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Inherent process monitoring for piezoceramic transducer integration

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Abstract

A new technology enables the integration of piezoceramic fibres as functional elements into micro-structured aluminium sheets by forming processes. Scope of the paper is the development of a novel method for monitoring the condition of piezoceramic fibres during the joining by forming process. For this purpose, the piezoceramic fibres are utilized as material inherent sensor during forming tests. Test samples are fabricated and electrically characterized by impedance spectroscopy. Furthermore, numerical results of the stress state of the piezoceramic/metal composites are presented. Depending on the results a novel process-control is outlined that aims on preload-monitoring of the piezoceramics with the surrounding metal structure.

Keywords: piezoceramic transducer, piezoceramic/metal composite, joining by forming, process monitoring, impedance spectroscopy

1. Introduction

Structurally integrated sensors and actuators enhance lightweight composite parts with new functionalities. State of the art for application of piezoceramic patch transducers on structural components is adhesive bonding on the surface. Thus, between the component and the piezoelectric element are adhesive or other polymer layers, which damp the active power transfer of the transducers [1].

However, a new direct integration technology allows the integration of lead-zirconate-titanate (PZT) fibres or interconnected fibre-arrays into micro-cavities in aluminium sheets. With this technology the fibres are connected in form-fit and interference-fit with the micro-structured sheet metal through joining by forming [2]. The obtained compressive preload prevents a separation of the joining partners caused by tensile load on the structure. Potential applications for this technology are structural health monitoring [3], active noise reduction [4] or smart structures [5].

The focus of this paper lies on the development of an in-situ monitoring method for piezoceramic components during joining by forming operations, which should be transferable for a high-volume production of piezoceramic/metal composites.

2. Design of PZT transducers and force calibration

2.1. Design

The design for integrated PZT fibres in metal sheets is illustrated with Figure 1. The PZT transducer consists of five PZT fibres with geometrical dimensions of 12 mm x 0.56 mm x 0.46 mm, which are placed in a 1.5 mm thick micro-structured aluminium sheet. This microstructure comprises five cavities that are 40 µm wider than the fibres. The resulting gap is necessary for the assembly of the fibres and is closed with a joining by forming process. After this joining step the fibres are form-fitted, interference-fitted and preloaded in the aluminium sheet without any elastic interlayers.

All experimental investigations were conducted on piezoceramic fibres with 60 µm thick central interface electrode (CIE). The manufacturing of the fibres was accomplished by soldering two PZT plates (material M1100 from Johnson Matthey) of 250 µm thickness with S-Pb60Sn40 solder. Afterwards the double plates are divided by a cutting process in fibres. The cavities of the aluminium sheet were produced by micro-milling. Wires were attached to each CIE and the metal sheet for the later process-monitoring.

For insulating the CIE against the sheet metal two approaches are investigated. In the first approach the bottom section of the cavities is insulated by a silicon carbon nitride film (SiCN:H) deposited in a PECVD process [6]. In the second approach the sheet metal is not insulated. Instead, the fibres are coated with a silicon carbon nitride insulation film in the vicinity of the CIE. The sensor signal is generated by the piezoelectric longitudinal effect (d_{33}-effect) between the fibre's CIE and aluminium sheet as ground electrode.

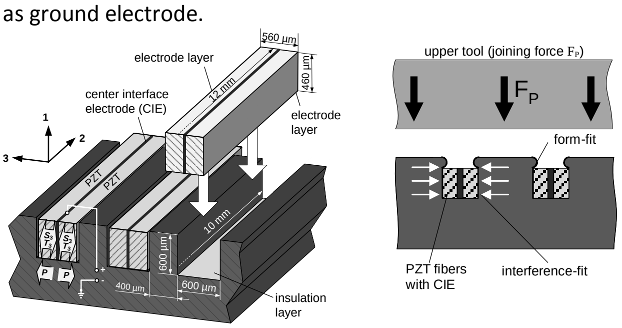

Figure 1. Design of piezoceramic/metal composite.

2.2. Force calibration

In the vicinity of a mechanical resonance, the electrical impedance of piezoelectric ceramics can be approximated with the simplified equivalent circuit model with lumped parameters which embodies the true electrical capacity and the mechanical impedance of the first mechanical resonance mode. In [6] a dependency between the electrical impedance of piezoceramics and their axial loads which cause destabilization or stiffening of a piezo patch was found and used as sensor-principle in this work.

In order to enable the piezoceramic joining partner as material inherent sensor during the forming process, a correlation between acting force and electrical impedance is needed. Therefore compression tests of single fibres were conducted. During the compression tests a network analyser recorded the impedance spectrum at different force levels. Figure 2 exemplarily shows a sequence of impedance spectra at different compression forces. At a frequency of 2 MHz the impedance shows a good sensitivity and monotone characteristic to the applied force. A regression analysis yields the following calibration formula (Eq. 1), where F_3 is the applied force in longitudinal polarization direction (d_3) and Z_{2MHz} the magnitude of electrical impedance at 2 MHz.

$$F_3 = 4 \cdot 10^{-37} N \cdot \left(\frac{Z_{2MHz}}{1\Omega} \right)^{12.946} \quad \text{(Eq. 1)}$$

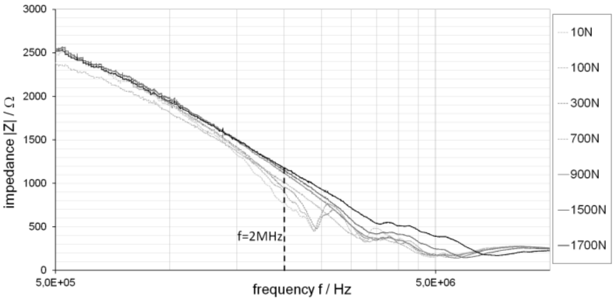

Figure 2. Measured impedance spectra of a single piezoceramic fibre with CIE at different compressive forces F_3 in d_3-direction.

3. Joining by forming experiments

For the joining tests, the fibres were assembled in the microstructure and electrically connected to the network analyser. During the joining operation the upper tool moved downwards and applied stepwise an increasing force F_P up to 20 kN to the webs of the microstructure. Hence the fibres were continuously clamped through narrowing of the cavities. At every load step the movement of the upper tool was stopped and the impedance of the fibres was recorded and converted into a compressive force F_3 and stress T_3 according to the calibration formula (Eq. 1). After joining, a microscopic inspection showed no cracks for most of the joined fibres.

For the aluminium sheets with insulated cavities good joining results were achieved. As exemplarily shown in Figure 3, the compressive stress of fibre steadily rose after the beginning of the plastic deformation of the webs at 8 kN to a final level at the maximum joining force of 20 kN.

The second approach with uninsulated aluminium sheet was not successful. During the forming a short-circuiting of the CIE against the sheet metal occurred. This indicates a damage of the insulation film of the CIE. Nevertheless, the proposed impedance analysis proved its feasibility for failure mode detection during the joining process in this case.

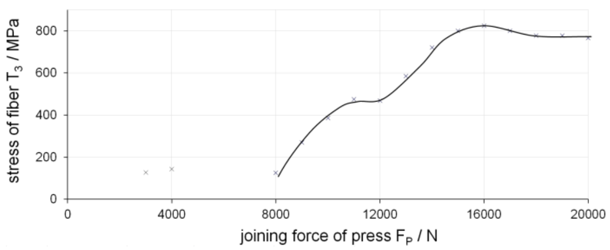

Figure 3. Calculated compressive stress T_3 of a single fibre in metal structure over joining force F_P applied by a pressing machine.

4. Simulation of joining process

Within a numerical study the joining process of piezoceramic/metal composites was investigated. The geometry model is based on a 2-dimensional cut through the micro-milled sheet, tools and fibres, but excludes the outer sheet metal regions for reasons of computation efficiency. The section model in LS-Dyna consists of 2-dimensional plane strain elements. The rigid upper tool moves force-controlled against the micro-structured sheet metal located on a fixed support. The nodes on the left and right boundaries of the sheet metal are constrained to account for the 3-dimensional nature of the problem (the cavities have a limited extent while the pure plane strain state would model cavities of infinity length).

The maximum joining force of 20 kN causes a centre fibre clamping stress of 550 MPa. The clamping forces decrease from the maximum of the centre fibre to the minimum of the outer aligned fibres. The simulated maximum amounts only 69 % of the experimentally determined maximum of 800 MPa. Further deviations exist between the curve slopes of experiment and simulation. Possible reasons are the unknown exact friction conditions between sheet metal and tool surfaces, uncertainties caused by milling of the aluminium sheet and dicing of the fibres as well as a possible change of the electromechanical coupling during the forming. A detailed study is planned within future research to examine the reasons.

5. Conclusion

In this paper, the new approach with directly integrated PZT fibres in metal sheets has been investigated with respect to the electro-mechanical behaviour. For this purpose, single PZT fibres were prepared and inserted into micro-structured aluminium sheets. Thereby, the impedance analysis demonstrated its applicability as in-situ method for monitoring preload and failure mode detection during joining by forming operations. Within a numerical study the fibre stresses were evaluated dependent on the joining load level. Further work deals with the study of the electromechanical behaviour of integration of interconnected parallel PZT fibres.

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