Sheet metal forming of piezoceramic–metal-laminar structures—Simulation and experimental analysis

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Abstract
Adaptive systems with piezoelectric components offer significant opportunities for the active control of dynamic behaviour. Vibration and acoustics control as well as structural health monitoring are also possible. However ineffective production technologies prevent industrial applications. The authors are therefore proposing the integration of piezo-modules inside a double-layer sheet. The use of semi-cured adhesive avoids shear-forces being transferred to the piezo-modules during forming. After forming the adhesive will cure and the transfer of piezoelectric strain to the sheet is made possible. A detailed finite-element-model incorporating the electro-mechanical characteristics of the piezo-modules has been developed. The simulation results were validated experimentally.

Keywords:
Sheet metal, Forming, Piezoceramic–metal-laminar structures

1 INTRODUCTION
Adaptive structure applications require appropriate production technologies. Sensor and actuator modules with integrated piezofibres or -foils are the basis of adaptronic technologies (Fig. 1). Many studies deal with the assembling of separate piezo-modules such as active fibre composites [1], macro-fibre-composites [2], or foil actuators [3]. Direct integration of such piezo-modules in fibre composites was not only the object of investigations but led to patents [4]. To mount laminar piezo-modules on sheet metal, manual fixing with adhesives is necessary [5]. To achieve real economic benefits, a new process chain has to be developed in conjunction with the production of mechanical structures and this has been an expensive procedure until now. The main objective is to directly integrate sensors and actuators during the production of structural parts (Fig. 2).

The inconsistency between the formability and the sensor and actuator functionality must be resolved by means of the design of the composite as well as by the development of an appropriate production technology. The problem lies in the brittleness of the piezoceramics. The mechanical characteristic values for example the fracture strain < 0.1% indicates that piezoceramic fibres for example can be bent with low radii (r < 50 mm at 100 µm fibre diameter) but the fibres cannot be formed by tensile or pressure load. The interaction between the mechanical loads and the polarity must also be taken into account. Otherwise the higher mechanical loads may destroy the crystallographic texture of the piezoceramic, which is necessary for the sensor and actuator function.

There are two solutions to facilitate the interaction of piez-ceramic sensors and actuators in sheet metal:
1. The direct „micro“ integration of several piezo-elements, i.e. the production of functionalized semi-finished products (Fig. 6a) [7]
2. The application of pre-packaged piezo-modules (e.g. Fig. 1) on the sheet prior to forming the car body part (Fig. 4) [8]

The advantage of solution 1 is the high actuating performance in combination with a low driving voltage (Fig. 3).
Application of MFC –
Driving Voltage: 1000 V
Bending performance:
0.0023 mm per mm

Integrated Piezo-Fibres
(Figure 6a) –
Driving Voltage: 250 V
Bending Performance:
0.0022 mm per mm

Figure 3: Performance comparison of MFC-application with the direct integration of single piezo-fibres [9]

The disadvantages of the direct integration technology are the high costs of module production and the low level of potential for a three-dimensional forming process. The direct coupling may cause damage and deformations in the piezo-fibres during the plastic forming of the surrounding sheet. It is for this reason that an immediate solution for higher forming rates in the production of car body parts with a temporary elimination of shear loads needs to be developed. A typical solution is the use of uncured adhesive as an interface layer to connect the sheet and piezo-module like a “swimming” bed. The shear stiffness and the thickness of the cured adhesive layer define the efficiency of the sensor and actuator.

2 MODEL GENERATION AND SIMULATION

The basis for the analyses of the piezo-fibre–metal-compounds as well as the forming of piezo-module–metal-compounds is a combined finite-element-model. It is impossible to simulate the function or production technology of an adaptive structural component using FE models with a discretization based on the scale of the individual piezoceramic fibres. Discretization of a similar magnitude to the piezo-fibres (diameter 200 µm) would result in extremely large models. For this reason the use of averaged material parameters is justified. These parameters are obtained by means of homogenization. In addition to simulating component behaviour and production technology it is necessary to be aware of the loads on the individual component parts of the composite such as insulation layer or individual piezo-fibres to assess the mechanical strength or the fracture behaviour. The calculated loads from the simulation with the homogenized material will be transferred to the single compound elements by means of localization (Fig. 5).

Figure 5: Method of homogenization and localization

This method can be applied to piezo-fibre–metal-compounds as well as to commercial piezo-composites like the MFCs (Fig. 1). It is only necessary to define the correct detailed unit cell (Fig. 6).

Figure 6: Concept of different piezo-modules and according unit cells

The basis for the methodological developments in homogenization and localization algorithms is described in method [9] for elastic compounds. This method was upgraded in [10, 11] for piezoelectric materials. Central to the unit cell method is equivalence of the specific strain energy of the unit cell and the effective (averaged) material. In the case of piezoelectric materials, elastic, dielectric and piezoelectric energy proportions have to be taken into consideration. The homogenized material parameters (elastic constants, piezo- and dielectric constants) will be calculated by using the unit load cases of strain tensors or tensors of the electrical field at the unit cell model. The calculated phase concentration tensors (phase strain concentrations, phase field concentrations) will be used as scaling factors for the loads on the homogenized material. In this way the loads of the internal components (e.g. the piezoceramic fibre) of the unit cell can be calculated. A detailed description of the method is given in [10, 11].

In the application of this method, very low load gradients at the boundaries of the unit cell are assumed. This implies a small unit cell relating to a global load gradient. This restriction had to be overcome due to the geometry of the piezo-metal-compounds and the stresses caused by bending of the base sheet metal.
The volume of the unit cell extends to the height of the whole module, respectively, sheet metal. The module is replicated by means of unit cells made from homogenized material. In this case the model of the unit cell has to represent not only the homogenous loads on the boundaries but also the bending loads. The relation between the degrees of freedom (displacements and electrical potential) has to be modified as a first step in such a manner, that the representation can not only be on periodic boundary conditions but also impose linear deformations on the boundary [12]. Fig. 7, for example, shows the result of the calculation of the unit load case flexure at the unit cell of a MFC-module.

As a result of the mechanical loadings the material parameters for the modelling are determined as an elastic-orthotropic shell which can be used in the forming simulation for a car body component. For example the parameters for the macro-fibre-composite-module (Fig. 1) are:

E-Modulus \( E_{11} = 31.01 \text{ GPa (fibre direction)} \)

E-Modulus \( E_{22} = 20.37 \text{ GPa (across the fibre)} \)

Shear-Modulus \( G_{12} = 6.74 \text{ GPa} \)

Poisson’s ratio \( \nu_{12} = 0.301 \)

The viscosity of the adhesive layer is represented by a friction coefficient. Within an inverse transformation the determined stresses in the global model are used as loads in the unit cell model (Fig. 8). The various load cases (e.g. tension, bending) are superimposed in the calculation of the unit cell to analyze the resulting stresses and strains of the piezo-fibre.

3 EXPERIMENTAL RESULTS

3.1 Selection of adhesive for „swimming“ bed

The rheological behaviour is a decisive factor for the mechanical integrity and the sensor/actuator function of the piezo-module during and after the forming process. General guidelines for adhesive bonding of sheet metal and forming of adhesive bonded sheet metal can be found in [13].

The requirements for the adhesive can be divided into three phases:

1. Requirements pre-forming
   - potential for manual and automatic application,
   - reproducible setting of the viscosity,
   - complete wetting of the sheet and the piezo-module;

2. Requirements during forming
   - prevention of shear load transfer to the piezo-module,
   - “swimming” bed of the piezo-module,
   - no (or very limited) loss of adhesive;

3. Requirements for sensor/actuator function after curing
   - high E-modulus for a transfer of elongation,
   - high adhesion.

The adhesive Sika Icosit 220/15, a 2-component epoxy with low viscosity, was selected because there were good experiences with the forming of glued patch-structures.

3.2 Identification of adhesive parameters

To cope with differing requirements, adjusting the viscosity for the forming process is very critical. The lower limit is defined by two criteria. The piezo-module has to be adequately fixed whilst at the same time the loss of adhesive by reducing the double gap layer has to be minimized. Any leakage of adhesive impairs the tribological behaviour during the forming process. The upper limit is defined by the function “swimming” bed, corresponding to the maximum shear load transfer. The gel time and the temperature are the principal influencing parameters. It is for this reason that the viscosity was measured against temperature by a rotational viscosimeter at the Department of Fluid Mechanics at the Chemnitz University of Technology (Fig. 9).

These results were compared with forming experiments. Double-layer compounds of aluminium AA5182 with a sheet thickness of 0.8 mm for the basic sheet and 1.5 mm for the cover sheet were tested to find the minimum curing time. The technological period is 90-120 min. During this time period, any leakage of adhesive
from the gap can be prevented. The adhesive is not fully cured during this time period. The gel time can be reduced to 35 min by raising the temperature to 45 °C, and this is the preferred option. The experimentally tested range of viscosity, which is optimal for forming, is 200–500 Pa s.

3.3 Experiments in forming

After the pre-curing of the adhesive, the piezo-module–metal-compounds will be bent to radii of 75 mm, 50 mm and 40 mm, to create a number of load cases for the piezo-modules. The position of the piezo-module outside the neutral fibre can be precisely defined by using different sheet thicknesses of basic and cover sheet from 0.8 mm to 1.5 mm (Fig. 10). The load–displacement-diagram of the forming process serves to adjust the finite-element-simulation. Further researches into deep-drawing and stretch-bending of 3D-geometries are planned.

3.4 Test

Verifying the function of the piezo-modules is carried out by measuring the electric capacity and by testing the sensor and actuating function. The capacity measurement is made at the beginning and the end of the forming process. A comparison of these values aims to detect a loss of capacity as a result of broken piezofibres or a malfunction of the contact. Before measuring the capacity, the piezo-modules must already be integrated in the compound to eliminate errors in measurement. Furthermore the temperature has to be constant. To perform a test of the actuating function of the piezo-module–metal-compound, the piezo-module is activated by a trapezoid supply voltage with up to 1500 V and the displacement response will be recorded by a laser sensor (Fig. 11).

4 SUMMARY AND OUTLOOK

The forming of composites made from piezoceramic modules and sheet metal semi-finished items to produce active structural components is a challenging task. The core problem is the inconsistency of the characteristics of the intermediate layer. Actuator and sensor functions call for a rigid connection, but this would transfer damaging stresses to the piezoceramic module during the forming process. The solution is to adopt a time-based differentiation of the characteristics of the intermediate layer. During the forming operation a adhesive which has only just undergone initial gelling is used to avoid any transfer of damaging stresses; during the post-forming period when curing has taken place, the transfer function of the piezo-module as sensor or actuator is established. By using the method of homogenization in the finite-element calculation, the function and forming of the active structural component can be simulated and the stresses that occur simultaneously in relation to the individual components can be determined by means of localization. However, in order to ensure greater security in relation to the design, it is necessary to be able to describe the time-dependent rheological characteristics of the adhesive layer more precisely by means of characteristic values. A correspondingly structured test is being developed. Another significant step is the transition from double sheet metal couples to modules applied to one side of the sheet metal semi-finished component, which is aimed at the achievement of a simplified structure in relation to the semi-finished product.

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6 REFERENCES


