detect possible defects caused by the forming process. Furthermore the functionality of the specimen is to be characterized.

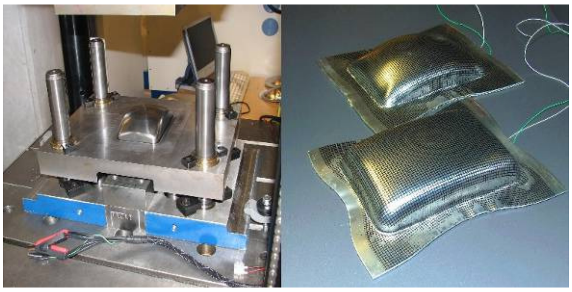

Fig. 1.1 Tool system and formed parts

1.3 Test of functionality

The usability of manufactured specimen as a sensor device depends on the functionality of the compound after forming. For its characterization different tests can be performed. One method uses the measurement of capacitance. MFC consist of a network of small capacitor cells connected in parallel (fig. 1.2) [3]. Summation of all capacitances leads to the total capacitance of the MFC.

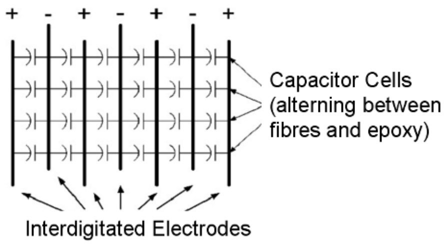

Fig. 1.2 Schematic builtup of MFC capacitance [3]

Every capacitor cell, which means exactly one part of one piezofibre, located between a pair of positive and negative electrodes, can be described in simplified terms as a plate capacitor, because the influence of the adhesive can be neglected. If this capacitor has no damage (fig. 1.3. left), its capacitance is calculated with eq. 1. If a crack is induced by too high forming loads, the capacitance is reduced (fig. 1.3, right).

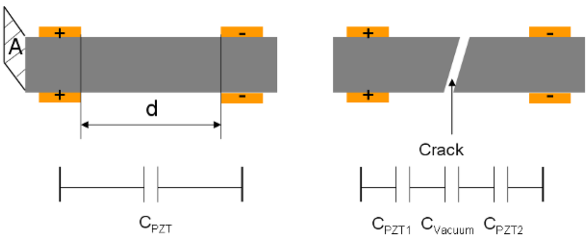

Fig. 1.3 Influence of cracks on capacitance C_{PZT}

Like a plate conductor with an additional dielectric of lower permittivity ε the capacitance C_{PZT} of the capacitor cell is reduced because of a serial connection of the broken PZT-fibre with a vacuum inside the crack. Its capacitance is computed with eq. 1.2.

$$C_{PZT} = \varepsilon_0 \cdot \varepsilon_{rPZT} \cdot \frac{A}{d} \tag{1.1}$$

$$\frac{1}{C_{PZT-crack}} = \frac{1}{C_{PZT1}} + \frac{1}{C_{vacuum}} + \frac{1}{C_{PZT2}} \tag{1.2}$$

A crack of 10 µm in the middle of such a capacitor cell, leads to a reduction of capacitance about factor 38 in this cell. Summation of capacitances of intact and damaged cells results to a reduced total capacitance in comparison to a non-damaged MFC. The detection of a reduction of the total capacitance during the forming process enables a prediction of induced cracks and a damage of electrodes of the MFC. If no reduction is detectable, no cracks or defects of contacting are expected.

Another possibility for the characterization of functionality is to deflect the compound by a defined displacement. Simultaneously the electrical answer is measured. If the stiffness of the specimen (for example for bended specimen) allows an elastic deformation with little forces, a shaker is used (fig. 1.4).

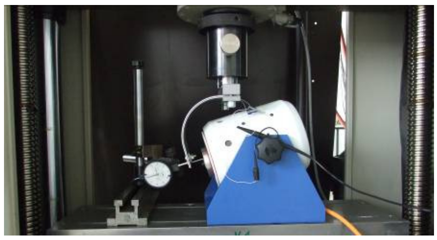

Fig. 1.4 Test of sensor functionality (bending specimen)

A defined displacement of one end of the specimen causes a strain of the integrated piezoelement. Because of the direct piezoelectric effect electric charges are induced which are visualized by a voltage metering on oscilloscope. If the stiffness of the formed specimen is very high, e.g. for rotationally symmetric structures, only a little displacement is possible in the elastic strain range, whereby high forces are necessary. Therefore the generation of a defined displacement can be performed e. g. with a static materials testing machine (fig. 1.5). To generate a measurable electric signal a high traverse velocity is necessary. Moving with high velocities and small traverse path in the range of a tenth of a millimetre is not possible because of the position resolution of the machine. Therefore only lower velocity ranges were used.

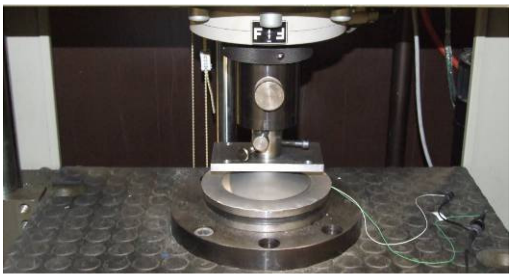

Fig. 1.5 Test of sensor functionality (with a rotationally symmetric structure)

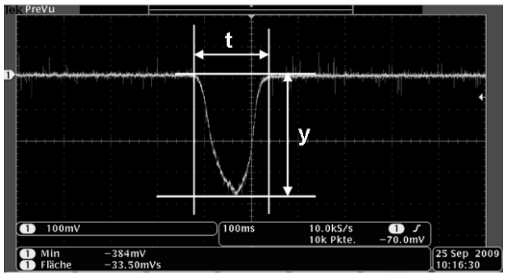

Fig. 1.6 Signal output of sensor functionality test

Result of this is an elastic deformation of the specimen. If the traverse is now moved away quickly, the specimen springs back in its unstressed condition. During this, the MFC is getting stretched and an electric charge is induced. The generated voltage signal is illustrated on an oscilloscope. The amplitude (y) and the time (t) of the voltage signal (fig. 1.6) depend largely from the parameters: displacement of the specimen/traverse path, traverse velocity, functionality of MFC and the geometry of the part.

A closer examination of the area below the voltage peak gives information on the electric charge, generated by the piezo element. The higher the degradation of MFC, the lower is the generated electric charge. Different velocities from 10 mm/min to 100 mm/min were used. The area below the peak is constant, whereby the duration of the signal peak increases and the maximum peak decreases in case of lower velocities.

In order to vary the loading of inserted MFC, different geometries and positions were determined. The functionality of the specimens is characterized by the measurement of MFC capacitance during the forming process and the evaluation of the electric charge generated by a defined elastic deformation of geometry after the forming process. Table 1.1 shows the averaged values for capacitance after forming, the remaining functionality (capacitance after forming divided by capacitance before forming) and an equivalent for the generated electric charge by a defined elastic deformation.

It is shown that forming is possible without a damage of MFC (M8528-P1) in case of positioning the patch on the top of the punch. Even a position in the upper and the lower radii on the long vertical side of the cup allows a forming with a reduction of capacitance of 25 %. All of these specimens can be used as a sensor device.

1.4 Numerical investigation

Deep drawing with punch radii of 100 mm and 250 mm were numerically simulated. The comparison of experimentally and numerically determined punch-force-displacement curves shows a good accordance. In the rear region the simulation force curve for the radius of 100 mm is situated below the experiment. The possible reason is a development of micro-wrinkles, which can only be modeled by a massive increase of mesh density in the forming simulation. With the method [4], detailed described in [5], a back-transformation of forming loads is possible to evaluate the stresses acting on the piezoceramic fibre (fig. 1.4 and 1.5). In accordance to the experimental results bending over double-curvatured punches with bigger bending radii of about 250 mm produces low load levels (max. 90 MPa) which result in zero function degradation. The load level for the punch radius 100 mm leads to a maximum of fibre stress in fibre direction of 580 MPa (basic stress level: 450 MPa).

Table 1.1 Different specimen and function analysis

Specimen	Averaged Capacitance after forming [pF]	Averaged remaining functionality [%]	Averaged electric charge equivalent [mVs]
R100, M8528P1, top of punch	3815	100	477
R250, M8528P1, top of punch	3700	100	633
R100, M2814P1, upper radius	582	90	268
R100, M2814P1, lower radius	620	73	135

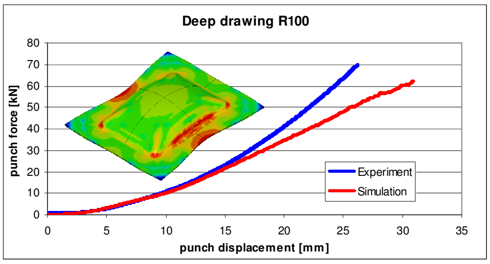

Fig. 1.2 Deep drawing - punch radius 100 mm

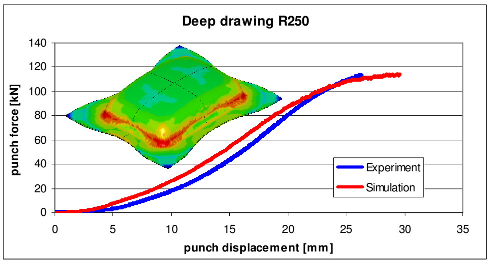

Fig. 1.3 Deep drawing - punch radius 250 mm

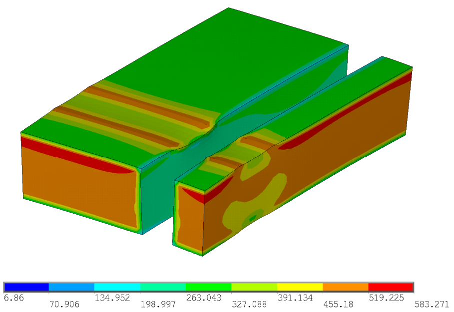

Fig. 1.4 Fibre stress in fibre direction - punch radius 100 mm

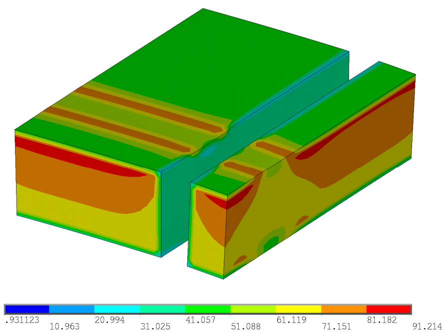

Fig. 1.5 Fibre stress in fibre direction - punch radius 250 mm

Within the described method the fibre loads are overestimated in the simulation due to the linear-elastic nature of the approach. For higher load levels further numerical investigation for the prediction of the exact material behaviour is planned.

1.5 Summary

It is shown that the new process chain with material and functional integration in one process allows the production of piezo-metal-compounds by deep drawing. Different geometries were determined experimentally and numerically. The specimen can be used as sensor devices. Researches for a use as actor devices are planned. For the characterization of the remaining functionality of formed piezo-metal-compounds the measurement of capacitance and a sensor test were performed. Both methods allow the estimation of MFC-functionality after forming. The integration of MFC is possible even in areas of high forming loads. A partially damaged MFC also works as a sensor, whereat the generated electric charge is reduced in comparance to a non-damaged MFC.

1.6 References

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