Chapter 3
Piezocomposite Transducers for Adaptive Structures

Peter Wierach

Abstract Low profile actuators are a basic technology for smart structures. Bonded on surfaces or embedded in composite structures they work as actuators and sensors to control the structural behaviour. The simplest types are based on thin piezoceramic plates (typical thickness 200 µm) provided with surface electrodes to operate in the lateral d_{31}-mode. This type of actuator is able to generate strains of 500 µm/m. To achieve higher deformations it is necessary to use the d_{33}-effect. The difficulty is to generate the necessary in-plane electrical field. A common solution is the use of interdigitated electrodes consisting of two comb like electrodes with opposite polarity that are placed on the surface of the piezoceramic material. Known as Active Fiber Composites (AFC's) or Macro Fiber Composites (MFC's) these kinds of actuators can produce strains of 1,600 µm/m. The drawback of interdigitated surface electrodes is a very high driving voltage of up to 1,500 V. A promising concept to overcome this drawback is presented. It is based on the use of multilayer technology for low profile actuators. Within these actuators the electrodes are incorporated in the piezoelectric material during the sintering process as very thin layers with little impact on the actuator stiffness. This allows a significant reduction of the electrode distance and therefore also a reduction of the driving voltage. To utilize the multilayer technology for low profile actuators, standard multilayer stacks are diced into thin plates. In this configuration the electrodes are not only on the surface of the piezoelectric material but cover the whole cross section. In a second step these plates are embedded into a polymer to build a piezo-composite. Without the mechanical stabilization of the surrounding polymer the handling of the fragile multilayer

P. Wierach (✉)
DLR, Institute of Composite Structures and Adaptive Systems,
Lilienthalplatz 7, 38108, Braunschweig, Germany
e-mail: peter.wierach@dlr.de

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plate would be extremely difficult or nearly impossible. Several prototypes have been build and achieved an active strain of 1,200 μm/m at a voltage of 200 V. Using other materials an active strain of 1,600 μm/m is possible.

3.1 Piezocomposite Technology

Actuators and sensors on the basis of smart materials are essential parts of adaptive systems. As integral structural components these materials can also provide load bearing capabilities at the best. Due to several advantages, piezoceramic materials are most commonly used as smart materials for adaptive systems. The reasons for the popularity of piezoceramic materials are on the one side of technical nature but there are also some “practical” reasons. On the technical side it’s especially their ability to operate at high frequencies and the high stiffness of the material (typical 60 GPa), what is of special importance when used as actuators. In addition to that it is relatively easy to activate the material by a simple electrical field. The “practical” reasons are primarily the good availability and the reliable quality of the material. Piezoceramic materials are produced on an industrial level and a growing number of manufactures offer different types and shapes. Also the price is quite moderate in comparison to more exotic materials. The main disadvantage of piezoceramic materials is their inherent brittleness. Whereas it is no problem to apply high compression loads, tensile loads must be avoided at any time. Therefore the processing and structural integration of this sensitive material has to be done very carefully to avoid damages.

In adaptive systems, piezoceramic actuators are used to reduce, to generate or to detect deformations or vibrations with a special focus on distributed actuation and sensing systems. This means that the actuator forces are not transmitted at two discrete points but in-plane, usually by a laminar actuator, which is connected to the structure by a bonding layer. Especially for light weight and thin walled constructions this concept offers some advantages since no massive bearings are necessary. Because very thin laminar actuators are needed for this purpose, the brittleness of the piezoceramic material becomes even more serious. An appropriate solution for this problem is the use of so called “piezocomposites”. Piezocomposites are a combination of piezoceramic materials with ductile polymers to form a robust and easy to use actuator and/or sensor. Especially their susceptibility to damage is significantly reduced by this measure. By the arrangement of the piezoceramic material the properties of the composite (e.g. stiffness or damping) can be specifically adjusted. Components like electrodes, electrical contacts or insulators can also be embedded into the composite. Generally the embedding is done at the curing temperature of the polymer (typical 120–180°C). Because of the different coefficients of thermal expansion (CTE) of the polymer in comparison to the piezoceramic material and due to the shrinking of the polymer during curing, the piezo material is provided with a beneficial mechanical pre-compression. This pre-compression allows applying (limited)

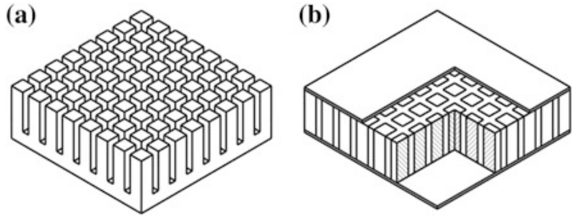


Fig. 3.1 Schematic drawings of a 1–3 piezocomposite for ultrasonic applications manufactured with the dice and fill process; (**a**) ceramic block after dicing; (**b**) piezocomposite with electrodes and filled with polymer

tensile loads to the actuator during operation. The following list summarizes the most important advantages of piezocomposites:

- Protection of the brittle piezoceramic material
- improved handling
- defined and easy to use electrical connectors
- electrical insulation
- pre-compression of the piezoceramic allowing to apply tensile loads
- reduction of stress peaks due to the soft surrounding material hence reduced crack propagation, larger passive deformations and improved lifetime
- possibility to realize complex architectures.

It should be mentioned, that the idea of piezo-composites is not totally new. Traditional applications for piezo-composites are ultrasonic transducers for medical diagnostic, health monitoring or sonar applications (Fig. 3.1). In comparison to monolithic devices piezo-composite transducers can be designed to have optimized acoustic impedance or to decouple radial oscillations.

3.2 State of the Art for Piezocomposite Transducers for Adaptive Structures

Considering the three piezoelectric effects

- longitudinal effect or d_{33}-effect,
- transversal or d_{31}-effect, and
- shear or d_{15}-effect,

in adaptive structures only the longitudinal and the transversal effect are used for technical relevant piezocomposites. More recently some research was published on actuators based on the shear-effect, but it seems that they only show limited advantages in comparison to extension mode actuators [1, 2].

The arrangement of the electrodes determines which effect will be used. The simplest configuration can be realized by using the d_{31}-effect. In this case the

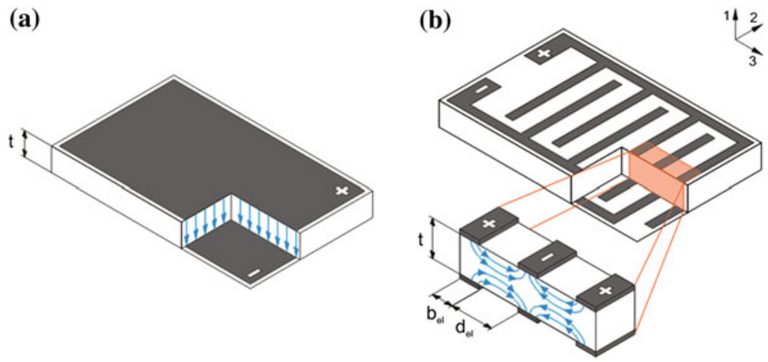


Fig. 3.2 Field distribution in different electrode configurations; (**a**) d_{31}-actuator; (**b**) d_{33}-actuator with interdigitated surface electrodes

in-plane contraction of the piezoceramic material is used when a positive electrical field is applied in perpendicular direction through the thickness of the piezoceramic plate. Thus the piezoceramic plate is provided with very thin layers of conductive material (a few μm) to build uniform surface electrodes. The electrical field is generated homogenously between these electrodes (Fig. 3.2a). The thickness of the piezoceramic plate defines the distance between the upper and lower electrode and therefore the voltage that is needed to generate a certain electrical field. With a usual plate thickness of 0.2 mm a voltage of 200 V is necessary to generate an electrical field of 1 kV/mm.

Up to three times higher deformations can be achieved with the d_{33}-effect. In this case the electrical field and the effective deformation have the same direction. Applying a positive field will result in an expansion of the piezoceramic device in the direction of the field and in a contraction perpendicular to this direction. The challenge is the generation of an in-plane electrical field. A feasible technical solution is the use of interdigitated electrodes. In this configuration the electrodes are made of two comb-like electrodes with opposite polarity, which are applied on the surface of the piezoceramic material. The electrical field is generated between the fingers of the electrode and penetrates the piezoceramic material as well. Due to this special design the electrical field is not very homogenous (Fig. 3.2b). This has a direct impact on the minimal electrode distance and hence on the operation voltage. If the distance between the electrode fingers is too small in comparison to the thickness of the piezoceramic material, the electrical field can not sufficiently penetrate the piezoceramic material and the efficiency of the actuator is reduced. In addition to that, the areas below the electrode fingers do not contribute to the actuation strain. If the electrode distance is reduced, the number of electrode fingers increases and also the “dead” areas below the electrodes. This can only partly be compensated by very thin electrode fingers. Besides technical limitations in producing very thin electrode fingers, such a configuration will also cause very high electrical field gradients in the vicinity of the electrodes. These high gradients are leading to high mechanical loads in the piezoceramic material, having an impact on lifetime and durability. A suitable electrode distance for a piezoceramic device with a thickness of 0.2 mm is between 0.5 and 1 mm. In this case, without considering the field inhomogeneity, a voltage of 500–1,000 V is necessary to generate an electrical field of 1 kV/mm.

Meanwhile several types of low profile piezocomposites for adaptive structures have been developed (and partly commercialized) and are shortly described in Table 3.1. For piezo composites with interdigitated electrodes, fiber like architectures that are referred to as Active Fiber Composites (AFC) turned out to be advantageous in comparison to monolithic designs. Cracks caused by the inhomogeneity of the electrical field will propagate through monolithic plates whereas these cracks are stopped at each interface between the polymer and the piezoceramic fiber. Besides this, fiber based actuators allow a directed actuation what is of advantage for some applications. A negative aspect of fibers with a circular cross section is that there is only a very small contact area between the electrode fingers and the piezoceramic fiber. Thus the penetration of the electrical field is aggravated resulting in even higher operation voltages or less performance. An improvement is the usage of fibers with rectangular cross sections to reduce the dielectric loss.

An essential drawback of fiber based composites is the very labour intensive manufacturing process. Up to know it is primarily handwork to place many single fibers close to another. This causes quality problems resulting in deviations of the actuator characteristics. Also the production and the following sintering process of PZT fibers are very cost intensive. An alternative manufacturing process uses commercially available PZT-wafers that are cut into ribbons. In this case the wafer is placed on a tacky film and cut with a wafer saw that is common within the production of silicon based integrated circuits. With this automated process the rectangular fibers or ribbons are aligned exactly in parallel. This type of piezocomposite is called Macro Fiber Composite (MFC). The last two examples in Table 3.1 refer to more exotic configuration, which haven't achieved a wider acceptance yet. Piezoceramic tubes or hollow fibers, which are provided with surface electrodes on the in- and outside allow a directed actuation in d_{31}-mode operation. They also offer the possibility to incorporate additional passive fiber materials like glass- or carbon fibers to improve their mechanical strength. The idea behind piezocomposites with very thin fibers is to improve the mechanical stability by assuming that the propagation of cracks can be reduced more efficiently. The problem is that due to the dielectric losses of the surrounding polymer the actuator performance is very poor. Possible applications are thin sensor sheets with minimal impact on the host structure.

The properties of the various designs differ with regard to voltage range, size, exact maximum strain and force. But at least it is the piezoceramic material and the operation mode that determines the performance. Therefore it is reasonable to look at some exemplary properties of d_{31}- and d_{33}-piezo composites that were derived using Macro Fiber Composite actuators from Smart Material GmbH. Some important properties are summarized in Table 3.2.

Table 3.1 Overview of state of the art low profile piezocomposites

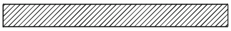
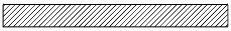
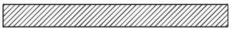
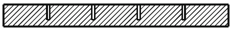
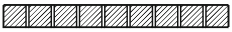
Name	Type	Cross section	Description
QuickPack	d_{33} d_{31}		A monolithic piezoceramic plate with uniform surface electrodes bonded between polyimide films with etched circuit paths to contact the electrodes. To operate in the d_{33}-mode a bare plate is bonded between polyimide films with etched Interdigitated electrodes [3, 4]
FlexPatch	d_{31}		A monolithic plate with surface electrodes glued between a polyimide films by melting the film up to 325°C. Stripes of nickel are applied on the surface to contact the electrodes [5, 6]
DuraAct	d_{31}		A monolithic plate with surface electrodes embedded by resin transfer moulding. Flexible fabrics of conductive material (e.g. copper) completely cover the electrode to provide a reliable and damage tolerant electrical contact [7–10]
PowerAct	d_{33}		A bare monolithic piezoceramic plate provided with creases by laser cutting (not intersected). Interdigitated electrodes are applied by gluing the plates between polyimide films with etched circuit paths [11]
Active fiber composite (AFC)	d_{33}		Piezoceramic fibers with circular cross section embedded in a polymer with interdigitated electrodes etched or screen printed on a polyimide- or polyester-film. Designs by means of fibers with rectangular cross-section are used to improve the performance [12–17]
Macro fiber composite (MFC)	d_{33} d_{31}		A bare monolithic plate is diced to ribbons and glued between polyimide films with etched interdigitated electrodes. Configurations using diced plates with surface electrodes also allow operation in d_{31}-mode [18–21]
Piezoceramic tubes	d_{31}		Piezoelectric tubes (or hollow fibers) with typical outer diameters of 800 μm and inner diameters of 400 μm, provided with inner and outer surface electrodes to operate in the d_{31}-mode are embedded in a polymer to allow an anisotropic actuation [22, 23]
Thin fibers	d_{33}		Very thin fibers ($\varnothing < 50$ μm) are embedded in a polymer to form a sheet with an arbitrary fiber distribution. Interdigitated electrodes are directly applied to the polymer with a special screen printing technique [24]

Table 3.2 Typical properties of state of the art low profile piezocomposites [25]

		d_{33}	d_{31}
Operation voltage	U_{max} [V]	1,500	360
	U_{min} [V]	−500	−60
Capacity	[nF/cm^2]	0.42	4.5
Charge constant	[pm/V]	460	−370
Strain/volt	[μm/m/V]	0.7–0.9	−2
Max. strain	[μm/m]	1,600	500
Charge/strain	[pC/ppm]	1,670	3,250

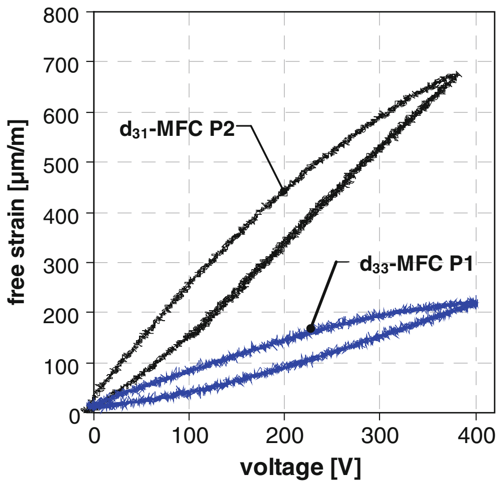


Fig. 3.3 Comparison of d_{31}-(MFC type P2) and d_{33} actuators (MFC type P1) over a voltage range of 0–400 V

As mentioned before, for the price of very high voltages it is possible to generate much higher strains with d_{33}-actuators as with d_{31}-actuators. Hence it makes sense to look at the ratio of applied voltage and active strain. For state of the art piezo-composite actuators this ratio is much better for d_{31}-actuators. Figure 3.3 shows exemplary strain-voltage curves of a d_{31}-MFC (type P1) and a d_{33}-MFC (type P2) over a voltage range of 0–400 V and −500–1,500 V respectively. Both types of actuators had the same active area. For comparability reasons the absolute strain values of the d_{31}-actuator were plotted in the diagram. In this voltage range the superiority of the d_{31}-actuator is obvious. If the d_{33}-actuator is driven over its complete voltage range (−500–1,500 V) much higher strains can be achieved (Fig. 3.4).

Expectedly the capacity of the d_{31}-device is much higher, because the capacity is among others a function of the electrode distance. That means that the power, which is needed to drive a d_{33}-piezo composite is not inevitable higher. On the other side, if the device is used to generate energy (especially by means of energy

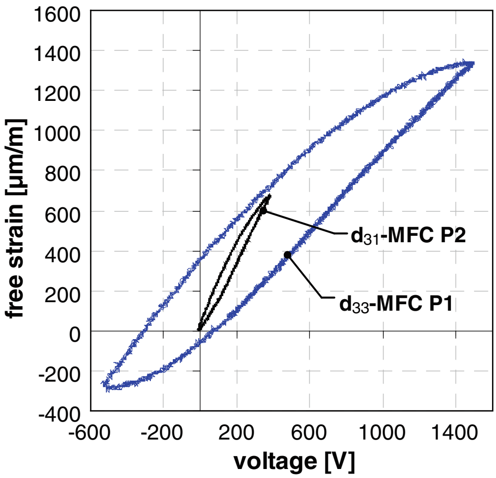


Fig. 3.4 Free strain of a d_{33}-actuator (MFC type P1) over a voltage range of −500–1,500 V

harvesting) it is beneficial to have a high capacity because more charge is generated when the transducer is deformed.

It becomes clear, that there is no perfect piezocomposite suitable for all purposes. The choice must always be made based on the given requirements and application scenarios.

3.3 A Modular Manufacturing Concept for Piezocomposites

Besides the operation voltage and the piezoceramic the complete material composition of a piezocomposite is of great importance. With respect to the variety of possible applications for piezocomposites the use of standardized solutions is very often not feasible. The goal was to develop new piezocomposites with improved performance parameters that can easily be adapted to different requirements. This requires the possibility to access every component of the piezocomposite to enable a material specific selection of the components to get a compatible material system:

- Piezoceramic material
- design and material of the electrodes
- shape of the piezoceramic
- insulation material
- surface quality
- design of electric contacts.

Figure 3.5 shows the principle design of the developed piezocomposite. For the development of the manufacturing technology, standard piezoceramic wafers provided with uniformly electroded surfaces to operate in the lateral d_{31}-mode and

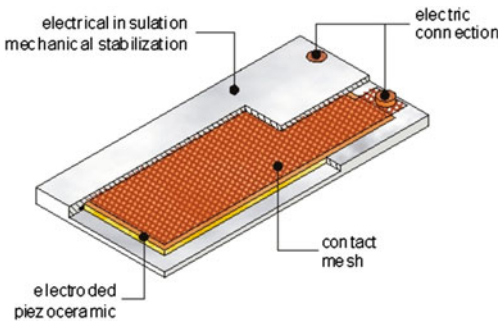


Fig. 3.5 Design of the pre-encapsulated patch

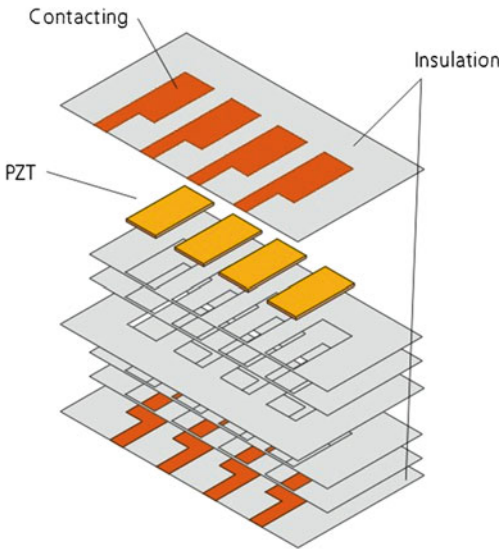


Fig. 3.6 Manufacturing of the encapsulated PZT-patches

a typical size of 50 × 30 × 2 mm^3 were used. Good experiences have been made with plates from PI-Ceramic (PIC 255) and CeramTec (SONOX P53), but it is also possible to use any other piezoelectric material.

Figure 3.6 shows the manufacturing procedure for the new type of actuators. Considering the productivity of the process a set of piezocomposites is manufactured in one step and cut to size afterwards (Fig 3.4). The piezoceramic is embedded between thin layers of insulating fiber material (d < 0.05 mm) and layers with contacting structures. The contacting layer is made of a copper mesh (wire diameter 0.03 mm) or a metalized polyester fleece having the shape of the piezoceramic wafer. In case of a break the patch will still work because the contacting covers the whole electrode of the piezoceramic so that the broken pieces stay in the electrical field where they can be controlled.

Table 3.3 typical material parameters to calculate the pre-compression in a piezocomposite with RTM 6 resin and PIC 255 ceramic

Curing temperature	T	180	[°C]
Temperature difference to room temperature	ΔT	160	[K]
CTE insulation	α_{ISO}	64	[10^{-6}/K]
Young's modulus insulation	E_{ISO}	3	[GPa]
Thickness insulation	t_{ISO}	0.1–0.3	[mm]
CTE ceramic in 1-direction	α_{PZT}	5.8	[10^{-6}/K]
Young's modulus ceramic in 1-direction	E_{PZT}	62	[GPa]
Thickness ceramic	t_{PZT}	0.2	[mm]

The piezocomposites are produced with an improved RTM technology, the so-called DP-RTM (Differential Pressure—Resin Transfer Moulding) [26]. This guarantees an extreme high quality and reproducibility of the components. The fiber material is laid out in dry state which facilitates the positioning of the contact structures and ceramics. The DP-RTM procedure becomes especially interesting as it is not necessary to provide massive moulds since the clamping forces in the autoclave are created by the differential pressure. Thus, a simple sheet plate can serve as sub mould while a vacuum foil is applied for the upper mould. Fiber volume content and fluid rate can directly be controlled by adjusting differential pressure during the stages of injection. In order to minimize the weight of the active fiber composite a high fiber volume content is required. This can be achieved by increasing the differential pressure. Simultaneously, the increasing mechanical load on the ceramics has to be considered since it might result in mechanical damage of the brittle actuators.

Piezocomposites are cured at elevated temperatures. This result in a very beneficial pre-compression of the ceramic material since the coefficients of thermal expansion (CTE) of the resin and the insulating materials are higher than the CTE of the ceramic material. The pre-compression in the ceramic material can be calculated with Eq. (3.1).

$$\sigma\text{th} = \Delta T\left[\frac{2E_{PZT}E_{ISO}\,t_{ISO}(\alpha_{ISO}-\alpha_{PZT})}{2E_{ISO}\,t_{ISO}+E_{PZT}\,t_{PZT}}\right] \tag{3.1}$$

Using the material parameters of Table 3.3 the resulting pre-compression σth is 26 MPa for an insulation layer thickness of 0.1 mm and 73 MPa for an insulation layer thickness of 0.3 mm. In this case a resin (RTM6 from Hexcel Composites) that cures at 180° in combination with a PIC 255 ceramic from PI-Ceramic was chosen. It has to be noted that the young's modulus and the CTE of a polarized piezoceramic are depending on the polarization direction. Experimental measurements [27] confirmed these calculated results.

The materials and components of the piezocomposites had been selected and optimized with special regard to the integration into fiber composite structures but

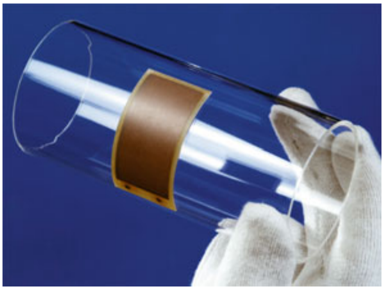


Fig. 3.7 Standard piezocomposite transducer ($54 \times 34 \times 0.4$ mm^2) with solder points as electrical contact bonded on a tube to demonstrate the flexibility of the piezocomposite

Fig. 3.8 Piezocomposite with three circular shaped piezoceramics and embedded BNC connectors as a sensor array for structural health monitoring (SHM)

they can also be attached on any surface. By default the electric contacts are realized as solder points (Fig. 3.7) but the use of insulated wires or any kind of plugs is also possible. Figure 3.8 shows a piezocomposite with special bayonet nut connectors (BNC) that were directly embedded into the composite. Due to the adaptability of the manufacturing process it is possible to produce patches of nearly any shape. This is very interesting for circular or curved structures where hexagonal or curved patches are most suitable. Figure 3.9 demonstrates the possibilities to manufacture customized patches. The separated pieces were cut into shape by laser and embedded into an array to form a complex piezocomposite. Besides piezoceramic plates it was also demonstrated that the manufacturing concept is applicable to fiber based piezocomposites as shown in Fig. 3.10.

3.4 Multilayer Piezocomposites

In many applications it is required to significantly reduce the operation voltage of piezoelectric actuators without reducing the active strain. The use of high voltages in technical systems is associated with some severe drawbacks. Besides harder official safety regulations there are insulation issues and high voltage electronic

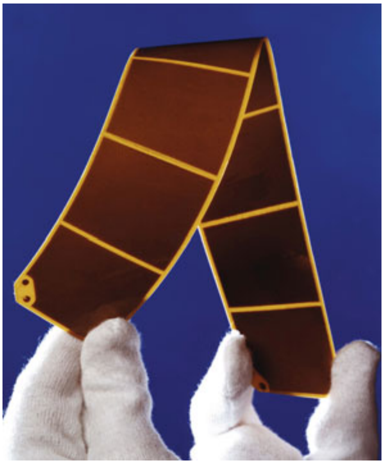


Fig. 3.9 Piezocomposite with complex design to cover the surface of an adaptive satellite mirror for high precision shape control [28]

Fig. 3.10 Piezocomposite with interdigitated surface electrodes and piezoceramic fibers (200 μm fiber diameter)

components are usually more expensive. Also the acceptance of the user is may be lacking. The desire to reduce the operation voltage of piezoelectric actuators led to the development of multilayer stack actuators [29–31]. Conventional stack actuators are made of piezoceramic plates, which are glued together in a stacking sequence. To contact the electrodes, sheets of copper are also incorporated within the glue layer. The drawback of this design is the decreasing stiffness of the actuator with increasing length (or increasing number of glue layers). Also the operation voltage cannot be reduced significantly because this would mean a reduction of the piezoceramic plate thickness; hence an increased number of plates with even more glue layers. Also the manufacturing and handling of individual thin plates is difficult.

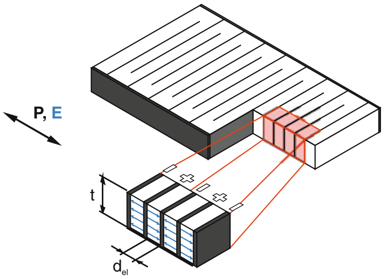


Fig. 3.11 Field distribution in a multilayer plate cut from a multilayer stack

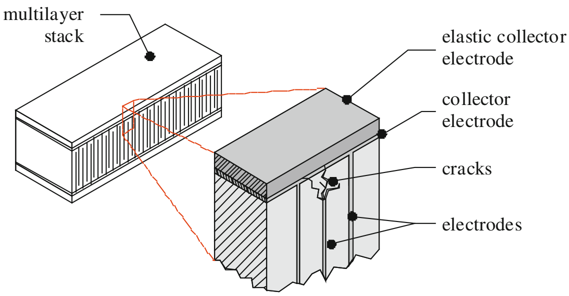


Fig. 3.12 Cracks caused by inhomogeneous electrical fields at the electrode tip

In the manufacturing process of multilayer stacks the electrodes are incorporated during the sintering process as very thin layers. The stack itself is a monolithic block with integrated electrode layers. Therefore their influence on stiffness and performance is very low. This allows a reduction of the distance between the electrodes, what leads to a significantly reduced operation voltage

To utilize the multilayer technology for low-profile piezocomposites a technology has been developed that allows to cut multilayer stacks into thin (0.2–0.3 mm) plates and to embed the fragile multilayer plates into a composite to form a robust and easy to use transducer. As depicted in Fig. 3.11 this design results in a homogenous field distribution over large areas of the piezoceramic material.

3.4.1 Manufacturing of Multilayer Piezocomposites

Starting point for the manufacturing of a multilayer piezocomposite is a commercial available multilayer stack. The dimensions of the stack configuration, which has been used for the technology development, are 18 × 5 × 5 mm^3. The stack is provided with passive ceramic endplates, so that the actual active length of the stack is 15 mm with an electrode distance of 53 μm.

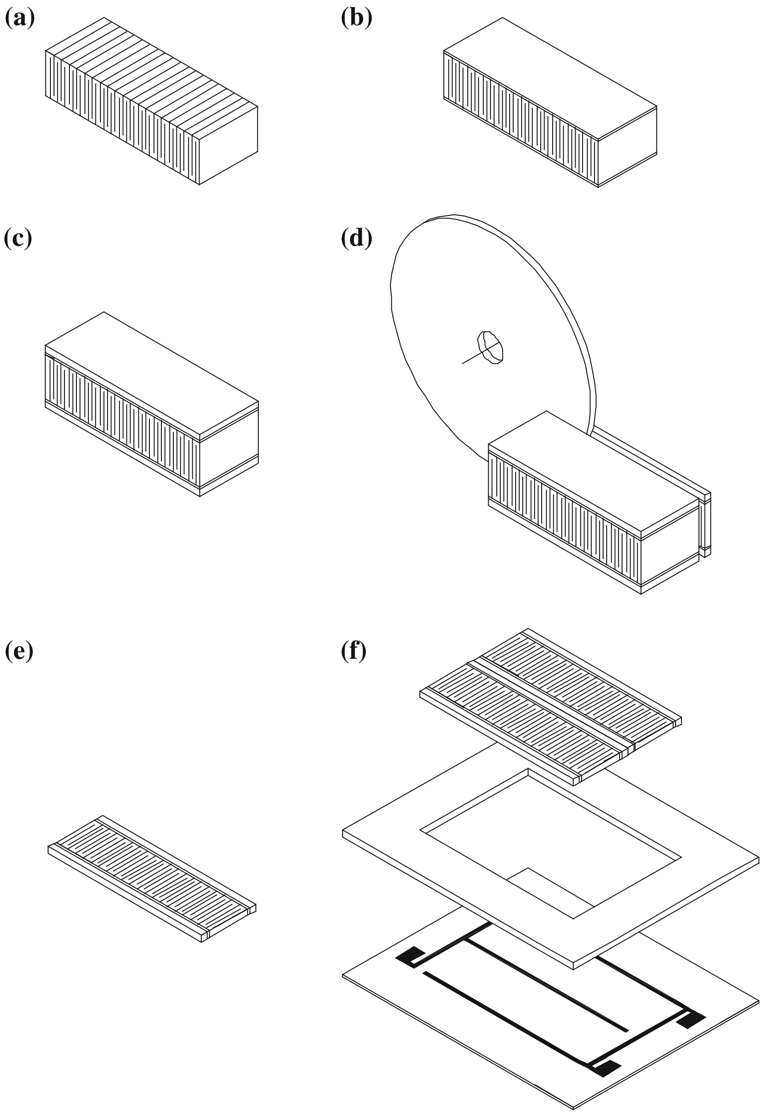


Fig. 3.13 Manufacturing steps; (**a**) multilayer stack; (**b**) collector electrode; (**c**) flexible collector electrode; (**d**) dicing; (**e**) multilayer plate; (**f**) packaging

In a first step the multilayer stack (Fig. 3.13a) is provided with a thin conductive collector electrode (Fig. 3.13b). External loads or loads that are generated during operation of the stack actuator can lead to cracks in the collector electrode (Fig. 3.12). Main causes for cracks are inhomogeneous electrical fields, which appear only at the tips of the electrodes. Because these cracks are limited to certain

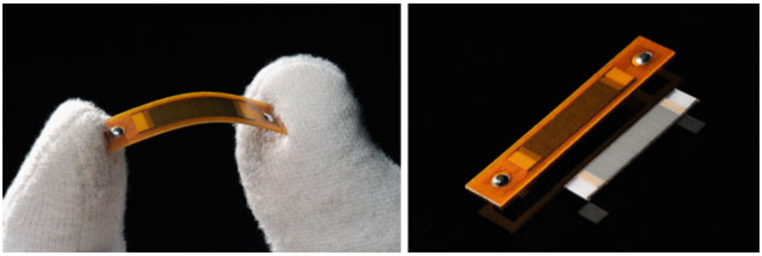


Fig. 3.14 Piezocomposites made of a stack with dimension of $18 \times 5 \times 5\ mm^3$

regions they do not have a critical impact on the actuator performance, but they can cause cracks in the collector electrode as well. This would result in a partially or complete failure of the actuator. To compensate for this problem an additional elastic collector electrode is applied (Fig. 3.13c). The collector electrode is made of an elastic conductive fiber material to stop the propagation of the cracks. After the application of the elastic collector electrode thin plates with a thickness of 0.3 mm are cut from the stack (Fig. 3.13d, e).

The next step in the manufacturing process is the embedding of the brittle and sensitive multilayer plate in a polymer to form the actual composite. This is done using the modular manufacturing concept for piezocomposites as described before. The outer layers of the composite consist of thin polyimid films (25 μm) to guarantee a good electrical insulation. To fix the position of the multilayer plates during the manufacturing process, but also to enable the resin flow, a frame of non conductive fiber material is used. Preferably this frame is made of a polyester fleece with cut outs having the size of the multilayer plates. Because the dimensions of the multilayer plates are limited, an array of plates can be arranged in one composite to enlarge the active area. To increase the productivity of the process several composites are manufactured at once and separated afterwards.

Figure 3.14 shows exemplary piezocomposites that were build with the standard multilayer stack configuration. These composites have been used to characterize the performance of this new actuator configuration.

3.4.2 Free Strain of Multilayer Piezocomposites

A typical strain-voltage curve of the multilayer piezocomposite is plotted in Fig. 3.15. The strain of the multilayer piezocomposite was calculated using the results of the measured displacement with respect to an active length of 15 mm. With an electrode distance of 53 μm and a maximum voltage of 120 V, a maximum electrical field of 2.26 kV/mm was applied. All measurements were made applying a quasi static excitation of 0.1 Hz with a triangle wave form.

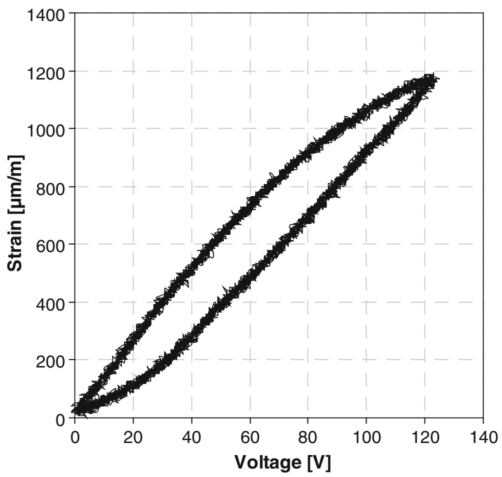


Fig. 3.15 Exemplary strain-voltage curve of a multilayer piezocomposite

Table 3.4 Results of the free strain measurement with a set of 12 specimens

Average free strain	[µm/m]	1,285
Standard deviation	[µm/m]	56.5
Standard deviation	[%]	4.4
Min	[µm/m]	1,193
Max	[µm/m]	1,380

Table 3.4 summarizes the results of the free strain measurement with a set of 12 specimens. The average active free strain that was measured with an operation voltage of 120 V was 1,285 µm/m. In comparison to state of the art d_{33}-piezocomposites with interdigitated surface electrodes, which need voltages of up to 1,500 V to achieve same active strain levels, this actuator has demonstrated that it is possible to drastically reduce the operation voltage of d_{33}-piezocomposites.

3.5 Summary and Conclusion

A considerable number of developments in the area of piezocomposites for adaptive systems demonstrate the relevance of this technology. This is also emphasized by an increasing number of commercial products in this context.

Based on fiber composite manufacturing processes a new technology was developed to build up reliable and easy to use piezocomposites. Due to their design these piezocomposites are characterized by a high damage tolerance and a mechanical pre-compression of the brittle piezoceramic material. It is also possible to realize very complex configurations that can be adapted in shape and material composition to meet the requirements of different application scenarios.

Fig. 3.16 Piezocomposite with integrated acceleration sensor

State of the art d_{33}-piezocomposites incorporate surface mounted interdigitated electrodes. The drawback of such a configuration is a very high operation voltage (typical 1,500 V). The utilization of multilayer technology for low profile piezocomposites allows a significant reduction of the operation voltage. A technology to fabricate multilayer piezocomposites is presented. It was demonstrated that an active strain of 1,285 μm/m can be achieved with an operation voltage of 120 V.

Following the basic idea of adaptive systems the potential of the piezocomposite technology is not yet fully explored. It is also feasible to integrate more functionalities than a piezoelectric transducer into the composite. An example is shown in Fig. 3.16. During the manufacturing process also a micro system (in this case an acceleration sensor) including all necessary circuits and electronics was integrated into a composite to form a combined actuator and sensor module. This module is useful for the control of plate vibrations, since it allows a vibration measurement perpendicular to the plate surface. A piezoceramic transducer alone would only measure the in-plane strain of the plate. Another example is the incorporation of aerodynamic flow sensors as part of an active flow control system [32].

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