Polskie Towarzystwo Materiałów Kompozytowych
Polish Society of Composite Materials

Kompozyty 11: 2 (2011) 147-151

KOMPOZYTY
COMPOSITES

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Otrzymano (Received) 16.02.2011

CHARACTERIZATION OF NOVEL THERMOPLASTIC-COMPATIBLE PIEZOCERAMIC MODULES FOR FUNCTION INTEGRATIVE COMPOSITE STRUCTURES

For the mass production of adaptive fibre-reinforced thermoplastic structures, the development of process-adapted piezoceramic modules is gaining central importance. Thermoplastic-compatible piezoceramic modules are being developed which are suitable for matrix-homogeneous adhesive-free integration of the modules in fibre-reinforced thermoplastic structures during a simultaneous welding process. The presented studies illustrate the destructive and non-destructive characterization of novel thermoplastic-compatible piezoceramic modules. Aiming at continuous improvement of module design and its manufacturing technology based on an adapted hot-pressing process, the adherence strength of the combined material partners after consolidation and suitable methods of defect detection are investigated. In addition, high voltage actuation tests under static and dynamic loading account for competitive module performance.

Keywords: **piezoceramic actuators, thermoplastic composites, functional integration, destructive and non-destructive testing**

CHARAKTERYZACJA NOWYCH KOMPATYBILNYCH Z TERMOPLASTAMI MODUŁÓW PIEZOCERAMICZNYCH PRZEZNACZONYCH DO ZASTOSOWANIA W WIELOFUNKCYJNYCH STRUKTURACH KOMPOZYTOWYCH

Obecnie w produkcji seryjnej adaptacyjnych struktur termoplastycznych wzmocnionych włóknami na znaczeniu zyskują badania elementów piezoceramicznych odpowiednio dopasowanych do procesu wytwarzania. Opracowywane są takie elementy piezoceramiczne, które są kompatybilne z materiałami termoplastycznymi, jednocześnie pozwalające na homogeniczną integrację z osnową podczas jednoczesnego procesu spawania, bez konieczności zastosowania dodatkowych klejów. Przedstawiona praca prezentuje wyniki niszczących i nieniszczących badań nowych modułów piezoceramicznych kompatybilnych z materiałami termoplastycznymi. Dążąc do ciągłego doskonalenia procesu projektowania i wytwarzania elementów piezoceramicznych, w oparciu o dostosowany proces prasowania na gorąco, przebadano siłę przylegania partnerów procesu, a także metody wykrywania wad po procesie konsolidacji materiału. Ponadto, zastosowane wysokie napięcie sterowania podczas statycznych i dynamicznych testów potwierdza konkurencyjną sprawność prezentowanych elementów piezoceramicznych.

Słowa kluczowe: **wzbudniki piezoceramiczne, kompozyty termoplastyczne, integracja funkcji, badania niszczące i nieniszczące**

INTRODUCTION

Due to their highly-specific mechanical properties as well as various design options combined with economic and reproducible manufacturing processes, fibre-reinforced composites based on thermoplastic matrix systems exhibit a great potential for application in lightweight structures suitable for mass production. Moreover, the integration of additional functional components like material-embedded piezoceramic actuators or sensors in thermoplastic lightweight structures enables purposeful manipulation of the dynamic and vibro-acoustic structural behaviour [1-3]. Among function integration like quality monitoring or active vibration and noise control, structural applications e.g. in morphing structures and compliant mechanisms are also possible [4-11].

The separated manufacture of the composite structure and application of piezoceramic function modules in extensive bonding processes is predominant in the state-of-the-art production of existing adaptive lightweight components [12-15]. Due to the adhesive bonding of the function module to the composite structure, the additional adhesive film between the module and the fibre-reinforced polymer structure leads to a loss of deformation transfer and inefficient use of sensor and actuator potentials. In the case of a high volume production of intelligent lightweight structures, however, a transition from assembly-oriented to technology-oriented actuator integration is necessary [16, 17].

For the application of active structural parts appropriate for mass production, novel piezoceramic modules are developed, which are specifically tailored to the fibre-reinforced thermoplastic composites. These piezoceramic modules with their highly-regarded compatibility to the thermoplastic matrix system, permit their substantially coherent and homogeneous embedding in the composite structure by hot-melt adhesion technology during a hot-pressing process, and thus without additional bonding efforts [18, 19].

Aiming at continuous improvement of module design and its manufacturing technology, the following investigations focus attention on the adherence strength of the combined material partners after consolidation and to the detection of defects by specially-deigned technologies. In addition, highvoltage actuation tests under static and dynamic loading are accomplished in order to evaluate TPM performance.

MODULE BUILD-UP AND ADHERENCE STRENGTH INVESTIGATION

Thermoplastic-compatible piezoceramic modules (TPM) contain thermoplastic carrier films made of polyetheretherketone (PEEK) or polyamide 6 (PA6) respectively (Fig. 1). Thus the thermoplastic carrier film is from the same material as the matrix material of the fibre-reinforced thermoplastic composite structure. As the active layer, a lead zirconate titanate (PZT) piezoceramic film or piezoceramic fibres, also embedded in the respective thermoplastic matrix system, are used. To supply electric voltage, the active layer is provided with interdigitated electrodes (IDE), so that the so called d_{33} active principle is used for actuation.

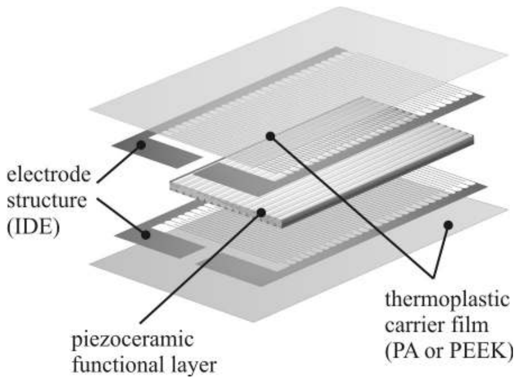

Fig. 1. Lay-up of novel thermoplastic-compatible piezoceramic module

Rys. 1. Budowa nowych elementów piezoceramicznych kompatybilnych z osnowami termoplastycznymi

For the analysis of the adherence strength of the interface of thermoplastic carrier film and PZT-ceramic by means of peel tests, appropriated specimens made of PZT films and thermoplastic carrier films of different configurations were prepared with regard to the main processing parameters (temperature, pressure) of the TPM manufacturing process (Table 1). The specimens were laminary fixed on a metal carrier to allow for clamping in a universal testing machine.

TABLE 1. **Specimen configurations for peel tests**
TABELA 1. **Zestawienie próbek do badań**

	PZT-thickness µm	carrier film	film thickness µm	IDE	Temperature °C]	pressure bar
1	180	PA6	100	-	280	3
2	180	PA6	100	Ag	280	3
3	180	PEEK	75	-	380	3
4	180	PEEK	75	Cu	380	3

Besides the connection of PZT and thermoplastic material, investigation of the influence of the electrode structure is of great interest as well. Therefore, in configurations 2 and 4 according to Table 1, printed silver electrodes on PA6 film and etched copper electrodes on PEEK film were used for the specimen set-up. The alignment of the electrode fingers was perpendicular to the peel direction to reflect the main strain direction in operation conditions.

After application of the thermoplastic film on the PZT film by use of hot-pressing technology, the thermoplastic film was cut with a thin, sharp blade in order to achieve parallel film strips with 3 mm in width on the specimen surface. The inspection of adherence quality was performed by means of a peel test according to DIN standard 60249 using a universal testing machine (Fig. 2). The film strips were fixed respectively via a clamp on a taut wire and peeled approximately perpendicular to the specimen surface (deviation < 5°), with a feed rate of 50 mm/min and simultaneous recording of the tensile force. Dividing the tensile force by the average film strip width, the resulting peel force can be identified as a criterion for the adherence strength. In this investigation at least five specimen strips were used for average determination.

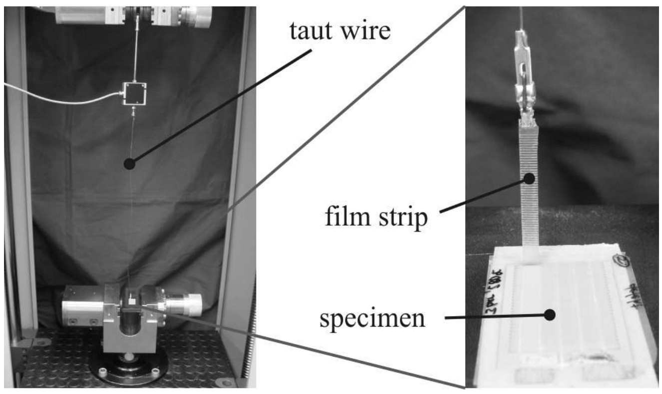

Fig. 2. Peel test setup for determination of peel force

Rys. 2. Stanowisko badawcze

Table 2 shows the average peel forces of the investigated configurations, whereas the studies on PEEK films with copper electrodes did not deliver reproducible test results. Nevertheless, the qualitative influence of the electrode structure can be retraced by means of the test results with PA6 film.

TABLE 2. **Average peel forces of investigated PZT-thermoplastic-composites**
TABELA 2. **Uśrednione wartości siły potrzebnej do zdarcia powłoki zewnętrznej badanych elementów piezoceramicznych w kompozytach termoplastycznych**

	Carrier film	IDE	Peel force N/mm
1	PA6	-	0.45
2	PA6	Ag	0.37
3	PEEK	-	0.78
4	PEEK	Cu	-

In comparison to PA6, PEEK film exhibits almost twice better adherence quality on PZT. Furthermore, the electrode structure induces a reduction of the peel force by 20%, which approximately correlates to the surface covered by the electrode structure (here: electrode finger distance of 500 μm, electrode finger width of 140 μm). For evaluation of the determined peel forces, the printed circuit standard DIN IEC 326 part 3 can be used exemplarily. In this standard, peel forces of at least 0.8 N/mm are demanded but for a metal conductor in thermosetting material. Even though only the combination of PEEK film on PZT maintains this value, no dissolution effects owing to actuator life-time tests under permanently changing elongation and contraction of prototypic TPM could be seen either with PA6 or with PEEK film. Yet, in order to enhance the adherence quality, current studies concentrate on purposeful surface adaptation and treatments of the material partners.

NON-DESTRUCTIVE DEFECT DETECTION

For the detection of process induced defects like air inclusions, cracks in the functional ceramic layer, or deformations of the electrode structure in the consolidated TPM, ultrasonic and the X-ray analysis were employed.

During high voltage testing of the first prototypic TPM, sporadic electric breakdowns could be observed, which are caused by air inclusions between the PZT ceramic and thermoplastic carrier film (Fig. 3). The dielectric strength of air is approximately 2 kV/mm and accordingly below the maximum TPM operation field strength of 3.1 kV/mm. The detection of air inclusions is additionally verified by polished micrographs of TPM cross sections. By optimizing the process parameter for TPM manufacture, suitable for mass production, air inclusions between the material partners have been thoroughly eliminated.

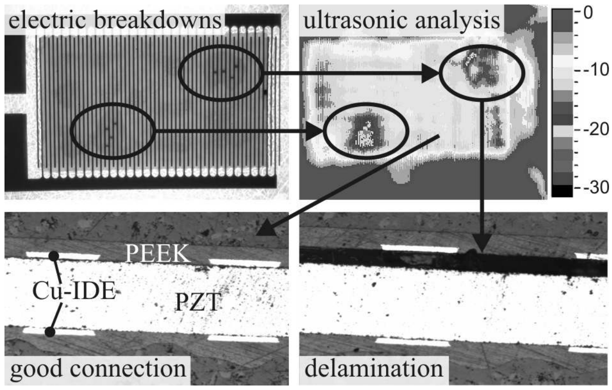

Fig 3. Ultrasonic and cross section analysis for evaluation of electrical breakdowns caused by delamination

Rys. 3. Ocena uszkodzeń spowodowanych rozwarstwieniem przy wykorzystaniu analizy ultradźwiękowej i rentgenowskiej

Process induced cracks, which likely occur in the tension sensitive piezoceramic functional layer, are detected by means of X-ray analyses (Fig. 4 left). On the right side of Figure 4, deformations of the electrode fingers in areas without a subjacent supporting functional layer can be seen, which arise as a result of the flowage of the thermoplastic matrix system before its consolidation during the manufacturing process. Such deformations likely lead to a short circuit of the antithetically poled electrode structures. The analysis shows the necessity for a high coefficient of friction between the functional layer and electrode structure to withstand matrix flowage and guarantee a reproducible dimensional stability of the sensitive electrode fingers.

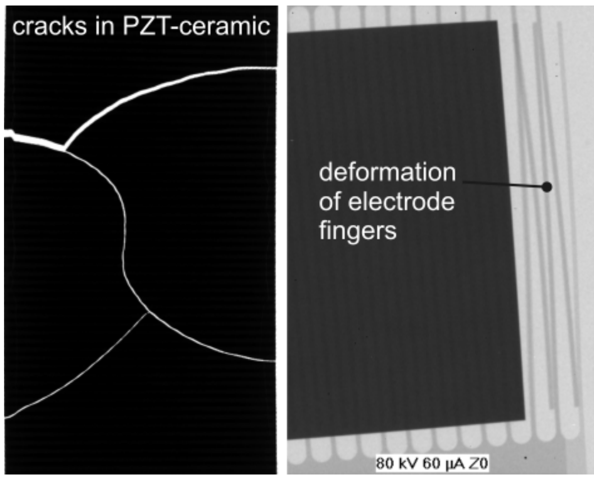

Fig. 4. X-ray analysis for defect detection in PZT-ceramic and electrode structure

Rys. 4. Analiza rentgenowska w celu rozpoznania wad w strukturze wzbudników piezoceramicznych

EXPERIMENTAL FUNCTION ANALYSIS

For proof of the actuation function of prototypic TPM, the TPM were polarized with respect to their electrode configuration by applying high voltage in order to achieve an average electric field strength of 3.1 kV/mm, which is also the maximum operating field strength of commercial modules named MFC [12-15]. A polarization time of 300 s was chosen to guarantee a sustainable polarization of the ferroelectric piezoceramic material. In the next step, the TPM were actuated utilizing a triangle signal and a frequency of 0.1 Hz, whereas the upper amplitude of the signal is related to the polarization voltage. The lower amplitude was set as one third of the absolute polarization value with an opposite sign so as to avoid an approach to the negative coercive field strength (here approximately −2 kV/mm) and the resulting beginning of the depolarization effect. Depending on the respective electric voltage, the recording and interpretation of the TPM strains is done by means of the optical in-process analysis of a previously applied random contrast pattern using the grey image correlation system ARAMIS of the GOM Company.

Figure 5 shows the measured strain hysteresis of selected TPM in comparison to a conventional MFC actuator with a similar functional area. The free strain ε_f in the main actuation direction is displayed as a function of both the applied operation voltage U and the maximum electric field strength that arises over the module cross section. In detail, the hysteresis is caused by inner material friction and microscopic inverting polarization effects. The measured TPM reveal a strain characteristic similar to that of commercial MFC, whereas the PEEK-TPM reaches a higher maximum strain even with a relatively low voltage of 1.2 kV compared to the MFC voltage of 1.5 kV.

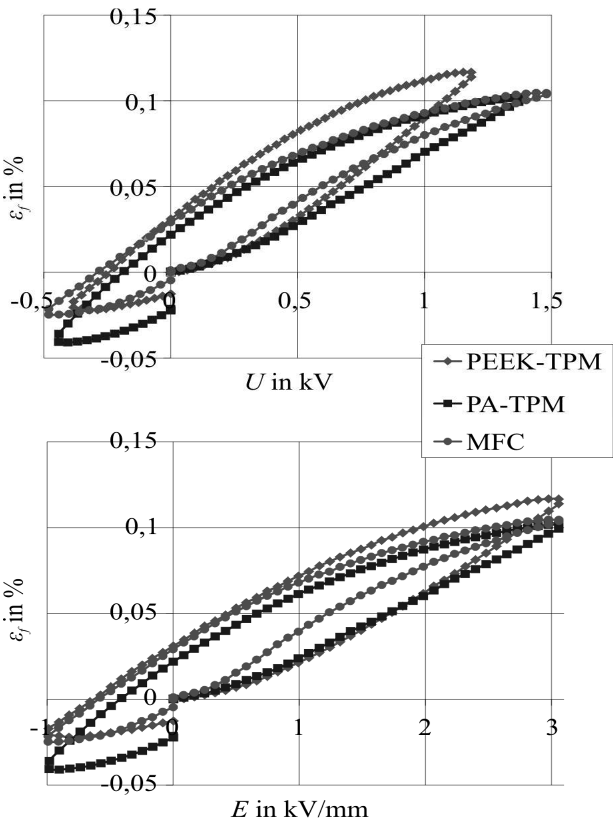

Fig. 5. Strain hysteresis of prototypic TPM with 0.1 Hz triangle signal

Rys. 5. Histereza odkształcenia prototypowych TPM o sygnale trójkątnym 0,1 Hz

By displaying the strain as a function of the maximum electric field strength arising in the PZT functional layer, the influence of slightly different electrode configurations is relativized. The PA-TPM shows a wide peak-to-peak strain hysteresis, while the positive peak strain is not as high as the one of the PEEK-TPM due to the slightly different geometry of the piezoceramic layer with respect to manufacturing restrictions. On the other hand, the absolute value of the negative peak is the highest as a result of the relatively low material stiffness of PA6 compared to PEEK, which allows for a higher contraction. A further reason for this characteristic deviation is the process induced pre-stressing of the ceramic layer during consolidation, which results from the different coefficients of thermal expansion of PZT and PEEK or PA6, respectively. After manufacturing, the pre-stressing in PA6-TPM decreases because of the high tendency of PA6 to creep at room temperature. The remaining pre-stressing in PEEK-TPM leads to an enhancement of the load capacity of the ceramic for tension and thus to an offset of the strain hysteresis in an elongated direction.

To gain/obtain fundamental information about the operating stability of prototypic TPM under dynamic loading, free vibrating modules were applied by sinus voltage between 2 kV/mm and –0.66 kV/mm in the amplitude of the electric field strength. The loading was respectively performed for a time of 60 s under a constant frequency of 1, 10, 100, and 1000 Hz. After each increasing step of frequency, the strain hysteresis measurement and recording was accomplished by means of the previously described method. Figure 6 illustrates the exemplary strain hysteresis results of a PA-TPM.

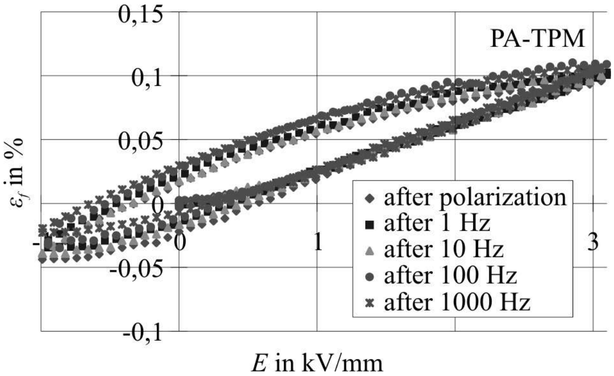

Fig. 6. Strain hysteresis after frequency dependent long-term loading between 2 and -0.66 kV/mm field strength

Rys. 6. Histereza odkształcenia po obciażeniu elementów sinusoidą o wartości pomiędzy 2 i –0.66 kV/mm

The measured results prove that the actuator function remains completely even after high dynamic loading under 1000 Hz sinus voltage. According to this, no degradation effects in the PZT ceramic or on the interface between the piezoceramic functional layer and the thermoplastic carrier film occurred. Slight differences between the single hysteresis curves are within the range of systematic errors of the optical measuring system.

CONCLUSIONS

Specially developed thermoplastic-compatible piezoceramic modules manufactured by novel technologies exhibit the possibility for material homogeneous integration in thermoplastic composites in order to create adaptive composite structures appropriate for mass production. In this context, quality control and defect detection methods accounted for the function and material dependent adaptation of the design and technology parameters. An adequate interface adherence strength and the avoidance of process induced defects could be achieved. Furthermore, the accomplished studies prove the qualitative and quantitative functional ability under static and dynamic loading of novel thermoplastic-compatible piezoceramic modules manufactured by an adapted hot-pressing process. In particular the obtained free strains are within the range of the maximum accomplishable strains of conventional actuators.

Current and future studies also concentrate on the utilization of functional layers made of parallel aligned piezoceramic fibres to enhance module flexibility with the intention to support integration in curved composite structures and to achieve a purposefully aligned actuation.

Acknowledgements

The authors express their thanks to the German Research Foundation (DFG) for the financial support of the investigations within the framework of Collaborative Research Center/Transregio 39 (SFB/TR 39), subproject A5.

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