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Modeling of the performance reduction of Macro Fiber Composites for use in numerical forming simulation of piezoceramic-metal-compounds

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ABSTRACT

With the objective of producing aluminum sandwich parts with a sensor and actuator functionality, a production method was proposed which uses an adhesive for the integration of a piezomodule. Complex shapes may cause a reduction in the performance of piezomodules. Uniaxial and biaxial transducer tensile tests and accompanying optical strain measurements were carried out to evaluate the residual performance taking into account the strain load combination. The model validation showed a very good agreement between forming experiment and numerical simulation. The simulation model including the functionality reduction enables the performance of the actuator to be predicted after the forming stage for complex shaped parts has been completed.

1. Introduction

Sensor and actuator modules with integrated piezoceramic fibers offer the possibility of implementing adaptive functionalities in different materials. Macro Fiber Composites (MFC) are often used in smart structure applications. Many studies deal with the assembling of piezo-modules in order to achieve health monitoring [1,2], energy harvesting [20] or active shape control [12] functionalities. In order to mount MFC on a sheet-metal a maximal stiff fixation is necessary [25]. It is preferable to use adhesive bonding which typically requires an elevated manual application effort. In contrast to the state of the art production, especially for greater quantities of pieces, appropriate production technologies are required. In previous studies, efficient manufacturing procedures were experimentally and numerically investigated [17] as part of a mass production process chain for piezomodule-metal-compounds. The process chain contains forming stages which allow the production of complex shaped aluminum-piezomodule-sandwiches by adhesive bonding. The advantage is the formability of the compound, realized by a floating mounting of the MFC inside the sandwich structure during the forming operation. While the forming process is taking place, the adhesive is present in a viscous state. After the forming process the adhesive fully cures by chemical reaction and provides a tight connection between MFC and sheets. The piezomodule-metal-compound acts as a smart structural part. Actuator and sensor functionality of the compounds were established in previous studies (e.g. [4]). Fig. 1 shows a microsection of the layered compound structure. The MFC is embedded in an epoxy layer and encapsulated between two formed aluminum sheets.

Shaping operations that produce moderate curved parts, e.g. deep drawing with double curvatured punch with main radii of about 250 mm induce low-level loading of the integrated MFC. More complex part geometries need the use of local punch curvatures with radii significantly below 250 mm. The liquid adhesive in the semi-finished compound acts as lubricant and hence reduces critical friction loads. However, the deformation of the surrounding sheet metals causes geometric constraints for the MFC which can induce high tensile stresses (especially for double curvature deformations, Gaussian curvature). MFC damage may occur which strongly affects the MFC functionality (direct and indirect piezoelectric effect). Thus, a knowledge of critical strain combinations is necessary to evaluate possible combinations of shaping process technologies and part geometries. The piezomodule consists of brittle piezoceramic macro

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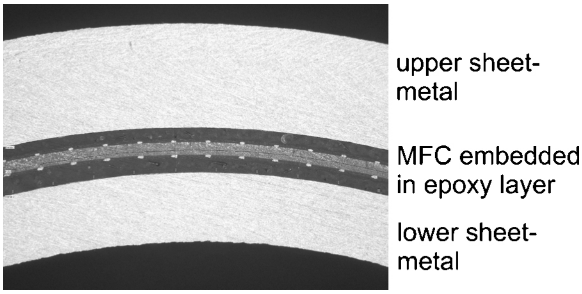

Fig. 1. Piezo-metal-compound with MFC embedded in an epoxy matrix. The compound is formed with uncured state of the adhesive. After shaping the epoxy fully cures and provides a tight connection between sheet metals and MFC.

fibers embedded in an epoxy resin. Many studies have dealt with damage to piezoceramic materials. Kuna [13] gives an overview. Park and Sun [19] investigated notched lead zirconate titanate (PZT) specimens under electrical and mechanical loads to compare several fracture criterions. It was found that the mechanical strain energy release rate is an appropriate fracture criteria. Furthermore, the crack propagation is inhibited under a negative electric field and supported by a positive field. Fu and Zhang [7] investigated the influence of the electric field on fracture toughness with notched plates. They found that an applied positive or negative electric field parallel or transverse to poling direction reduces the fracture toughness K_{IC}. dos Santos e Lucato et al. [15] modeled the crack growth and path direction in good accordance with experimental results. The crack path and length for raising electric fields depend on the electrode geometry and the poling state. Karastamatis et al. [11] used a 4-point bending specimen (polished bars) to obtain fracture toughnesses of a PZT-material. With a similar specimen type the mechanical, piezoelectric and electric parts of the total energy release rate were calculated by Swain et al. [21]. While loading and unloading the specimens in 6 cycles, mechanical, piezoelectric and electric compliances were obtained as a function of the crack length and further used for the computation of the energy release rate parts. Westram et al. [24] loaded notched bars with a sinusoidally changing electric field (alternately positive and negative) perpendicular to the crack path. The crack is initiated when the first cycle is applied due to cyclic electric fields above the coercive field strength of the material. After 60 cycles a maximum crack length of $a = 3.3$ mm for the maximum electric field amplitude of 1.9E+06 V/m was reached. Several studies take the micro-structure of the brittle materials at the grain-level into account (e.g. [5,22,23]). Gall and Thielicke [8] and Gall et al. [9] focus on the degradation behavior of d31-piezoelectric transducers (resultant strain perpendicular to the applied electric field). Quasi-static and cyclic load regimes were used to characterize the global transducer material behavior taking into consideration temperature effects. As part of the study, dependencies between damage and loading scenarios were deduced.

Generally, except for the latter study in the literature review, damage to piezoelectric materials with only one or two cracks were investigated previously. Most of the studies deal with piezoelectric bulk material without taking into consideration the isolation, electrodes and cover sheets of an entire transducer. In the present study and in the course of our previous investigation (e.g. [16,17]), macro-fiber d33-piezoelectric transducers manufactured by smart material were used. The applied electric field and the resultant strain directions coincide and are parallel to the macro-fiber direction. The parallel aligned macro-fibers are embedded in an epoxy matrix. Finger electrodes oriented perpendicular to the fiber direction contact the piezoceramic fibers. The perpendicular alignment of the module components leads to a distinct overall orthotropic material behavior of the piezomodule.

The aim of the present study was to evaluate critical strains that influence the performance of the MFC. The propagation of the performance reduction was also investigated. Finally, a database is given that allows a prediction of the residual performance of a piezomodule-compound after the shaping operation.

2. Testing procedure

2.1. Investigation into performance reduction

In the shaping operations for the piezomodule-compounds the MFC are loaded mainly with tensile membrane stresses. Numerical simulations showed a significantly perturbed stress field that causes local stresses oriented at different angles to the fiber direction. Because of the orthotropic material behavior of the MFC, the theory of principle stresses and strains is not applicable. Hence in the experimental investigation a focus on measurable strains was selected. Different specimen types were then defined to cover the relevant tensile strain space. Fig. 2 shows the experimental specimen.

The types (a), (b) and (c) are tension specimens with MFC types M8528P1 and M2814P1 adhesively bonded on an aluminum carrier sheet. The latter MFC type was also aligned with fiber direction transverse to the tension load axis to induce a loading perpendicular to the fibers (specimen type (c), compare also Fig. 3(a)). The type (d) specimen was used to apply several strain combinations in strain space to the MFC (transducer types M8556P1 and M8528P1) which is bonded on a biaxial aluminum specimen. With a biaxial testing machine with four axes (compare Fig. 3(b) and (c)), combined loads in fiber and transverse direction can be induced. In preliminary tests two adhesives were considered. Relevant performance reductions occur after the elastic limit of the carrier sheet metal is reached. Hence the adhesive system has to transfer high shear loads. The chosen

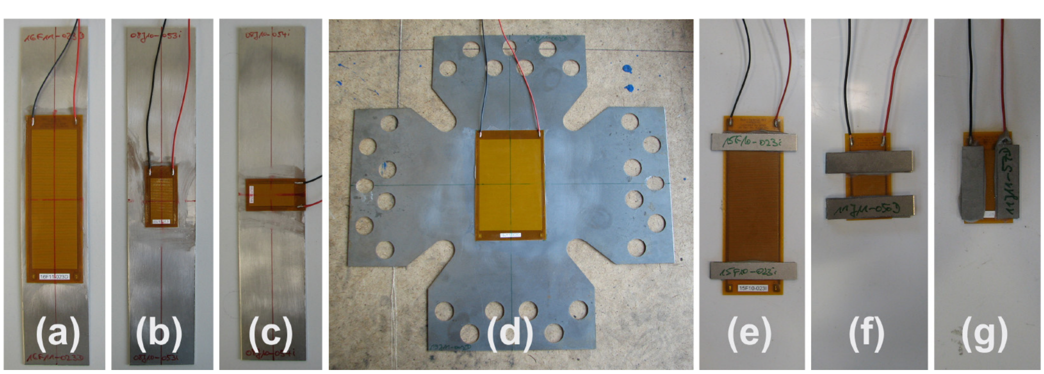

Fig. 2. Different specimen types for the evaluation of the performance reduction. ((a)–(c)) Different MFC types bonded on aluminum sheet carrier used in uniaxial tension tests. (d) MFC bonded on aluminum carrier used in biaxial tensile tests. ((e) and (f)) Pure MFC specimen for uniaxial tension tests.