

Development of novel piezoceramic actuator modules for the embedding in intelligent lightweight structures

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co-operating with

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ABSTRACT

Purpose: Piezoceramic actuators in lightweight structures enable a purposeful manipulation of the dynamic and vibroacoustic structural behaviour. Above it, further studies focus on the application of thin and flexible piezoceramic modules as power sources in morphing structures aiming at a shape adaptation.

Design/methodology/approach: A specific example of novel morphing structures is introduced, which rely on multistable deformation phenomena of fibre-reinforced composites with an unsymmetric lay-up. For the large-scale capable utilisation of such active structural parts made of fibre-reinforced thermoplastic composites, novel piezoceramic modules, which are specifically tailored to the structural material, and required manufacturing methods are developed.

Findings: The piezoceramic modules with the highly regarded compatibility to thermoplastic composites permit their substantially coherent and homogeneous integration in the fibre composite structure without intricate adhesive assembly effort. Furthermore, thermally induced residual compressive stresses during the manufacturing process serve for purposefully prestressing the piezoceramic components to reduce the module's sensitivity to tensile loading.

Research limitations/implications: For the manufacture of those novel piezoceramic modules, a continuously operating fabrication method has been developed. By the process-related integration of a hot press, residual compression stresses are thermally induced into the modules that considerably contribute to the decrease of the piezoceramic module's sensitivity to tension.

Originality/value: The successful development of the novel TPM offers a significant advancement in the efficiency within the large scale production of novel intelligent lightweight structures.

Keywords: Piezoceramic module; Fibre-Reinforced thermoplastic; Intelligent structure; Residual stresses

1. Introduction

As described by different authors in several publications before [1-6], anisotropic effects in polymer composites can lead to large out-of-plane deformations. Due to residual stresses resulting

from manufacture, composites with a unsymmetric lay-up often show two distinctive stable cylindrical deformation states which can be transferred to each other by a snap-through initiated by bending forces or moments. In combination with appropriate actuator systems like shape memory alloy wires or plane

piezoceramic modules those bistable composites can be advantageously utilised in technical applications, such as morphing structures or shifting devices. Previous research studies were subjected to composites with a duroplastic matrix. The present investigations on the other hand aim at the transition to intelligent thermoplastic composites for reasons of increased mechanical and chemical demands, better recyclability and an economical efficient manufacturing and processing, that only thermoplastic polymers are able to fulfil.

During manufacturing of suchlike adaptive lightweight components made of composite materials, presently piezo-ceramic functional modules are applied to predominantly after the fabrication of the supporting structure in an additional manual assembling step. An advantageous method is thereby the use of commercially available Macro-Fiber Composites (MFC) for instance, which consist of piezoceramic fibres and an electrode film made of coated polyimide being flexibly adaptable to the structure's surface [7-10]. First approaches for the integration of functional modules in lightweight materials aim especially for fibre-composite materials based on prepreps, whereupon the focus lies on the individual production for aeronautical applications [11-17]. Moreover, the present manufacture of functional modules with polyimide (PI) carrier film takes place in discontinuous processes with high manual effort, which is opposed to an economic, large-scale capable production of novel active structural components for lightweight applications.

Using a PI carrier film in the development of fibre-reinforced lightweight structures with thermoplastic matrices, like polyetheretherketone (PEEK) and polyamide (PA) respectively, would compromise the substantial compatibility, the recyclability and the profitability. Therefore, new holistic solutions for procedures are necessary, that are suitable for series production of thermoplastic compatible piezoceramic modules (TPM), allowing the transition from assembling-oriented actuator integration to a technology-oriented one, and that take restrictions of the manufacturing technology and the issue of bonding between functional module and carrying structure into account. As an alternative to PI carrier films, films made of thermoplastics, like PEEK for example, as basis material for circuit boards offer distinct advantages [18-21] and allow the specific adjustment to the thermoplastic matrix material of the structural component in addition.

In the context of the Collaborative Research Programme Transregio, financed by the German Research Foundation (DFG) under the title "Manufacturing technologies of components based on light metal and fibre composites with integrated piezoelectric sensors and actuators suitable for large-scale production (PT-PIESA)", novel piezoceramic modules compatible to thermoplastic composites are developed, whose thermoplastic carrier film is incorporated substantially into the fibre-reinforced thermoplastic composite structure during the subsequent module integration. By systematically smelting the thermoplastic carrier film of the TPM as well as the thermoplastic matrix of the support structure during the further treatment in a hot-press procedure, the desired homogeneous embedding of the TPM into the support structure is guaranteed and a morphing structure can be manufactured in only one step. Thus, the traditional supplementary assembling steps become obsolete, and therefore

potential local imperfections are not longer formed. For the efficient manufacture of the new piezoceramic modules with compatibility to thermoplastic composites, an automated, quasi-continuously operating production technique is used.

2. Concepts of morphing structures based on bistable composites

Multilayered fibre-reinforced composites with variable preference fibre direction per layer develop extensive residual stresses due to different directional expansion of each layer during their consolidation. Caused by thermal and hygroscopic effects, those intrinsic stresses can lead to considerable out-of-plane deformations with mono- or multistable deformation states in the case of an unsymmetric stacking sequence. For instance, initially flat formed laminates with a harmonised unsymmetric lay-up in the form $[0^\circ/90^\circ]$ show the bistable deformation behaviour with two cylindrical distortion shapes that can be observed in Fig. 1.

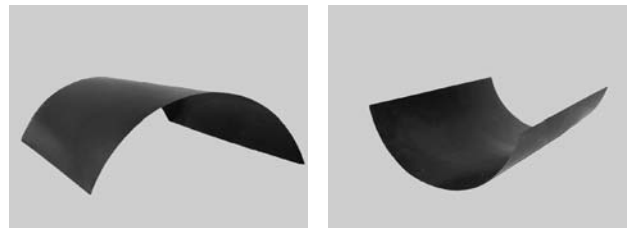


Fig. 1. Bistable deformations states of an unsymmetric cross-ply composite

By applying bending forces or moments respectively to suppress one of the deformation states, the structure responds at a certain point of flattening with sudden transition into the other state and generates large moments and deflections in the process. Equipped with appropriate devices that can introduce the required moments for such a snap-through, unsymmetric composites are suitable for technical applications like morphing structures. The advantage of such design lies in the impulse-like power input to shift between the different shapes rather than the requirement of a permanent force or moment supply as usual concepts rely on.

For the purpose of deformation and stress analysis of such laminates, a mathematical model has been developed, that relies on principles of variations and energies and takes into account large deflections by including nonlinear terms in the strain-displacement-relations [4]. Parameter studies that are based on the developed semi-analytical simulation method enable to estimate the influence of specific geometric or technological variables on the resulting extent of distortion. Exemplified with a two-layer cross-ply carbon fibre reinforced polymer (CFRP) composite, Fig. 2 illustrates the effects of different ratios in layer thickness on the laminate's curvatures, whereas the thickness of one layer (top or bottom) is compared with the height of the whole laminate [2]. The most interesting area in the context of morphing structures lies within the yellow marked rectangle. Only laminates, that have the specific stated dimensions, with layer thickness ratios between 0.3 and 0.7 show a bistable deformation behaviour due to residual

stresses, which can purposefully be used for snap-through effects in novel morphing structures. Laminates that have thickness ratios beneath or above are expected to offer just monostable distortions.

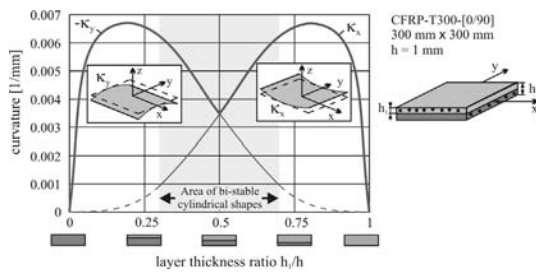


Fig. 2. Curvatures and area of bistable deformation states of a CFRP composite dependent on the layer ratio

In order to initiate the snap-through process in bistable composites external forces or moments are required, which can be conveniently supplied by attached or embedded actuators. Shape memory alloy wires, spanned along the convex surface of the curved laminate, or a piezoceramic composite system as the MFC, that is bonded on the concave surface (Fig. 3), have been found to be suitable. In the context of the short reaction times often required for morphing structures, the focus is put here on the application of actuator modules based on piezoceramics due to their higher actuation frequencies compared to memory alloys.

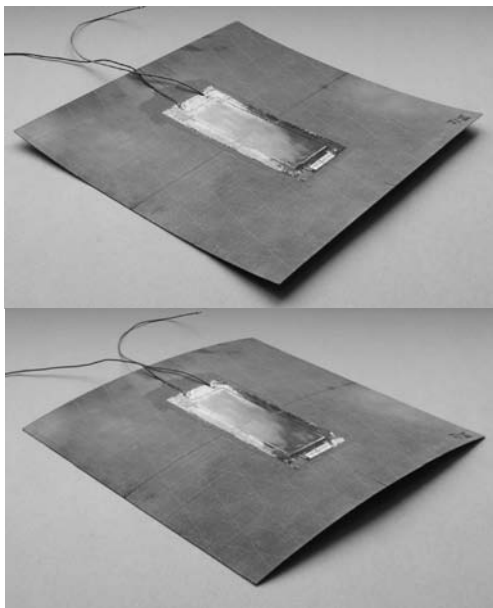


Fig. 3. Cross-ply CFRP-composite with attached MFC before (a) and after (b) actuator initiated snap-through

For instance, with the depicted assembly of a 200 mm x 200 mm cross-ply CFRP-composite and a MFC with an effective module size of 85 mm x 28 mm, a successful actuator initiated snap-through could be achieved. Here, the attached piezoceramic actuator is supplied with an increasing electrical charge, extends and thus starts to flatten the panel successively. At a certain point

of flattening the laminate snaps from the original distortion shape (Fig. 3-a) into the corresponding one (Fig. 3-b).

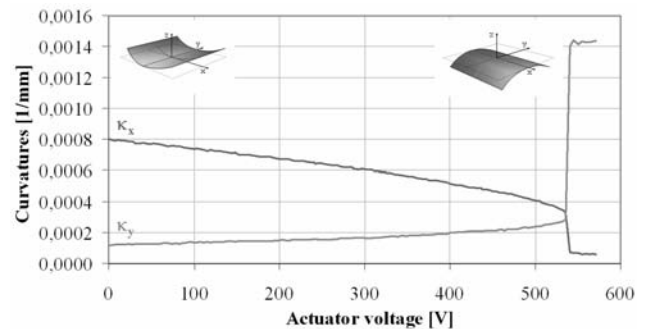


Fig. 4. Actuator caused distortion of a curved cross-ply laminate dependent on the prevailing voltage

Fig. 4 shows the associated deformation behaviour dependent on the applied voltage that supplies the actuator. Starting from its initial deformation state – expressed in the main curvatures κ_x and κ_y – the major curvature κ_x decreases by increasing the electrical voltage in the MFC. At a voltage of 536 V, κ_x reaches a critical value and the highly dynamical snap-through is initiated. Afterwards κ_y is the major curvature whereas κ_x nearly vanishes.

In the described first approach, the focus has been put on the commercially available MFCs, which allow fundamental studies and serve as a temporary replacement for the subject of the superordinate research project. With the more anticipated use of thermoplastic-based composites as structural parts, the use of MFC with its duroplastic carrier films becomes more problematic.

On the one hand further experimental investigations showed problems with the adhesion of the MFC to the composite during different test runs, where local debonding effects occurred. On the other hand to that the gluing process of the MFC to the composite after manufacture requires a higher effort, which should be avoided in the future. Therefore, novel actuators, which can directly be embedded into the thermoplastic-based composite within the manufacture processes, are needed. Here the material compatibility of the actuator modules and the composite itself has to be ensured, therefore, any use of adhesives will become unnecessary.

2.1. Conception of adapted piezoceramic modules compatible to thermoplastic composites

Because of their high creative freedom corresponding to an appropriate strength and stiffness as well as low weight, combined with economic fabrication technologies with a high reproducibility, fibre-reinforced composite materials based on thermoplastic matrix systems exhibit a high application potential for morphing structures in large-scale use. A particular interest is attached to PEEK as a matrix material for high-temperature applications and PA in large-scale applications thereby.

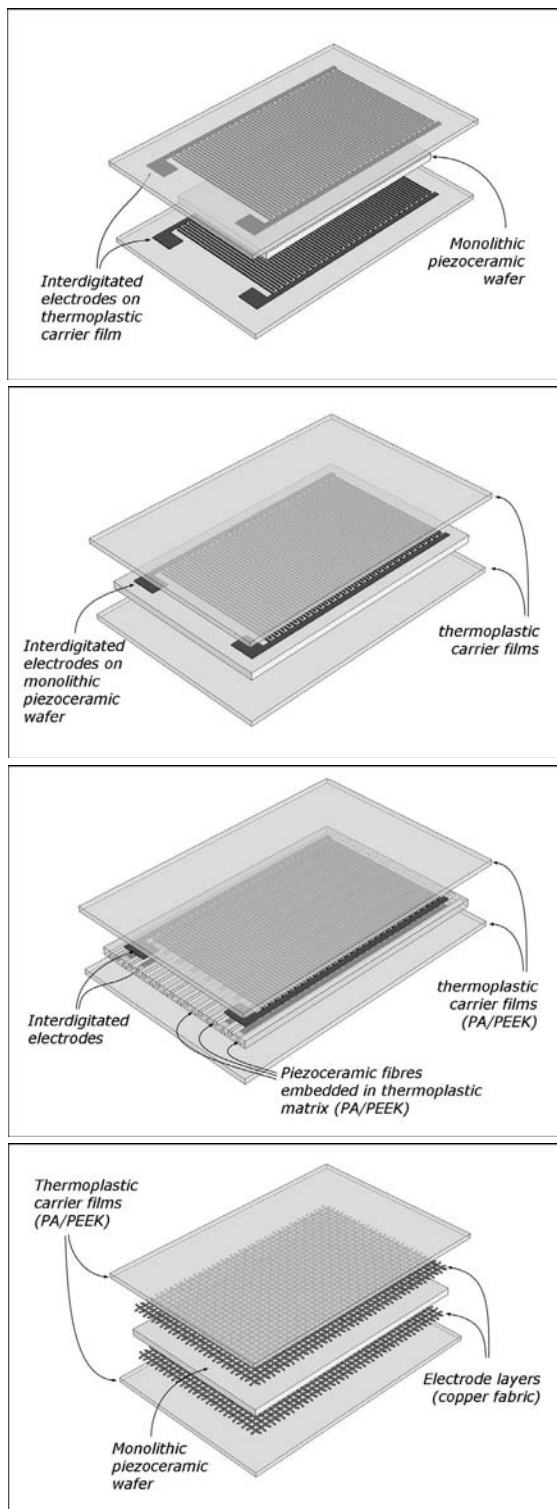


Fig. 5. Schematic illustration of feasible versions of the piezoceramic module compatible to thermoplastic composites with PEEK and PA films respectively

For the development of suchlike intelligent thermoplastic composite parts with active functional characteristics for shape adaptation, customised actuator/sensor modules are designed, whose single components (carrier film, electrode and transducer material) have to be adjusted. The thermoplastic carrier films of the functional modules are chosen in accordance to the utilised matrix material of the support structure regarding a later substantially homogeneous embedding.

During the conception of the piezoceramic modules, great significance must be attached to the selection of appropriate PEEK or PA films and piezoceramic elements regarding the bonding characteristics as such as high temperatures and pressures, which are inherent to the manufacturing process. As transducer material, lead-zirconate-titanate (PZT) ceramic in shape of films and fibres is chosen being utilised in novel laminates for instance (PZT-PEEK/PA-compounds). Beside the production requirements, material and electromechanical issues have to be resolved regarding: form stability of interdigitated electrodes (IDE) and piezoceramic films, bond strength to the thermoplastic carrier film after the pressing process at high temperatures, inducing and particular utilisation of procedure intrinsic residual stresses for specifically pretensioning the PZT components. Fig. 5 gives a survey of advantageous concepts of thermoplastic compatible piezoceramic modules.

For applying electrodes to the PZT, different metallisation techniques both of thermoplastic films and of piezoceramic films are examined. These include for the thermoplastic films laminating, hot stamping, in-mould coating, physical vaporising or chemical-galvanic metallisation methods, whereas the metallisation of piezoceramic films is accomplished by sputtering, vaporising and imprinting. Alternatively to the above described methods, electrode layers in form of copper fabrics, which are directly integrated in the functional modules at the pressing procedure, are methodically researched. Hereby, it has particularly to be ensured that adequate bond strength is achieved and will remain after the hot-pressing process of the functional module.

The considered subsequent integration of the TPM and their processing in composite structures based on carbon fibres (CF) or glass fibres (GF) in combination with PEEK or PA matrices lead to further demands towards those modules. Thus, the substantial homogeneous connection between functional module and supporting structure has to be guaranteed, and possible constraints according to the manufacturing process have to be taken into account. In the same context, especially questions about implications of the anisotropy of the fibre-reinforced support structure on the functional module, methods of insulation as much as contacting and polarisation technologies have to be resolved.

3. Preliminary manufacturing tests and examination of prototypic functional modules

In accordance to the design of the functional modules, the manufacture of first prototypic piezoceramic modules with thermoplastic carrier films is carried out using autoclave and hot-pressing technology. In those manufacturing tests, the producibility of fundamental hybrid modules could be shown in

principle, which possess a symmetric lay-up of outer PEEK or PA carrier films, copper fabric as electrode layers and an inner piezoceramic film (see Fig. 5d and Fig. 7). After the repolarisation of the piezoceramic film, a functional proof of the piezoceramic module could be achieved. However, the obtainable actuation strain has to be rated still insufficient.

The prototypic functional modules are therefore examined using non-destructive and destructive tests for evaluating the influence of different material and process parameters (temperature, pressure, time etc.) on the property and quality of these modules. Furthermore, the form stability of the IDE applied on the PEEK or PA film and PZT wafer respectively are examined due to the thermomechanical loads sustained during the hot-pressing. Examination and evaluation of form stability is done by non-destructive methods, like ultrasonic, lock-in thermography and radiological techniques.

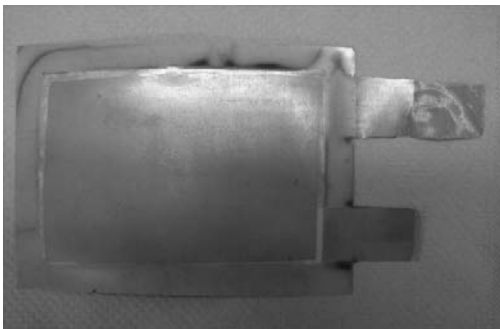


Fig. 6. Example of a hybrid PEEK/PZT/Cu-module

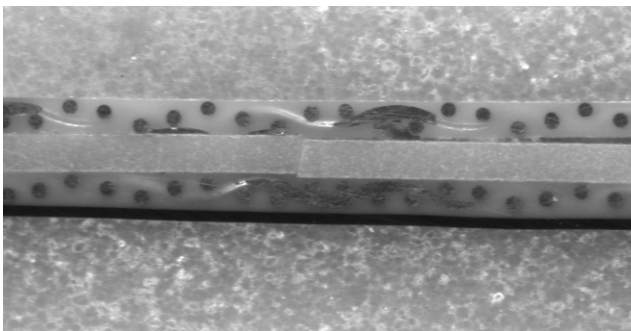


Fig. 7. Micrograph section of a hybrid PEEK/PZT/Cu-module

For detecting and differentiating predominant inclusions, imperfections and defective interfaces between thermoplastic (PEEK or PA) and copper or between thermoplastic and PZT, both ultrasonic analysis and thermography are used. Supplementary to the non-destructive examinations, destructive tests are furthermore conducted, by microscopy for instance, to locate defects.

Analysing the sections of selected modules with the aim of microscopy reveals defects in the piezoceramic film and local debonding between PZT and thermoplastic films (Fig. 7). To avoid such imperfections, giving the ability to tap the full potential of the functional modules, further modifications and

examinations of module construction and process parameters are ongoing.

4. Thermo-mechanical design and residual stress analysis of functional modules

The functional modules are subjected to both high mechanical and thermal loading conditions during the hot-press processing. In particular, the huge differences of thermal expansion coefficients of the piezoceramic, copper and thermoplastic components at a ratio of about $\alpha_{PZT} : \alpha_{Cu} : \alpha_{PEEK/PA} = 1 : 3 : 20$ lead to the formation of process-related inhomogeneous residual stresses when cooling down from the necessary elevated processing temperature of up to 230 °C in the case of PA and 400 °C for PEEK respectively. Those residual stresses can conveniently be used in terms of compression prestresses, which reduce emerging tension when put into operation.

Numerical simulations of the thermomechanical induced states of stress and deformation states allow the determination and assessment of the process specific exposure to temperature and compression that is sustained by the heterogeneous functional modules. Furthermore, those calculations enable the optimisation of residual stresses, due to manufacturing procedures.

First calculation results for the example of a PEEK/PZT/Cu module let anticipate the advantageous adjustability of thermally induced residual stresses in the piezoceramic wafer (see Fig. 8). Assuming a perfect bonding of the piezoceramic, copper and thermoplastic components in the smelting phase at high temperatures, the piezoceramic components show high compressive stresses after cooling, which are induced by the thermally induced shrinkage of the thermoplastic components. Further theoretical studies will be performed to exactly analyse the arising of residual stresses especially taking into account a non-perfect bonding of the piezoceramic, copper and thermoplastic components and sliding effects between the different components.

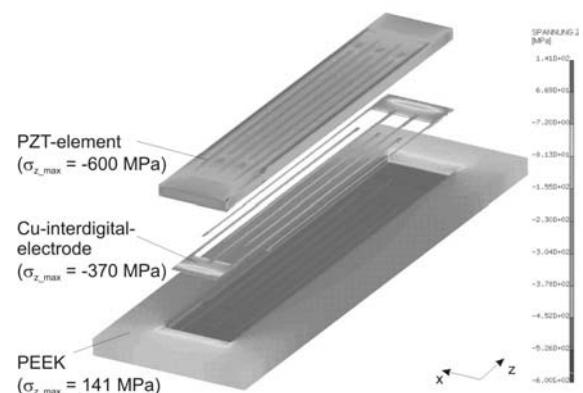


Fig. 8. Residual stresses due to manufacturing in the layer plane of the polymer based functional module for the example of a PEEK/PZT/Cu-compound (exploded view of the FE half model)

5. Continuous fabrication of functional modules

In a further development stage, the configuration of a continuously operating manufacture line for the new piezoceramic modules is designed, because the novel functional modules are not suitable for practical application until appropriate manufacturing and manipulating technologies are available and the fabrication can be done reliably and reproducibly in maintainable cycle times. Thus, a continuously working production facility for the manufacture of these innovative functional modules was conceived (see Fig. 1).

Thereby, a metallised thermoplastic film is taken from a roll in the first instance. To prevent the thermoplastic carrier film from becoming wrinkled and to guarantee a constant initial tension of the film when fed, the utilisation of a decelerated reel is intended. An appropriate driving and a deflexion reel conduct the film feeding. The filigree PZT wafer are gathered from a stack reservoir and handled by a 3-axis vacuum gripper. For the precise fixation of PZT wafer on the electrode carrying thermoplastic film, a temperature controlled spot welding unit with 2-axis handling is provided. After the cutting by a cutting device (longitudinal and transverse section) and heating-up by a heating device the preassembled functional modules are transferred to a gripper, that is loading the hot-press.

Because of the inevitable high process temperatures of the treatment in the hot-press, that reaches values of or above the Curie temperature of the piezoceramic, a subsequent polarising of the functional module is necessary. This may be carried out advantageously in a subsequent process step, in which the functional module is embedded in the fibre-reinforced thermoplastic support structure.

6. Conclusions

Due to residual stresses resulting from manufacture, endless fibre-reinforced composites with a unsymmetric lay-up often

show two stable cylindrical deformation states, which can be transferred to each other by a snap-through initiated by bending forces or moments. The actor induced snap-through behaviour can theoretically be described by a novel non-linear calculation model. The experimental functional proof of such morphing structures has been performed with the help of first demonstrators using commercial piezoceramic MFC.

Within a further development phase of those novel morphing lightweight structures based on bistable endless-fibre reinforced thermoplastic composites, novel piezoceramic modules are designed. The TPM are substantial complementary to the considered assembling partner. As a result of this, a later substantial homogeneous embedding of the piezoceramic modules into the structural part will be feasible by a specific smelting procedure. Additional laborious adhesive assembling steps are omitted, and therefore, the glue layers, that detrimentally effect the propagation of actuation strain, become obsolete.

For the manufacture of those novel piezoceramic modules, a continuously operating fabrication method has been developed. By the process-related integration of a hot press, residual compression stresses are thermally induced into the modules that considerably contribute to the decrease of the piezoceramic module's sensitivity to tension.

The successful development of the novel TPM offers a significant advancement in the efficiency within the large scale production of novel intelligent lightweight structures.

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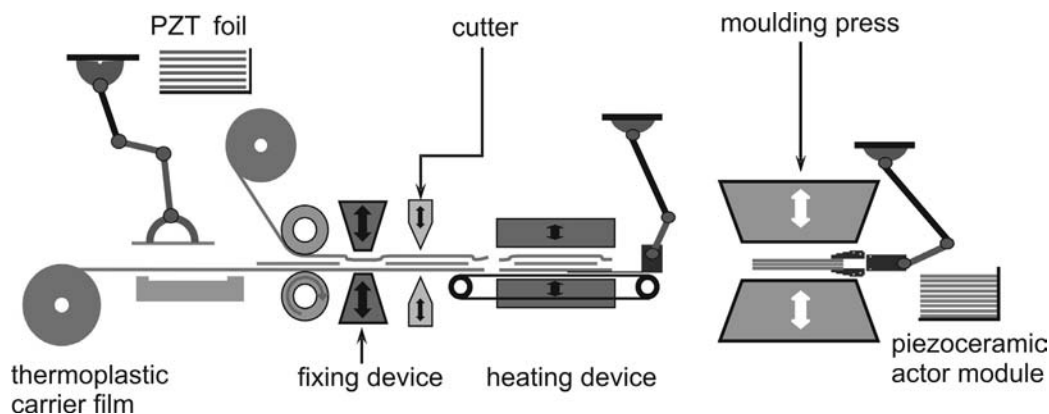


Fig. 1. Schematic diagram of the quasi-continuous fabrication of the functional module

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