Continuous Manufacturing of Piezoceramic Hybrid Laminates for Functionalised Formed Structural Components

Frank Ullmann [1)], Ricardo Decker [2)], Alexander Graf [3)], Verena Kräusel [3)], Michael Heinrich [4)], Wolfram Hardt [1)], Lothar Kroll [2/4)], Dirk Landgrebe [3/4)]

1) Professorship of Computer Engineering, frank.ullmann@informatik.tu-chemnitz.de, cera@cs.tu-chemnitz.de, Chemnitz University of Technology, Straße der Nationen 62, 09111 Chemnitz

2) Department of Lightweight Structures and Polymer Technology, ricardo.decker@mb.tu-chemnitz.de, slk@mb.tu-chemnitz.de, Chemnitz University of Technology, Reichenhainer Straße 31/33, 09126 Chemnitz, Germany

3) Professorship for Forming and Joining, alexander.graf@mb.tu-chemnitz.de, verena.kraeusel@mb.tu-chemnitz.de, uff@mb.tu-chemnitz.de, Chemnitz University of Technology, Reichenhainer Straße 70, 09107 Chemnitz, Germany

4) Fraunhofer Institute for Machine Tools and Forming Technology IWU, Michael.Heinrich@iwu.fraunhofer.de, Reichenhainer Straße 88, 09126 Chemnitz, Germany

Keywords

hybrid assembly system, piezoceramic compound, forming, impact localisation, neural network

Abstract

While in general manufacturing and functional integration are separated steps, in this article a continuous mass-production enabled procedure is discussed. The essential component of the manufactured laminate is a functionalised thermoplastic film that is combined with piezoceramic powder (lead zirconate titanate - PZT) and carbon nanotubes (CNT). The challenge is to achieve optimal electrical and electromechanical properties and a good processability while simultaneously preserving the high toughness of the composite and the required adhesive strength with the joined metal sheet. Determining the optimal joining and surface treatment parameters by identifying the interlaminar shear strength between the metal and plastic components allows for a continuous rolling production process with a subsequent roll forming process. Further investigations on the forming properties are concerned with the optimal placement of the sensors as well as the arrangement and shape of the electrodes. A neural network approach is evaluated to facilitate detection and localisation of external forces in order to use such functional hybrid laminates for new operating concepts in the interior of motor vehicles or for structural health monitoring.

1 Introduction and motivation

The research and development of technologies for the production of complex plastic/metal-based composite components have been the subject of intense scientific and application-oriented efforts for many years. By contrast, the technological basis for the production of semi-active and active polymer-based systems with mechatronic and electrical properties, which are suitable for the integration in plastic/metal-based composite components, is still pending, in spite the high potential of such multifunctional lightweight structures regarding structure monitoring, vibration and noise reduction, and energy harvesting [1-3].

In particular, the plastics processing extrusion technology allows for an efficient roll to roll production of microelectromechanical systems (MEMS). To embed such systems in hybrid laminates, semi-finished sheet products are joined with electromechanical functionalised polymer films by combining the extrusion technology with the metalworking rolling technology. These smart semi-finished sheet products are also suitable for the integration into hybrid metal/fibre-reinforced composite (FRP) structures using a subsequent downstream in-line tape-laying process. As a result of shorter cycle times and process costs, "smart" hybrid structures can be thus manufactured more economically and with more energy efficiency, compared to classical sequential technologies. Moreover, this method allows the first large-scale in-line production of a PZT-based transducer system without the use of energy-intensive sintering processes.

Besides the exploration in materials and processing technologies to enable the manufacturing of multifunctional lightweight structures we focus on the development of an embedded signal processing system that processes the signals adaptively and forwards them to the control unit. The sensor system could be used, for example, in the development of an intelligent input device with gesture control. The requirements for the materials used in such a system are an application-oriented forming behaviour and high-quality sensory properties, which allow subsequent digital signal processing.

The combination of a process chain suitable for mass production, structural components with integrated sensors and an intelligent evaluation system provides the possibility to develop new smart materials whose manufacturing and functionalisation are adaptive to new structural geometries and application scenarios. The semi-finished hybrid laminate can be processed with a wide range of established manufacturing technologies and the evaluation system can be trained according to the respective functionality. On the one hand, the smart composite can act as human machine interface and thereby help to save resources and reduce mass by omitting separate components and integrating its functionality into the structure. On the other hand, the integrated sensor technology enables structural health and condition monitoring. As a result, the structural behaviour is known and possible functional failures can be estimated. Thus, the component itself does not have to be overbuilt and consequently the lightweight design improves. As part of the bivalent resource efficiency strategy, the following objectives have been achieved:

- Energy efficient manufacturing by merging several different production processes and using their residual heat
- Resource saving operation due to integrated functionalities

2 State of the art

Most adaptronic components have been developed for aerospace applications and use integrated piezo sensors and actuators in conjunction with equipment and control electronics for the adjustment of their geometry and structure dynamics to external loads [4-6]. Suitable support materials used are typically thermoset fibre composites based either on prepregs or on the Resin Transfer Moulding (RTM) process, neither of which considers the suitability for mass production of the associated technologies [7-9]. Specifically, the research of different technologies for the production of textile-reinforced composite components with semi-active and active elements has long been an important objective of scientific and application-oriented work [10-14]. In contrast, in-depth theoretical and experimental analyses on the technological implementation of active thermoplastic semi-finished products with electromechanical functions using the extrusion technology and its embedding in metal components in large series are still largely pending. In order to detect impacts that might cause damage to the structure and to localise the according points onto the surface, several approaches have been developed. Due to their adaptiveness, machine learning algorithms are widely and successfully used in this field [15-21]. Especially neural networks [17-21] are a promising method to be used to develop a smart touch-alike input device.

3 Composite structure and properties of the piezoceramic hybrid laminate

In order to meet the requirements of manufacturing, signal processing and future application scenarios; the composition and properties of the developed smart composite are crucial. The initial point of research is a functionalised hybrid laminate consisting of three different layers (Fig. 1):

- a metal sheet as a structural main component and carrier of the functional components,
- a functionalised film to generate the sensory properties and
- electrodes for receiving sensor signals and their forwarding to the evaluation electronics

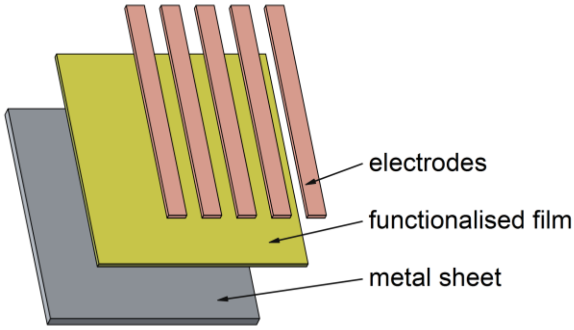


Fig. 1 Composite structure of piezoceramic hybrid laminate

An aluminium sheet in accordance to EN AW-6082 T4 with a thickness of 0.5 mm will be used as basic metallic structure. It has a microstructured surface for better adhesion with the sensory film. In addition to its supporting function, it also constitutes the common ground electrode for all sensors of the hybrid composite.

The active component of the hybrid laminate consists of a piezoceramic thermoplastic compound. The polypropylene (PP) Moplen HP501H by LyondellBasell (Rotterdam, the Netherlands) was used as a matrix plastic. Initial experiments showed that PP filled with ceramic material has much better processing properties in comparison to other filled thermoplastics, such as polycarbonate or polyethylene terephthalate [22]. For functionalisation purposes the polymer melt was filled with a piezoceramic powder of PZT (NCE55 by Noliac A / S, Kvistgaard, Denmark). To achieve high sensory effect, the compound requires a large proportion of PZT. However, the rising ceramic content decreases the processability significantly, whereby the maximum ceramic content is limited to approximately 70 to 80 wt.%. As an additional filler, a small amount of CNTs was admixed to improve the electrical properties of the compound. In previous experiments optimal filler contents of 70 wt.% PZT and 0.5 wt.% CNTs constituted a good compromise between the electromechanical properties and processing [23].

The electrodes of the individual sensors consist of a 35 µm thick copper foil. Through the geometry and arrangement of the electrodes in the hybrid laminate, a network of sensors is created, whose signals are suitable for impact detection or structural health monitoring of the formed components.

4 Process chain for manufacturing of piezoceramic hybrid laminates

The continuous manufacturing process of the sensory hybrid laminate is schematically illustrated in Fig. 2. It starts with the film extrusion of the piezoceramic thermoplastic compound (1). Parallel to this, the microstructuring of the aluminium surface takes place in the first rolling step (2). In the following rolling steps the sensor sheet (3) and the copper electrodes (4) are continuously joined onto the metal sheet. After the polarisation (5) and the cutting of the manufactured semi-finished product, the hybrid laminate is formed into components with functional characteristics (6). Through an embedded evaluation system the sensor signals of the components are processed (7) and classified based on neural networks (8). The individual sub-processes are detailed below.

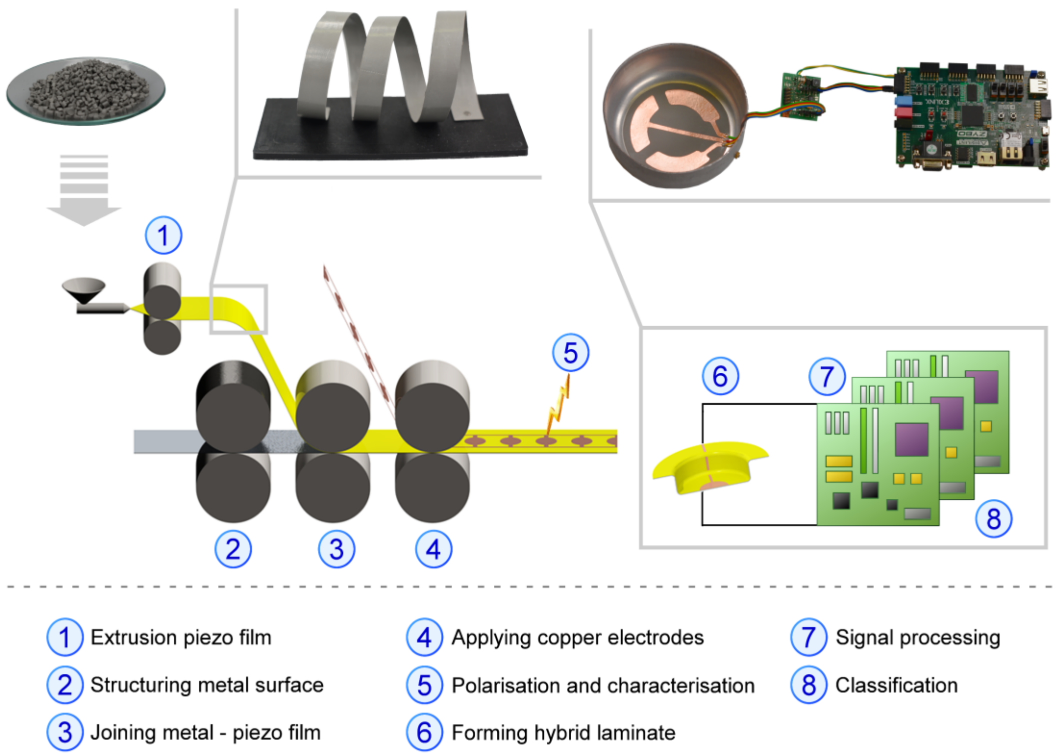


Fig. 2 Process chain for producing the piezoceramic hybrid laminate

4.1 Film extrusion of a highly filled piezoceramic thermoplastic film

The manufacturing of the sensory film was carried out continuously in the extrusion process with a subsequent calendering operation (Fig. 3). The thermoplastic material filled with piezoceramic powder was heated up to 240 °C in the extruder and sent to the calender unit through a wide slot die with a cross section of 350 mm x 0.5 mm. The deduction and consolidation of the film took place in the calender by tempered rolling. The temperature of the rolls close to the die were set to 120 °C and the ones farther away were set to 80 °C. The roll speeds in the calender allowed for a variation of the stretching and thereby the thickness of the film. An increase of the roller circumferential speed from 0.9 m/min to 3.0 m/min resulted in a reduction of the film's thickness from about 325 µm to about 100 µm. In the further course of the process, the film was cooled to ambient temperature, wound into a roll and made available for the continuous joining process.

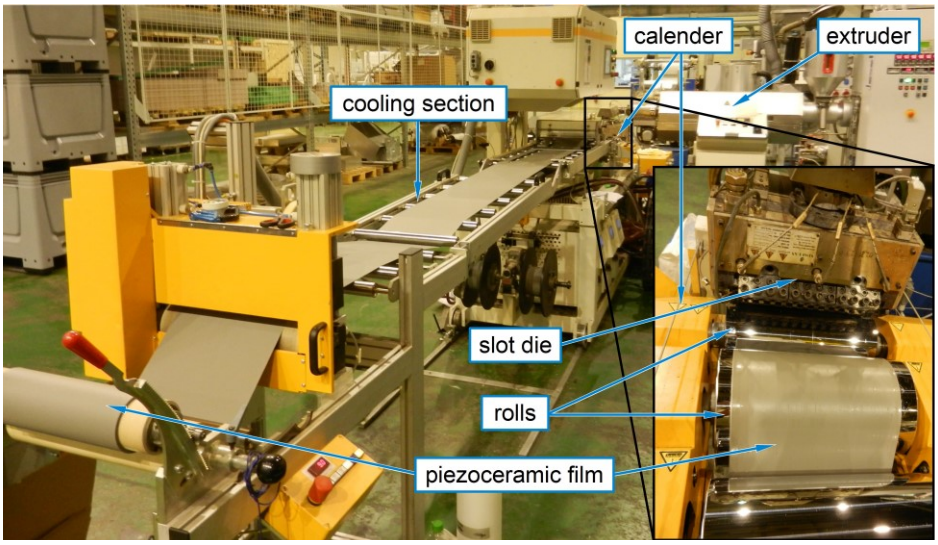


Fig. 3 Continuous production of the sensory film by extrusion

4.2 Continuous joining of the piezoceramic film with aluminium sheet

The essential parameters for joining the sensory film with the aluminium sheet were determined discontinuously in a joining tool with integrated heating elements (Fig. 4). For this, the aluminium sheets (EN AW-6082 T4; 40 mm x 40 mm x 0.5 mm) were inserted into the mould, the piezo compound granules were added and heated at bonding temperature. After heating, the temperature was maintained at a pressure of 12.5 bar for three minutes. In Table 1 the joining temperatures for the various composite structures are listed. The subsequent cooling occurred by means of compressed air. For the determination of interlaminar shear strength by 3-point bending in accordance with DIN EN ISO 14130, the bonded samples were cut into test specimens (20 mm x 10 mm).

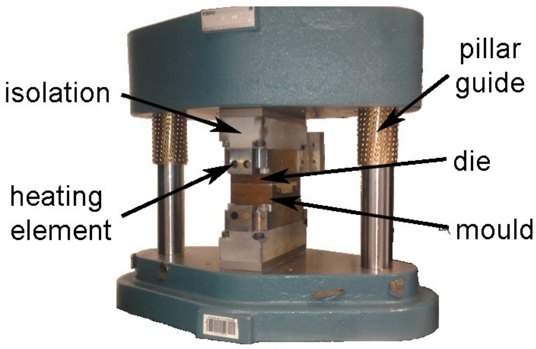


Fig. 4 Joining tool for the discontinuous joining of the piezoceramic film with aluminium sheet

Table 1 Overview of the bonding temperature for the discontinuous process

	Composition piezo compound	Joining temperature [°C]
unfilled	PP	165
filled	PP + 60 wt.% PZT + 0.5 wt.% CNT	175
	PP + 70 wt.% PZT + 0.5 wt.% CNT	185

The discontinuous process examined how the composition of the piezo compound affected the interlaminar shear strength, with the parameter surface treatment remaining constant. The aluminium sheets were pretreated via sandblasting (Ra = 6.96 µm). Fig. 5 shows the experimental results for interlaminar shear strength. It is evident that an increasing weight proportion of PZT equals an increase in shear strength.

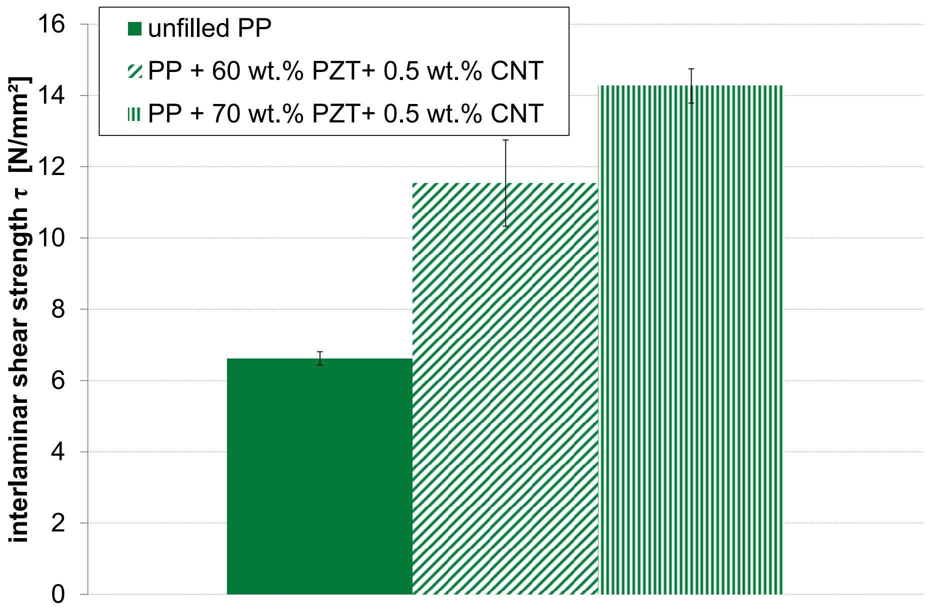


Fig. 5 Interlaminar shear strength of the discontinuously bonded samples depending on the filling content

With the knowledge gained from the discontinuous joining test, a test bench was designed for continuously joining the piezo film with aluminium sheets (Fig. 6).

The experimental setup consists of a run-in table with a short-wave infrared radiator (6 kW). This is used to heat the aluminium sheet prior to the joining operation. The joining temperature is monitored by a pyrometer just prior to entering the rolling mill. By merging the heated aluminium sheet and the thermoplastic sensory film, the piezo compound can be melted and joined by the acting contact pressure of the rolls.

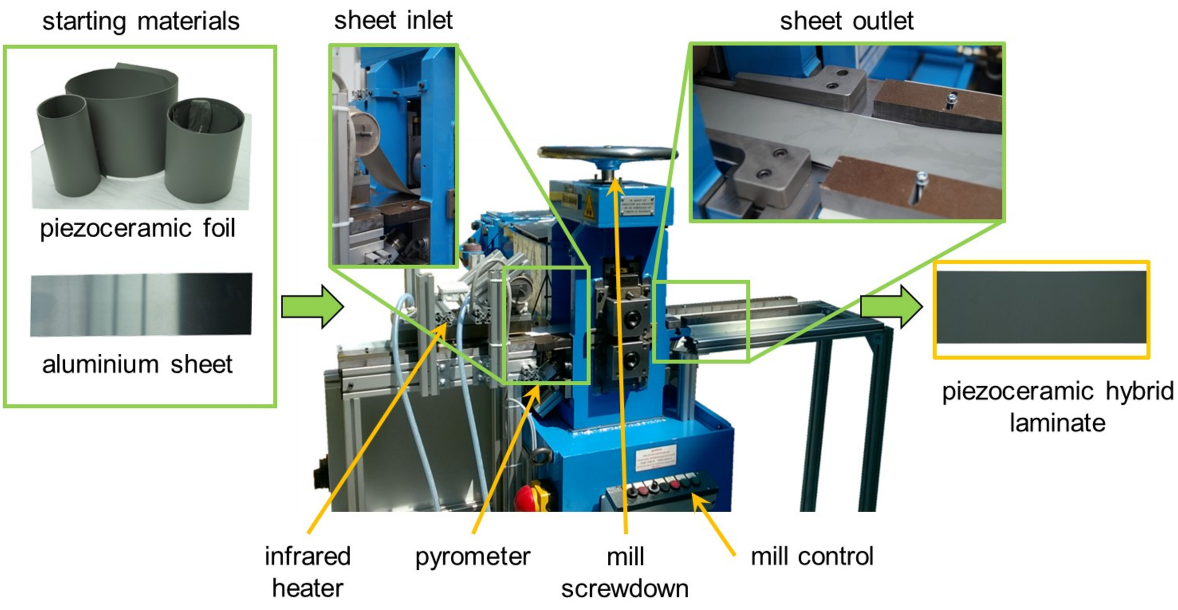


Fig. 6 Pilot plant for the continuous joining of piezoceramic films with aluminium sheets

To set the test rig, the parameters listed in Table 2 have been proven to be important factors. In this case, the pyrometer was used as an essential measuring device for recording the time-temperature curve.

Based on the processes the following factors were evaluated:

- the moment when the required bonding temperature is achieved just before the rolls (depending on the distance and the power of the infrared radiator)
- which rolling speed is needed for the necessary bonding temperature and how the temperature profile changes over the length of the metal sheet

For these preliminary tests, a sheet with a length of 2 m was used.

Table 2 Experimental design to determine the optimal bonding temperature

Parameter	Min	Max
Distance infrared heater – metal sheet	15 mm	30 mm
Rolling speed	0.5 m/min	2 m/min
Power infrared radiator	50 %	100 %

A constant temperature profile was reached at the necessary bonding temperature (185 °C) at

- a distance of 15 mm between the sheet and the infrared radiator
- maximum power of the infrared radiator and
- a rolling speed of 1 m/min

In a further experiment the temperature loss was determined through the contact of the sheet with the rollers. As shown in Fig. 7 top right, the measurement was made with two thermocouples at a distance of 100 mm. The first experiments with the polished steel rollers showed a significant temperature drop of 179 K. Through a 3 mm thick heat-resistant rubber layer on the rolls, the temperature loss could be reduced to 85 K.

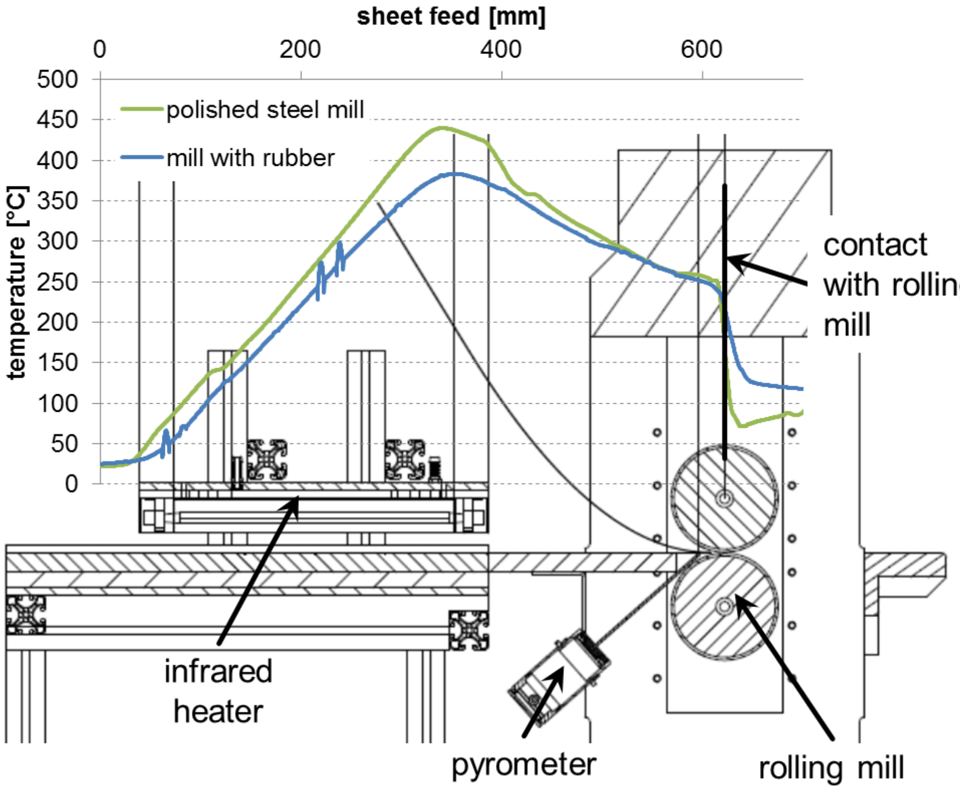


Fig. 7 Measured temperature profile during continuous joining

4.3 Forming the piezoceramic hybrid laminate

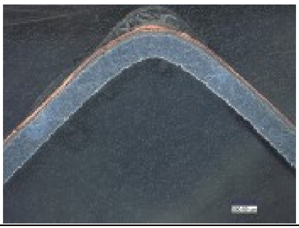
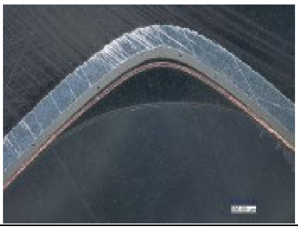
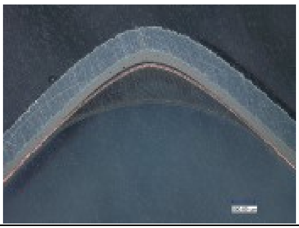
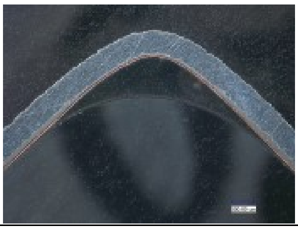
The tests for the forming behaviour of the piezoceramic hybrid laminates were carried out with the aid of a heated V-bending tool. The preparation of the test specimens was performed using the discontinuous joining process. The key parameters for the forming test are the forming temperature and the position of the piezo compound to the active elements. The bend radius remained constant at 1 mm in the test series (Table 3).

Table 3 Parameter for the V-bending

Parameter	Value
Location piezo compound	facing the die or the punch
Forming temperature	20 °C; 100 °C; 180 °C
Bending radius	1 mm

The formed samples were embedded, cut and evaluated with the help of a digital microscope (Table 4). The results for the forming at room temperature show fractures in the copper electrode, when the piezo compound is placed facing the die. Furthermore, fine cracks formed in the thermoplastic piezo film (not visible in the figure). This failure results from the dominant tensile stress and low formability of the copper electrode. However, if the compound is placed facing the punch, compressive stresses affect the piezoceramic film and the copper electrode. This leads to delamination between the copper electrode and the piezo film. By increasing the forming temperature to 100 °C the failure in the tearing copper electrode can be avoided when the piezo compound is placed facing the die side. In contrast, delamination occurs as a failure case when placing the piezo compound towards the punch. This behaviour changed with increasing the forming temperature to 180 °C. This temperature corresponds to the melting temperature of the thermoplastic piezoceramic-reinforced plastic. Thus, the brittle copper electrode can move in the softened plastic and permits forming without the failure of the composite. The disadvantage of increasing the forming temperature is the thinning of the thermoplastic piezo compound. Further experiments will investigate an optimum between fail-free forming and minimum thinning.

Table 4 Micrographs of the V-bend specimens

forming temperature **location piezo compound**	**20 °C**	**100 °C**	**180 °C**
die side copper electrode piezoceramic compound			
punch side			

4.4 Signal processing using neural networks

The developed hybrid laminate enables the integration of structural health monitoring in the component itself. Its purpose is to detect impacts in realtime, classify the caused damage and locate potentially faulty areas. Another application is related to the domain of human machine communication. The smart structures can be used as an intelligent input device, for example, in automotive applications. For this, machine learning methods have great potential to detect and localise structural impacts. Due to the complexity of technical components especially in the field of automotive engineering analytic methods are only applicable in a limited way. Complex components require a time-consuming and extensive simulation in order to determine the parameters the localisation depends on. This can be avoided when using adaptive algorithms based on machine learning techniques. In this area, artificial neural networks combine the required performance with good accuracy and are focussed on in current investigations.

Neural networks are a family of models from neuroinformatics applied to simulate the human brain. Such a network consists of multiple neurons and weighted connections (synapses) between them. The output of a neuron is based on a so-called activation function in conjunction with the weighted inputs and a threshold value. Neurons are normally organised in layers, through which information from the input neurons flows via one or more intermediate layers (hidden layer) to the output neurons. Through feedback a dynamic (learning) behaviour can be modelled. The desired output pattern is generated by the use of various learning methods such as the supervised learning. Hereby the network is presented with a desired output for each input. The error between the actual and the desired state of the output is propagated back through the network and the weights of the synapses are adjusted (back propagation), which imprint the net with the desired behaviour.

A neural network can be used for classifying records and in this case serves to localise the stimulation points on a demonstrator, consisting of a metallic U-shaped profile with an applied piezo film. For this purpose the voltages tapped at the different electrodes were investigated in the time domain. Since such a network can only process discrete states or patterns, a transformation of the stress curve is necessary. While the characteristics of the mentioned voltage curves are generally influenced by the shape of the test object, i.e. formed or unformed, there are still features that can be used for signal processing [24]. The propagating mechanical wave in the demonstrator results in a time shift of stress curves while tapping these at the electrodes. These timing differences can be detected and calculated with an analogue-to-digital converter of appropriate speed. To generate the training data required for the learning process, the demonstrator was stimulated at certain points (Fig. 8) and the stress curves were recorded. The resulting time differences along with the position of the impacts were presented to the neural network as input and output. Details about the detection and localisation process and the data recording can be found in [25].

The Fast Artificial Neural Network Library [26] was used for modelling the network. With this library different scenarios based on an MLP model (Multilayer Perceptron) were designed, each varying in the number of dimensions to be classified (one or two-dimensional), the number of neurons in the hidden layer, the learning rate to be used for training and the desired mean square error that is the stopping criterion. The activation function used was sigmoid. The library adds a so-called bias neuron to every layer except the output layer. In the following paragraphs the denoted number of neurons do not include this neuron.

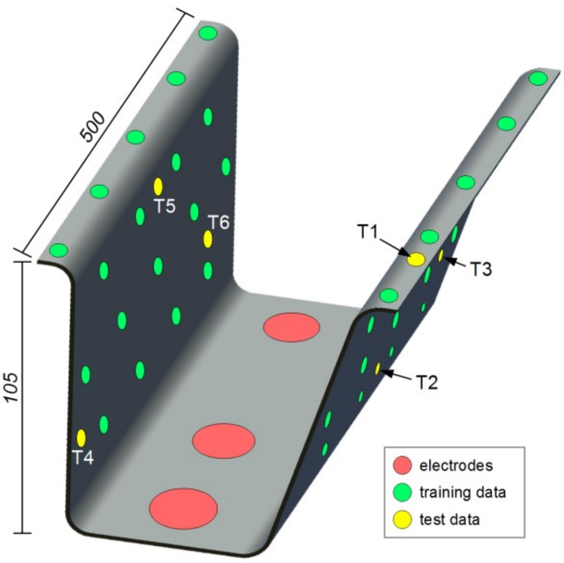


Fig. 8 U-profile with stimulation points

Since all weights are randomly distributed in the initialisation due to a favourable algorithmic time behaviour, the results can only be evaluated statistically. In contrast to the tests in [25] where 20 points were used to generate training data, now 36 points were used. As a result the longitudinal accuracy, which is the deviation of the physically stimulated points compared with the estimated ones, was increased.

The best result regarding location accuracy was achieved in a configuration of three input neurons, nine hidden layer neurons and a one-dimensional longitudinal position estimation (one output neuron), where the learning rate was set to 0.4 and the network weights were adjusted till the mean square error was less than 0.001 or the maximum number of 750 iteration cycles was reached, whatever came first. For each stimulation point (T1 – T6) 1000 tests were performed and evaluated. The position differences are depicted in Fig. 9. To test the classification capabilities with the achieved accuracy the U-profile was virtually divided into three parts. The network was then trained with the desired section to be classified as output. In 1000 test runs only three runs generated a non-optimal output, which results in an overall accuracy score of 99.9 % (Fig. 9).

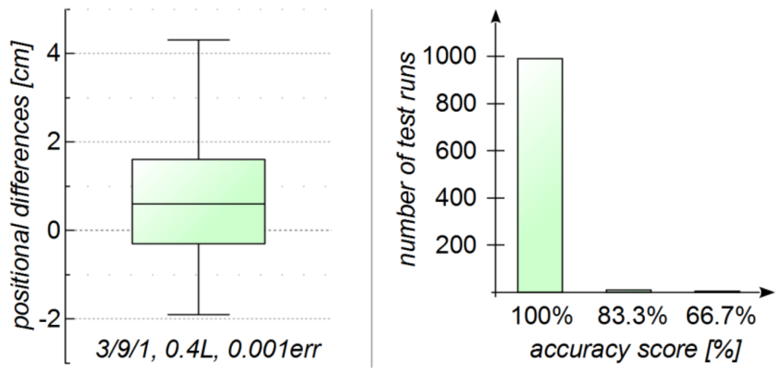


Fig. 9 Localisation and classification result (longitudinal direction)

Because of the symmetrically arranged electrodes the ability to localise impacts in transversal direction is not sufficient, but in combination with the longitudinal estimation the network is partly able to distinguish the sides. In the underlying test the U-profile was virtually divided into six parts, three per side, and the network was trained to estimate the according section for each excitement. To benchmark the output a score was calculated. If the network correctly estimated either the longitudinal or transversal position one point was added to the score. If the network correctly estimated the precise section two points were added. After 1000 runs the score was evaluated and the according result can be seen in

Fig. 10. The best network, which achieved an overall score of 87.1 %, is based on a configuration of three input neurons, twelve hidden neurons and six output neurons at a learning rate of 0.4 and a desired error of 0.005. The iteration cycles were limited to 1000 cycles, but every run finished within an amount lower than that limit.

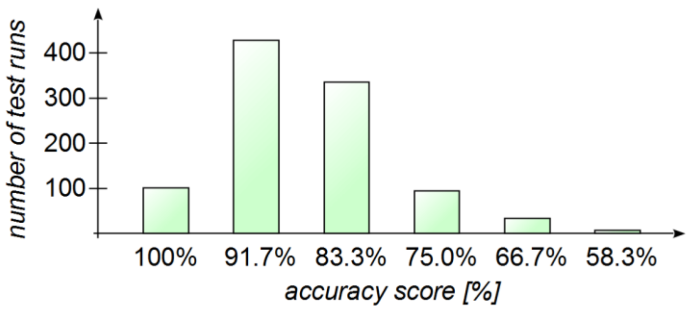


Fig. 10 Classification result (6 classes, longitudinal and transversal)

The results imply that the presented approach can be used to detect and localise impacts, which allows for its use in new user input concepts or for structural health monitoring. To be able to use the presented approach in an embedded system that can be integrated into any environment, i.e. a motor vehicle, the portability of the technology has to be investigated in further research.

5 Summary

Using the film extrusion process an active thermoplastic film highly filled with piezoceramic powder was produced continuously. By varying the rolling speeds in the calender unit, film thicknesses between 100 and 325 µm could be achieved. After extensive tests on the discontinuous joining of the composite, the optimal parameter (temperature and rolling speed) was determined for the continuous joining process of the hybrid laminates using a test rig. In further studies on the forming behaviour of the piezoceramic material composite, the optimal forming temperature emerged close to the melting temperature of the thermoplastic material. Hereby a thinning during forming must be taken into account. To localise the stimulation points, a classification system was evaluated based on neural networks. It could be shown that, with the current test setup, a one-dimensional localisation using such a network is possible. The median position deviation is about 7 mm along the longitudinal direction of the 500 mm test structure. This accuracy shows that the developed smart composite manufactured at large-scale in combination with the described evaluation system can be used reliably as a user input interface.

6 Outlook and Application Potential

The combination of the individual sub-processes into a coherent process chain offers the possibility of a continuous and resource-saving production of the piezoceramic hybrid laminate. During the manufacturing of the semi-finished products, the energy demand for heating the individual components during the preparation for the joining process can be reduced by using the residual heat from the film extrusion. Similarly, energy is saved when applying the copper electrodes. Further advantages of the combined process chain result from the reduced production times and the saving of storage between the individual sub-processes. In upcoming studies the joining process will be further developed with the help of the presented test stand for the continuous joining of piezoceramic hybrid laminates. Measuring the energy consumption is planned as well. Using the knowledge gained, the continuous rolling process should be extended to a semi-finished width of 300 mm. To improve the localisation of the stimulation points, further optimisation is carried out based on neural networks. In addition, other methods from the field of machine learning are evaluated. Changing the electrode arrangement on the demonstrator will also improve the localisation accuracy of stimulation points in other dimensions. This multi-dimensional signal processing is the subject of future work.

In a current series of measurements the influence of the forming process on the behaviour of the composite is investigated. It can be assumed from the signal analysis that the component's residual stresses significantly affect the propagation of the mechanical waves within the component and in turn the resulting electrical signals that are measured at the electrodes. With the acquired expertise, the developed methods will be adapted to complex component geometries.

For demonstrational purposes we plan building a centre console of an automobile composed of the developed smart composite covered by a veneer.

7 Acknowledgement

We gratefully acknowledge the cooperation of our project partners and the financial support of the DFG (Deutsche Forschungsgemeinschaft) within the Collaborative Research Center/Transregio 39 "PT-PIESA" and the Federal Cluster of Excellence EXC 1075 "MERGE".

References

[1] Ahmed, S.; Mayer, D.; Poigne, A.; Riedel, M.: Eingebettete Systeme zur Regelung adaptiver Strukturen. 9th Adaptronic Congress, 2005, Göttingen. http://publica.fraunhofer.de/documents/N-35312.html

[2] Bein, T.; Seipel, B.; Koch, T.; Melz, T.; Zimmermann, E.: Aktive Systeme im Crash. 9th Adaptronic Congress, 2005, Göttingen. http://publica.fraunhofer.de/dokumente/N-34588.html

[3] Donoso, A.; Sigmund, O.: Optimization of piezoelectric bimorph actuators with active damping for static and dynamic loads. Structural and Multidisciplinary Optimization, 38 (2009) 2, pp. 171–183. doi:10.1007/s00158-008-0273-0

[4] Boller, C.: Adaptronic systems for aerospace applications. at – Automatisierungstechnik, 54 (2006) 6, pp. 276–283. doi:10.1524/auto.2006.54.6.276

[5] Miu, D. K.: Mechatronics: Electromechanics and Contromechanics. Berlin: Springer, 1993. doi:10.1007/978-1-4612-4358-8

[6] Das, A.; Ormbrek, G.: Obal, M.: Adaptive Structures for Spacecraft: A USAF Perspective. AGARD Conference - Smart Structures for Aircraft and Spacecraft, 1992, Lindau.

[7] Herrmann, A. S.; Kleineberg, M.; Pabsch, A.: Kostengünstige Faserverbundstrukturen – eine Frage neuer Produktionsansätze. 3. AVK-TV Tagung, 2000, Baden-Baden.

[8] Müller, J.; Flüeler, P.; Just, C.; de Kalbermatten, T.: Faserverbundwerkstoffe – Hochleistungswerkstoffe für den Maschinenbau. Kunststoffe, 80 (1990) 9, pp. 1023–1028.

[9] Hintermann, M.; de Kalbermatten, T.; Stieg, J.: Status und künftige Potentiale durch Faserverbund in RTM-Verfahren. In: VDI-Berichte 1505, VDI-Verlag, 1999, pp. 181–213.

[10] Ramos, C. A.; de Oliveira, R.; Marques, A. T.: Implementation and testing of smart composite laminates with embedded piezoelectric sensors/actuators. Materials Science Forum, 587 (2008), Trans Tech Publications, pp. 645–649. doi:10.4028/www.scientific.net/MSF.587-588.645

[11] Zhao, X.; Gou, J.; Song, G.; Ou, J.: Strain monitoring in glass fiber reinforced composites embedded with carbon nanopaper sheet using Fiber Bragg Grating (FBG) sensors. Composites Part B: Engineering, 40 (2009) 2, pp. 134–140. doi:10.1016/j.compositesb.2008.10.007

[12] Algermissen, S.: Ohne Ruckeln und Vibrieren, Adaptronik macht Montage-Roboter noch schneller. In: DLR-Nachrichten 121, 2008, pp. 12–17.

[13] Heinrich, M.; Kroll, L.; Elsner, H.; Leibelt, J.: Lightweight structures with autarchic functional piezoceramic modules for energy harvesting. 17th International Conference on Composites and Nano engineering, 2009, Honolulu.

[14] Kroll, L.; Gelbrich, S.; Ulbricht, J.; Elsner, H.: Material integrated textile sensors in lightweight structures. 4th International Conference on Structural Health Monitoring on Intelligent Infrastructure (SHMII-4), 2009, Zurich.

[15] Fu, H.; Xu, Q.: Locating impact on structural plate using principal component analysis and support vector machines. Mathematical Problems in Engineering, 2013 (2013). doi:10.1155/2013/352149

[16] Fu, H.; Vong, C.-M.; Wong, P.-K.; Yang, Z.: Fast detection of impact location using kernel extreme learning machine. Neural Computing and Applications, 27 (2016) 1, pp. 121–130.
[17] Tsou, P.; Shen, M.-H.: Structural damage detection and identification using neural networks. AIAA journal, 32 (1994) 1, pp. 176–183.
[18] Jones, R. T.; Sirkis, J. S.; Friebele, E.: Detection of impact location and magnitude for isotropic plates using neural networks. Journal of Intelligent Material Systems and Structures, 8 (1997) 1, pp. 90–99.
[19] Haywood, J.; Coverley, P.; Staszewski, W.; Worden, K.: An automatic impact monitor for a composite panel employing smart sensor technology. Smart Materials and Structures, 14 (2004) 1, pp. 265–271.
[20] LeClerc, J.; Worden, K.; Staszewski, W.; Haywood, J.: Impact detection in an aircraft composite panel—a neural-network approach. Journal of Sound and Vibration, 299 (2007) 3, pp. 672–682.
[21] Mahzan, S.; Staszewski, W.: Impact damage detection in a composite structure using artificial neural network. In: Composite Materials Technology: Neural Network Applications, CRC Press, 2009, pp. 135–162.
[22] Graf, A.; Kräusel, V.; Landgrebe, D.; Decker, R.; Kroll, L.: Joining and forming of hybrid assembled composites with sensory function. Euro Hybrid Materials and Structures, 2016, Kaiserslautern.
[23] Decker, R.; Heinrich, M.; Tröltzsch, J.; Rhein, S.; Gebhardt, S.; Michaelis, A.; Kroll, L.: Development and characterization of piezo-active polypropylene compounds filled with PZT and CNT. 5th Scientific Symposium CRC/Transregio 39, 2015, Dresden.
[24] Kräusel, V.; Graf, A.; Heinrich, M.; Decker, R.; Caspar, M.; Kroll, L.; Hardt, W.; Göschel, A.: Development of hybrid assembled composites with sensory function. CIRP Annals - Manufacturing Technology, 64 (2015) 1, pp. 25–28. doi:10.1016/j.cirp.2015.04.054
[25] Ullmann, F.; Hardt, W.: Towards Impact Detection and Localization on a Piezo Metal Composite. The 2016 Summer School on Information and Communication Technology, 2016, Harbin, China.
[26] Nissen, S.: Implementation of a fast artificial neural network library (fann). Report, Department of Computer Science University of Copenhagen (DIKU) 31, 2003, Copenhagen.