Fabrication method for series production of sheet metal parts with integrated piezoelectric transducers

Matthias Nestler\textsuperscript{a}, Welf-Guntram Drossel\textsuperscript{a}, Sebastian Hensel\textsuperscript{a,\*}, Roland Müller\textsuperscript{a}

\textsuperscript{a} Fraunhofer Institute for Machine Tools and Forming Technology IWU, 09126 Chemnitz, Germany

Abstract

The paper presents a high volume compatible production method for the fabrication of sheet metal parts with integrated piezoelectric transducers. The functionality of the integrated piezomodule is shown on a wing assembly, consisting of two sheet metals shaped with roll bending and three point bending operations. The stimulation of the structure is performed with a shaker, the reduction of the acoustic noise was realized with the integrated piezomodule and monitored with vibrometer measurements. Impedance measurements were performed for health monitoring of the multiple bolted joint. Furthermore, a simulation of the structure was used for the determination of resonance frequencies. The results show a good correlation between experiment and simulation.

Keywords: piezo-metal-compound; adhesive; MFC; piezoelectric transducer; vibration compensation; health monitoring

1. Introduction

Hybrid materials, especially sandwich structures, allow the combination of advantages of various materials in one part \cite{1}. One group of hybrid materials are aluminum sheets with an integrated adhesive or polymer layer. They offer high lightweight potential and good damping properties. Like Hylite, manufactured by Corus, some of them are available at the market. Other metal/polymer/metal hybrid systems are currently under development. A lot of studies deal with the formability of these compounds \cite{2-5}. Formability, damping behavior and stiffness are strongly

\* Corresponding author. Tel.: +49 351/4772-2421; fax: +49 351/4772-2403.
E-mail address: sebastian.hensel@iwu.fraunhofer.de
influenced by the thickness and the material of the inner layer. Furthermore, the design of these compounds allows an integration of additional functionalities in the inner layer. For example, a local increase of stiffness can be achieved by local metal reinforcements [6]. Integration of piezoceramic materials leads to additional sensor and actuator functionalities of sandwich parts. The active damping of piezo-composite beams is presented in [7]. An adaptive sandwich beam containing a piezoelectric shear actuator is used for vibration suppression in [8]. In dynamic loaded systems the sensor answer of integrated piezoceramics can also be used for health monitoring. In [9] it is shown, that the sensor answer of a glass fiber-epoxy composite with integrated PFCT sensor indicates a damage of the structure. Another possibility for health monitoring applications is the self-diagnostic of structures using the imaginary part of the impedance. A well bonded or a disbonded sensor was diagnosed by additional resonance frequencies in the impedance spectrum in [10]. An impedance-based structural health monitoring method is presented in [11] for different field applications, including the health monitoring of a bolted joint. In the present work a high volume compatible process chain for the manufacturing of sheet metal based hybrid materials with integrated piezomodules is presented. The paper shows the production steps for the fabrication of a wing assembly as well as acoustic noise compensation and structural health monitoring.

Nomenclature

| Symbol | Description |
|--------|-------------|
| \( f \)  | frequency [Hz] |
| \( c_1 \)  | coeff. of thermal expansion [1/K] |
| \( L_V \)  | surface velocity [dB / (1 m/s)] |
| \( i \)  | loop parameter [-] |
| \( \theta \)  | phase difference angle [°] |
| \( k \)  | moving width parameter [-] |
| \( Z \)  | impedance [Ω] |
| \( n \)  | measurement data points [-] |

2. Fabrication of the wing assembly

The wing assembly was chosen to demonstrate different functionalities of piezomodules integrated in a system of single components. It has basic dimensions of 500 mm x 300 mm and consists of a pillar, a framework, a rear and a front sheet (Fig. 1). The framework is fixed on the pillar. The rear and the front sheet are bolted on the side plates of the framework. Furthermore, they are bolted together on the abutting surfaces.

The front and the rear sheet are made of aluminum EN AW 5083 with a thickness of 1.5 mm. The manufacturing of the rear sheet took place in the following steps. At first, the upper and lower radii were formed by roll bending with three different radii (Fig. 2 (a), upper left). Die bending leaded to the sharp bend (Fig. 2 (a), lower left). Fig. 2 (b) illustrates the front sheet fabrication. At first, a piezomodule type MFC M8557P1 is applied on the basic sheet in a layer of adhesive (Fig. 2 (b), upper right). Then a local aluminum layer (EN AW 5083) is fixed on the basic sheet, covering the piezomodule according to the proposed method of floating mounting [12]. Before curing of adhesive took place, bending with a punch radius of 17.5 mm against a polyurethane insert was performed, so that a relative movement between the layers was possible, leading to reduced friction loads for the brittle piezoceramic fibers. After curing of adhesive, the front and the rear part were bolted on the framework. Additionally front and rear sheet are bolted together with three screws on each joint (Fig. 1 (b)).
3. Compensation of vibrations

In order to demonstrate the functionality of shaped parts with integrated MFC and to highlight possible fields of applications a test setup for the compensation of vibrations was built (Fig. 3). It consists of the wing assembly with integrated MFC M8557P1, stimulated with a shaker on the end of the rear sheet. The MFC is driven by a signal generator and a high voltage amplifier. In order to analyze the frequency dependent vibration behavior a 3D laser scanning vibrometer was used.
Starting with the analysis of the vibration behavior of the structure a frequency sweep between 100 Hz and 1 kHz was performed with the shaker and monitored with the vibrometer. The first significant audible noise was detected at a resonance frequency of 222 Hz. In the next step the structure was stimulated by the shaker with a sinusoidal signal at this frequency. Using the vibrometer, frequency dependent surface velocities were detected. Aiming on a reduction of noise level the piezomodule was then additionally driven with the same frequency but with a delayed phase angle. As a result the audible noise was drastically reduced, which is verified with vibrometer measurements. Fig. 4 shows a comparison of FFTs of the measured surface velocities in case of shaker stimulated and piezo reduced vibrations. At a frequency of 222 Hz a reduction of 10 dB was achieved.

Fig. 4. Comparison of surface velocities $L_v$ of shaker stimulated vibrations and piezo reduced vibrations at a frequency of 222 Hz.
4. Numerical investigation

The vibration behavior of the structural part was investigated with a numerical model (Fig. 5) to demonstrate the ability of part evaluation at an early design stage. The model consists of surface shell elements for the aluminum skin and layered shell elements for the cover sheet with MFC. The frames are modeled with solid elements, inner stiffening rods with beam elements.

In a first fully transient calculation a sweep load with a moving sinusoidal shaker force from 0 Hz up to 1100 Hz in 8 s was applied. The displacements normal to the surface on the upper wing skin were recorded and for eight single positions the FFT signals calculated. The resulting averaged FFT signal was compared with the experimentally determined averaged FFT signal for the upper wing skin (Fig. 6). Up to a frequency of 600 Hz the simulated structure response of the complex shaped part is very similar to the experiment. Higher deviations occur in the upper frequency range. Possible reasons are simplified joint model (tied line contact), complex structure shape and local prestressing caused by the part assembly.

![Fig. 5. Numerical model of the wing structure. (a) Shaker position near the wing trailing edge; (b) edge plot of the model with MFC position at the leading edge.](image)

![Fig. 6. Comparison between experimentally and numerically determined FFT sweep (averaged over several measurement locations). Surface amplitudes are averaged for single measurement locations at the upper wing surface.](image)
In a next step the noise reduction was simulated at the lower frequency of 223 Hz according to the experimental vibrometer measurement at 222 Hz. The MFC strains induced by voltage load were modeled with thermal analogy: only for the MFC shells a coefficient of thermal expansion different from zero was defined ($c_t=0.43E-06$ 1/K according to the data used in a previous study [13]). Fig. 7 shows the comparison between the model with excitation of the structure only with the shaker forces and the model with additional excitation with MFC. The MFC regulation leads to a displacement reduction of 8.5 % which is lower than the experimental determined reduction. However, the additional contribution of oscillation energy into the system results in a clear vibration reduction. Further improvements can be achieved if the amplitude and phase angle offset between both vibration sources are investigated in additional simulations in detail.

![Fig. 7. Numerically simulated structure response. Averaged FFTs from calculation with and without MFC regulation.](image)

5. Health monitoring

Application of piezoelectric materials on structural parts leads to a coupling of mechanical impedance of the structure and electrical impedance of the piezoelectric material. In case of a coupled system, monitoring of the electrical impedance is easy and provides information about the integrity of the mechanical structure. In a pre-selected frequency range a characteristic impedance signal is monitored. Because of the electromechanical coupling, a damage of structure leads to a phase shift or a change in magnitude of the signal and is fundamental for impedance based structural health monitoring [11, 14]. As shown in Fig. 1 the wing assembly consists of two aluminum sheets – the front sheet with an integrated piezomodule and the rear sheet. The integrated piezomodule allows monitoring of the multiple bolted joint between the two sheets. Therefore an impedance analysis of the structure was performed with fixed screws in comparison to the structure with one loose screw. Fig. 8 depicts the wing assembly with the joint to be monitored and the screw, which is loose in one case.
The impedance analysis is performed with an impedance meter ST2819A of the manufacturer Sourcetronic. At first, a frequency range from 20 kHz to 100 kHz was analyzed for case one (fixed screw) and case two (loose screw). The comparison of results showed significant deviations in a frequency range of 26.50 kHz to 27.50 kHz for the impedance $Z$ and the phase difference angle $\theta$, which indicates a resonance frequency, dependent on the status of the bolted joint. Secondly, this frequency range was monitored with a high resolution using an input voltage of 5 V and a measuring in steps of 5 Hz. Three test series with alternating status for the (fixed/loose) screw were performed. Fig. 9 shows the results of the impedance analysis.

![Fig. 8. Wing assembly with highlighted multiple bolted joint and loose/fixed screw.](image)

![Fig. 9. Comparison of impedance and phase angle dependent on frequency for fixed screws and with one loose screw.](image)
All test series show a very good reproducibility with only small deviations. The loose screw influences the vibration behavior of the structure in the chosen frequency range. In case of a fixed joint, there is a point of structural resonance at a frequency of 26.64 kHz, indicated by an inflection point of Z and a sharp peak of \( \theta \) (Fig. 9, left side). This resonance frequency is not visible regarding the case of loose screw, so that a significant change of the impedance Z and the phase angle \( \theta \) was monitored. This results show that an observation of the joint is possible with measuring the impedance of the integrated piezomodule. The measurement of the phase angle depends on the temperature and the test setup. Larger measurement intervals may result in deviations of the absolute values. However, the principle slope characteristic is not affected. The results shown in Fig. 9 were obtained within a continuous measurement series without breaks. Hence no deviation of absolute values was encountered. However, measurements between larger time intervals can lead to a shift of impedance and phase angle. In all measurements only a shift along the phase angle amplitude axis and no frequency shift was detected. Fig. 10 (a) shows phase angle measurements for the cases: screw fixed (\( \theta \) fixed 1), screw loosed after 12 hours (\( \theta \) loose 1), screw retightened after 12 hours (\( \theta \) fixed 2) and screw loosed again after 12 hours (\( \theta \) loose 2). An algorithm based on a summed error norm was used to evaluate and compare the signals in health monitoring. First, the data is normalized to the first data point of the calibration measurement (curve \( \theta \) fixed 1) and again elevated to the minimum value of all measurement curves (\( \theta \) fixed 2, \( \theta \) loose 1, \( \theta \) loose 2) to zero (Fig. 10 (b)). Then, the error norm \( N \) was calculated as a summation of the moving square deviation between the data point products of the measurement (index \( M \)) and the corresponding data point product of the calibration measurement (index \( C \)) at the evaluation frequency \( f_i \) (eq. 1). A prevailing condition is that, compared with the calibration data, nearly the same amount of point data of the measurement is available. In the calculations the moving width parameter \( k \) was set to 1, because measurement and calibration frequencies coincided. Fig 10 (c) gives the result of the error norm calculations. The case ‘screw loosen’ can be clearly identified and separated from the case ‘screw retightened’.

\[
N = \sum_{i=1}^{n-k} \left[ \frac{\theta_{i+k}^M - \theta_i^M}{2}(f_{i+k}^M - f_i^M) - \frac{\theta_{i+k}^C - \theta_i^C}{2}(f_{i+k}^C - f_i^C) \right]^2
\]

(1)

Fig. 10. (a) Phase angle shift due to temperature and test set-up change; (b) normalized and elevated phase angle; (c) summed error norm \( N \) for the loose and retightened cases.
6. Conclusion

Piezoceramic materials allow the integration of additional functionalities in sheet metal structures. The demonstrative part wing assembly shows the capability for an active vibration and noise reduction, realized with a phase-delayed drive of MFC referral to the stimulation signal. Within numerical simulations the oscillation behavior of the complex shaped part was investigated. The resonance frequencies of the structure are captured very well in a fully transient frequency sweep calculation. At a lower frequency of 223 Hz a significant noise reduction of the structure was achieved in the experiments. With the numerical model the reduction of displacement amplitudes showed the capability of the model to predict the vibration behavior of the complex shaped structures, manufactured with the described MFC integration method.

Furthermore, an impedance measurement of the MFC was performed for monitoring a multiple bolted joint of the assembly. Loosening of one screw leaded to a significant change of the impedance and the phase angle. An algorithm based on an error sum was used to identify structural changes due to an exemplary loose screw and to distinguish the changed status from the case with retightened screw.

In contrast to the time consuming and cost intensive subsequent state of the art application of piezomodules on shaped sheet metal parts, the presented parts were manufactured with a high volume compatible process chain. The integration of the piezomodule in a local double-layered sandwich with an adhesive layer takes place before the forming operation. The uncured adhesive provides a relative movement between MFC and sheet metals and ensures the formability of the piezomodule. The paper shows that the proposed production method allows the fabrication of parts with high functionality integration.

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