Experimental and Numerical Study on Efficient Forming Operations of Sheet-Metal-Compounds with Integrated Piezo-Modules

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For the manufacturing of piezo-metal-compounds, forming strategies are presented that allow an integration of piezo-module application in the fabrication process. Specimens of sheet-metal-compounds with piezoceramic modules between double-layer-sheets were manufactured and investigated under different forming operations. Simultaneously a numerical study was performed to determine and predict the locations of high load levels. The modules are embedded in a semi-cured adhesive to reduce tensile stresses in the brittle piezo components due to contact pressure and friction between blanks and module in the forming operation. The functionality of the specimens is characterised by the measurement of module capacitance during the forming process as well as actor and sensor tests after forming. The methods provide cumulated values for the functionality. A prediction of the locations of module degradation and the leading influencing parameters are to be achieved by numerical investigations. It is shown that the functionality of integrated modules is fully maintained for bent specimen down to radii of 10 mm, for rectangular cups with a double curvature of 100 mm and 250 mm. Axisymmetric specimens with a punch radius of 50 mm cause damage and lower radii of 25 mm cause significant damage until breakdown depending on the draw depth.

Keywords: piezoceramic fibre, macro fibre composite, MFC, adhesive bonded sheets, piezo-metal-compound, forming simulation, Representative Volume Element (RVE)

Introduction

Light-weight constructions with an integration of additional functions like the control of vibration behaviour, health monitoring or integrated crash sensors require appropriate production technologies. The state-of-the-art process chain for the production of piezo-metal-compounds consists of the production of structural parts and the subsequent application of piezo-modules. Forming of blanks is performed in a high productive way whereas the application of laminar piezo-modules is normally performed in manual operations [1] and for this reason it is time and cost-intensive. For a substitution of the subsequent application of piezo-modules an integration before the forming operation can be executed. Therefore the inconsistency between the formability and the sensor and actor functionality must be solved by means of the design of the composite as well as by the use of an appropriate production technology.

Approach of Temporary Soft Coupling

In order to develop a process chain which allows an integration of piezo-modules before forming, a deformable piezo-metal compound has to be designed. The challenge is to fit a brittle piezoceramic into a deformable blank in a way that reduces the tensile stresses in the brittle piezofibres caused by the forming process. The chosen design with a Macro-Fibre-Composite (MFC, manufacturer: Smart Material) embedded in an adhesive between double-layer-sheets (**Figure 1**) allows a temporary soft coupling. During the forming operation the adhesive has a low viscosity. This ensures a relative movement between the MFC-module and the sheets during forming and hence a reduction of tensile stresses in the brittle piezofibres due to the contact pressure and friction between blanks and the module. After forming the hardening of adhesive occurs and allows a coupling with a high stiffness.

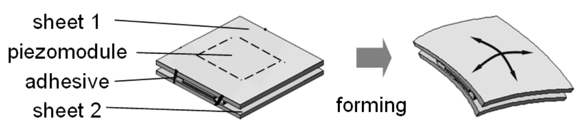

Figure 1. Forming of piezo-metal-compounds.

Experimental and Numerical Results

Characterisation of Materials. For the analysis of formability of the compound the basic materials (the sheet metal, the MFC and the adhesive) have to be investigated. The stress-strain curves of the aluminium sheets were obtained from a tensile test (DIN EN 10002 [2]). The characterisation of MFC was performed with a tensile test in three directions of loading because of the orthotropic material behaviour. The elongation fields were detected with an ESPI-system (electronic speckle interferometry). Because of the non-uniform surface of MFC the investigated displacement fields contain errors and cannot be used. Therefore the mechanical properties were identified by numerical investigation. The results are presented in [3]. A very important part in material characterisation is the study of the adhesive properties. To obtain the temporary soft coupling an appropriate viscosity has to be used. The investigation of storage and loss modulus as a function of the temperature was performed by the Institute of Polymer Technology LKT of the Friedrich-Alexander-Universität Erlangen-Nürnberg. **Figure 2** shows the modulus of the 2K-adhesive for a temperature of 40 °C. The higher the temperature, the faster the hardening of the adhesive. This fact can be used to reduce the time for gelation and hardening of the adhesive. The forming operation has to be performed below the gel point, which is located in the point of intersection of storage and stress modulus. Above the gel point a macroscopic crosslinking prevents the glue from flowing [4]. The use of temperatures of 40 °C offers the possibility to reduce the time for gelation, so forming can be performed after 35 to 40 minutes instead of 120 min at room temperature. The aim of further research is a reduction of gelation time down to 2 minutes.

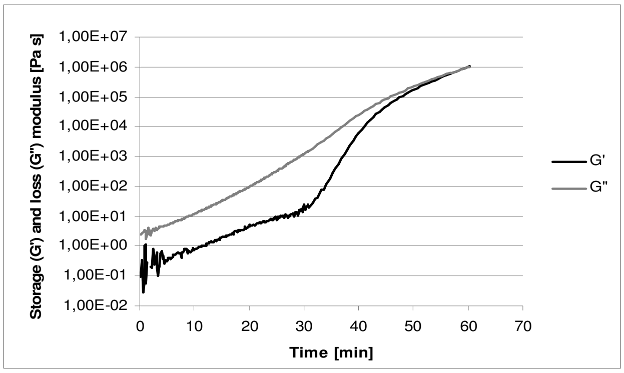

Figure 2. Storage and loss modulus of adhesive at 40 °C.

Forming Operations. To analyse the correlation between the forming loads and the functionality of the piezometal compounds different geometries were investigated. Based on positive results of bending experiments, additional geometries with 3D-deformations were analysed. Through the use of an Erichsen testing-facility axisymmetric cups with different punch radii and a variation of sheet metal thicknesses have been investigated. Deep drawing and stretch forming operations are performed by controlling the downholder forces. The preset viscosity of adhesive allows a forming without a discharge of adhesive. A punch radius of 50 mm causes a damage in the integrated MFC. A smaller radius of about 25 mm causes a significant damage and in some cases, it causes a complete breakdown to the MFC. In a next step application-oriented geometries like a rectangular cup with punch radii of 100 mm or 250 mm in the two directions were manufactured on a servopress. The double curvature of the punch does not cause any damage of the MFC, which is situated on the cup bottom, as **Figure 3** shows.

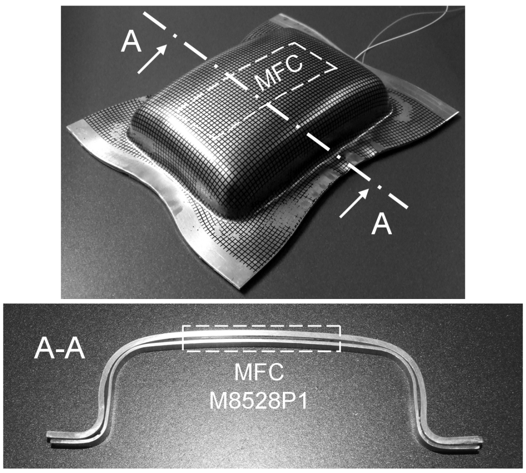

Figure 3. Rectangular cup with double curvature of 250 mm.

Test of Functionality. In addition to the forming experiments an examination of functionality of the integrated elements has a high priority in the research. Therefore different methods are used. The measurement of capacitance gives information on functionality during the forming operation. MFCs consist of a network of capacitance cells connected in parallel. If the piezomodule is not getting damaged during the forming operation, its capacitance stays constant. A damage of MFC, e. g. cracks of ceramic fibres or a damage of contacting, leads to a reduction of the total capacitance. If the MFC completely loses its functionality, for example because of a fracture of cords, its capacitance tends to zero. Furthermore this method allows an examination of critical draw depths, when the capacitance is reduced at a specific stage of forming for example. **Figure 4** shows the loss of capacitance due to the forming of an axisymmetric cup with a punch radius of 25 mm. With this punch a draw depth of only 18 mm leads to a significant reduction of capacitance from 750 pF to 300 pF.

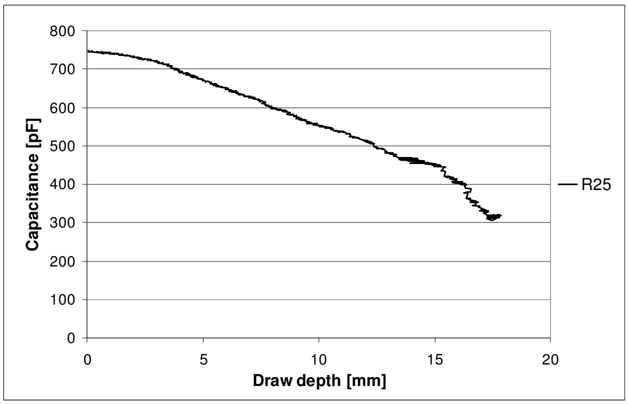

Figure 4. Capacitance over draw depth of axisymmetric specimen with a radius of 25 mm.

A later examination with X-ray (**Figure 5**), performed at the Fraunhofer IKTS Dresden, illustrates the cracks induced by the high forming loads for a small punch radius. X-ray inspection offers the possibility to detect and to localise defects of piezo modules.

Furthermore the sensor and actor functionalities of manufactured specimens are tested to characterise their performance.

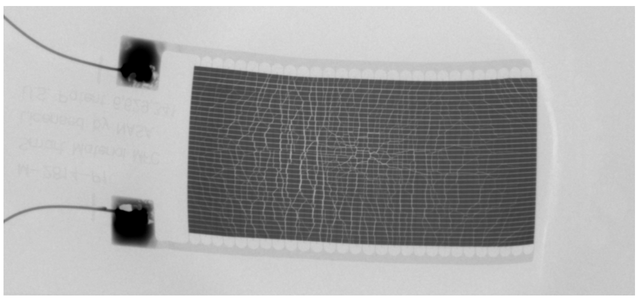

Figure 5. X-ray analysis of axisymmetric specimen with a radius of 25 mm.

Numerical Investigation. The modelling of the detailed build-up of the MFC, e. g. piezo fibres, in the global forming simulation would lead to too large model sizes and numbers of discretisation points. Therefore a homogenisation step, described in [5] and detailed in [6, 7], for the MFC material was implemented into the forming simulation. With the homogenisation calculations it is also possible to transfer the local MFC loads of the global forming simulation to the submodel of a representative volume element (**Figure 6**) used in the homogenisation step [7, 8].

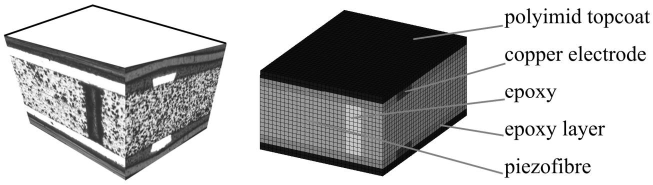

Figure 6. Unit cell submodel.

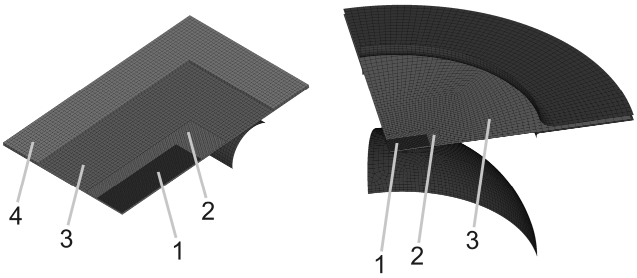

Figure 7. Geometry of the model (1 = active MFC region, 2 = non-active MFC region, 3 = lower blank, 4 = gap spacer).

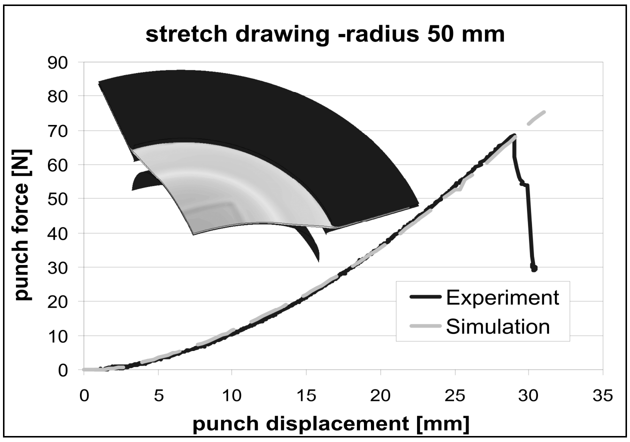

Figure 8. Punch-force/punch-displacement-plots for stretch drawing.

With the homogenised orthotropic material the piezo module was modelled with shell elements in the forming geometry model. For the three forming technologies 3-point-bending, stretch drawing and deep drawing tests were modelled. **Figure 7** shows the geometry of the model for 3-point-bending and stretch drawing. The upper sheet metal is not shown for clarity.

A validation of the three forming models was made by comparison of experimentally and numerically determined punch-force/punch-displacement curves. Examples of the experimental and numerical punch force plots are given in **Figure 8** for stretch drawing. All of the three investigated forming technologies show a very good agreement.

With the back-transfer the local loading of the MFC components is computed in highly loaded MFC zones. As the MFC dimension as well as the complexity of the homogenisation material model rises (e. g. additional load cases to describe thickness properties and nonlinearities), the computation times increase drastically. And a less complex approach had to be applied. A critical piezo fibre stress value can be evaluated with yield criteria based on the assumption that the brittle fibres break for elastic deformation without any plastic strains. For the homogenised orthotropic MFC material Hill's yield criterion [9] could be applied, but for the computation of an equivalent stress the critical stress values for loading along material axes are necessary. These values are sometimes hard to capture due to problems in applying constant boundary conditions in the experiment at the microscopic scale of the MFC specimen [10]. Furthermore in Hill's yield surface theorem the stress tensor is reduced by the hydrostatic stress state, which can cause damage of the brittle piezo fibres, in contrast to a ductile material which remains in the elastic state under hydrostatic pressure. Therefore an approach based on the elastic work for the piezofibre was developed and is described in [11] in detail. Because of the elastic nature of the method a deviation between experiment and simulation is considered. The bigger the loading of the MFC, the bigger the total error for this approach. However, the load distribution in the forming simulation is in very good agreement with the development of fibre breakage determined with x-rayed forming specimens (**Figure 9** and [11]). With the dotted lines in the picture of the x-rayed specimen of **Figure 9**, the region of the numerically investigated MFC-zone is displayed (the geometry represents a quarter of the whole specimen due to symmetry). To correct the total deviation, further investigation is planned within the subproject B2 of the Transregional Collaborative Research PT-PIESA.

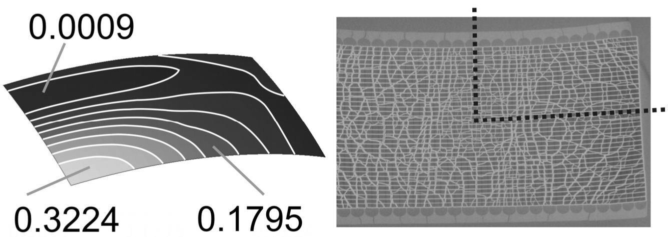

Figure 9. Elastic work distribution in Nmm (left) and x-rayed specimen with excessive fibre breakage development – deep drawing punch radius 25 mm.

By applying the homogenisation method to shell structures, the resulting bending stiffnesses are increased. The homogenisation provides uniform in-plane stiffness values over the shell thickness. Thus the outer low-stiffness zones are overestimated and the global bending behaviour is too stiff. A method was developed to correct this effect. The basis for the approach is the Classical Laminate Theory

(CLT). With insertion of two extra layers a stiffness distribution for the total three layers (two outer regions plus one middle layer) can be extracted with CLT by including the error for bending stiffness. The result is a corrected effective 3-layer material model that behaves like the detailed modelled unit cell under bending. The method is described in [11] in detail.

Summary and Outlook

The presented process development allows an integration of the time and cost consuming MFC bonding step direct in the production process of formed blank structures. The proposed process chain leads to a time and cost reduction of production cycles in high efficiency production branches, such as automobile production, railway-vehicle manufacturing and consumer industries.

The challenge of creating a formable piezo-metal-compound with brittle piezofibres inside is solved by the use of MFC modules which include thin fibres and the method of temporary soft coupling. The forming below the gel point of adhesive allows a relative movement between the MFC and the blanks during forming, and leads to a reduction of tensile stresses in the MFC due to friction. Different forming operations have been performed to analyse the formability of the compounds. It is shown that bending is possible down to radii of 10 mm. Using 3D test-structures with small radii caused partial damage of the fibres and the electrodes. In a next step the creation of application-oriented structures was possible without damaging the MFC. In order to characterise the functionality of specimens the capacitance has been measured during the forming operation. In this process a reduction of capacitance indicates damage. Further research has been performed with X-ray inspection. This method allows the detection and localisation of damage.

In the numerical investigation a homogenisation method is used to model the MFC structure behaviour in the global forming simulation. A detailed model at the scale of the MFC components is not used because of the large computation times. Instead an approach is developed based on the equivalence of elastic work for detailed modelled MFC RVE and an equivalent shell structure. With several mechanical load cases, e. g. tension along material axes and shear, in load case simulations with unit cell the elastic work is recorded. For the chosen material model, an equations system with the homogenized components of the elastic stiffness matrix is solved and the elastic properties are extracted. The retrieved engineering constants are in very good agreement with values published in the literature.

The global forming loads can be transferred to the local unit cell. Thus a refined evaluation of the loading of the MFC-components, e. g. piezofibres or electrodes, is available. But the computation times dramatically rise as the complexity of the material model increases. Therefore an approach based on the elastic work of the piezo fibres is developed to describe the fibre loading in the forming step. Because of the elastic nature of the method, the accuracy decreases with rising forming loads. Additional investigations are planned.

By applying the homogenisation method to shell structures, the bending stiffness of the homogenised shells is increased as shown in detailed modelled unit cell under bending. The outer regions with bending are overrepresented due to the use of uniform in-plane stiffnesses. By subdividing the material in three layers and with the use of the Classical Laminate Theory, the error in bending behaviour is reduced by 43 %. However, the error for the load case of drilling increases by 9 %. An optimisation is planned in further research.

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