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COMPOSITES

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PROCESSING STUDIES FOR THE DEVELOPMENT OF A ROBUST MANUFACTURE PROCESS FOR ACTIVE COMPOSITE STRUCTURES WITH MATRIX ADAPTED PIEZOCERAMIC MODULES

Active composite structures based on thermoplastic matrix systems exhibit a high application potential for lightweight structures ready for series production, due to the high specific mechanical properties as well as the high design freedom combined with economic and reproducible manufacture processes. Moreover, the integration of additional functional components like material-embedded piezoceramic actuators or sensors in thermoplastic lightweight structures enables a purposeful manipulation of the dynamic and vibroacoustic structural behaviour. Among function integration like quality monitoring or active vibration and noise control, also structural applications for example in morphing structures and compliant mechanisms are possible. Thus fibre-reinforced thermoplastic composites with embedded material adapted piezoceramic modules offer a wide area of new applications. Actually the lack of efficient manufacture processes impeded the spread of these new material systems. The use of adaptive composite structures in series applications requires novel actuators and sensors with related manufacture processes capable for series production.

This publication gives a contribution for the development of a robust and efficient manufacture process for such new active composites, which bases on a material and actuator adapted hot pressing technique for the realization of short cycle times. Therefore the main focus is put on experimental and theoretical studies for the integration of piezoceramic elements into fibre-reinforced structures. Besides the evaluation of design and process parameters, the influences of the processing parameters on the ceramic elements are investigated to create an adaptive composite structure without damaging of the brittle ceramic. Basic elements of these studies are new thermoplastic composite compatible piezoceramic modules (TPM), which are predestined for a material homogeneous actuator integration in fibre-reinforced thermoplastic composites by use of a welding process. The investigations show a successful manufacture and embedding of these novel piezoceramic modules into fibre-reinforced structures.

Keywords: **piezoceramic modules, fibre-reinforced composites, lightweight applications**

BADANIA NAD OPRACOWANIEM EFEKTYWNEGO PROCESU WYTWARZANIA AKTYWNYCH STRUKTUR KOMPOZYTOWYCH Z DOPASOWANYMI DO OSNOWY MODUŁAMI PIEZOCERAMICZNYMI

Aktywne struktury kompozytowe bazujące na osnowie termoplastycznej, dzięki swym specyficznym właściwościom mechnicznym oraz łatwości projektowania wraz z ekonomicznym i powtarzalnym procesem wytwórczym, posiadają ogromny potencjał aplikacyjny w seryjnej produkcji struktur lekkich. Ponadto, integracja dodatkowych komponetów, jak wzbudniki piezoceramiczne bądź sensory w lekkiej strukturze termoplastycznej, pozwala na celową ingerencję w jej właściwości dynamiczne oraz wibroakustyczne. Oprócz tego umożliwia monitorowanie zużycia elementów, tłumienie wibracji i kontrolę szumu, ale również może zostać wykorzystana jako aplikacja w strukturach morficznych oraz układach podatnych.

Kompozyty z osnową termoplastyczną wzmocnione włóknami ciągłymi wraz z umieszczonymi wewnątrz materiałowo dopasowanymi modułami piezoceramicznymi posiadają ogromny potencjał w zastosowaniach w dziedzinie aktywnych drgań oraz kontroli hałasu. Obecnie brak wydajnego procesu wytwarzania skutecznie hamuje popularyzację tych nowych systemów. Prezentowana publikacja przyczynia się do rozwoju stabilnego i wydajnego procesu wytwarzania tych nowych kompozytów aktywnych, opierającego się na dopasowanej metodzie prasowania na gorąco, pozwalającej na skrócenie czasu cyklu produkcyjnego. Z tego względu główny nacisk położono na badania eksperymentalne i rozważania teoretyczne dotyczące integracji układów piezoceramicznych w strukturach włóknistych. Podstawowym elementem tych badań są nowe moduły piezoceramiczne, kompatybilne z kompozytami termoplastycznymi (TPM), predestynowane do integracji jednorodnych wzbudników w termoplastycznych kompozytach włóknistych. Badania przedstawiają udane próby wytwarzania i wprowadzania tych nowoczesnych modułów piezoceramicznych do struktur wzmacnianych włóknami ciągłymi.

Słowa kluczowe: **moduły piezoceramiczne, kompozyty włókniste, zastosowania konstrukcji lekkich**

INTRODUCTION

High-performance automotive applications increasingly have to fulfil high requirements concerning passenger comfort and environmental compatibility. Here, fibre-reinforced thermoplastic composites with material--embedded piezoceramic modules offer specific advantages due to the possibility to actively control their damping and deformation behaviour [1-3]. The use of these innovative materials enables the development of a new generation of active lightweight structures with material--integrated noise control or active vibration damping functionalities. At present, the lack of robust manufacturing technologies is a major obstacle for the intensive use of these new active composites especially in automotive applications.

In the recent years the development of manufacture processes for passive thermoplastic fibre-reinforced structures were widely advanced but the integration of active functions is very complex [4]. The integration of piezoceramic modules into anisotropic fibre-reinforced structures requires the development of manufacture processes adapted to the interfaces between matrix, reinforcement and the piezoceramic material. Conventional piezoceramic actuators are predominantly manufactured and applied to the structure by adhesive technologies. This requires a high manual application effort and can cause compatibility problems at the interface between composite structure and piezoceramic module [5, 6]. First solutions for the integration of piezoceramic modules into thermoplastic fibre-reinforced composites on the basis of a diaphragm process are quoted in [1].

The consolidation of the novel thermoplastic composites with thermoplastic composite compatible piezoceramic modules (TPM) in an adapted press process premises a specific consideration of the control of:

- impregnation and bonding of fibre-reinforcement and the TPM with the matrix material,
- melting of the module carrier films,
- laminate consolidation,
- autohesion (autodiffusion of thermoplastic polymer chains in adjoining layers),
- contacting of the piezoceramic modules and
- online polarization of the piezoceramic material

to reach short cycle times with functional piezoceramic actuators and reproducible component qualities [7-11].

NOVEL THERMOPLASTIC COMPATIBLE PIEZOCERAMIC - MODULES (TPM)

For the application of active structural parts capable for series production, novel piezoceramic modules are developed, which are specifically tailored to the fibre--reinforced thermoplastic composites (Fig. 1) [12, 13].

These piezoceramic modules with the highly regarded compatibility to the thermoplastic matrix system permit their substantially coherent and homogeneous embedding in the composite structure by a welding technology during a hot-pressing process and thus without additional bonding efforts.

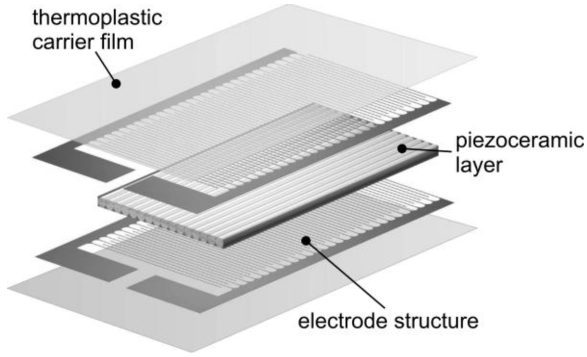

Fig. 1. Design of a novel matrix adapted TPM

Rys.1. Konstrukcja nowego elementu TPM dopasowanego do osnowy

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

MANUFACTURE TECHNOLOGY FOR ACTIVE THERMOPLASTIC COMPOSITES

The new active fibre-reinforced thermoplastic structural parts with embedded thermoplastic composite compatible piezoceramic modules (TPM) specially adapted to the thermoplastic matrix system are produced by means of the film-stacking process. These film-stacking compounds consist of:

- thermoplastic films with contacted TPM,
- thermoplastic films and
- fibre-reinforcement layers.

The production of the thermoplastic films with contacted TPM includes the metallization of thermoplastic films with conducting paths, the exact positioning of the TPM to these paths and the fixation of the TPM by thermal stapling. Finally the thermoplastic film contacted with TPM has to be cut to defined parts (Fig. 2), the thermoplastic actuator sheets (TAS).

The manufacture of the active fibre-reinforced thermoplastic composite parts is divided into two steps. It starts with the preform manufacture where a film-stacking lay-up of textile layers and thermoplastic films will be pressed to consolidated preforms under adjusted pressing parameters.

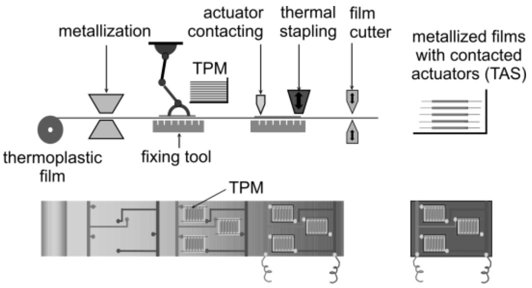

Fig. 2. Metallization and TPM contacting

Rys. 2. Metalizacja i połączenie TPM

The preform manufacture is followed by a quick and material adapted pressing process of the assembled composite. Here, the pressing parameters e.g. the process temperature, time and pressure have to be well adjusted to ensure a proper consolidation of the composite and no damage of the TPM. During the cooling process of the film-stacking compound a process adapted online polarization of the TPM realizes the change-over from a passive to an active composite (Fig. 3).

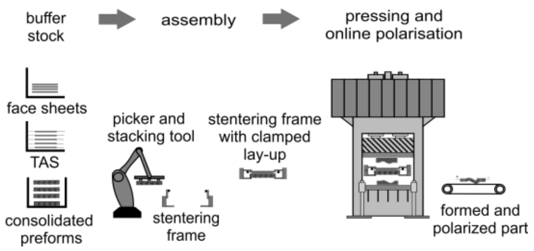

Fig. 3. Robust manufacture process

Rys. 3. Efektywny proces wytwarzania

PROCESSING STUDIES

Initial tests were made to adjust the set of process parameters like pressure, time and temperature regimes. For the specification of the processing temperatures of the used thermoplastic films a simultaneous thermal analysis (STA) was carried out, which combines a thermogravimetric analysis (TGA) with a differential thermal analysis (DTA). By the permanent comparison of the specimen temperature with a reference temperature, the calculated difference in temperature allows the identification of constitutional changes in material. The STA shows a melting temperature of 225°C for PA6 film and 340°C for PEEK film (Fig. 4).

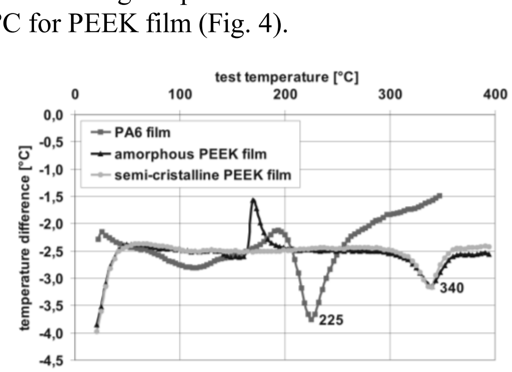

Fig. 4. STA of PA6 and PEEK film

Rys. 4. Wykres STA folii PA6 oraz PEEK

Investigations for the integration of the TPM into the composites have shown, that the pressure load during the pressing process has to be well adapted due to the brittleness of the piezoceramic material. Figure 5 shows the micrograph section and X-ray analysis of a textile--reinforced composite with an embedded piezoceramic module which was damaged during the manufacture process. This damage is mainly caused by high pressure loads in combination with the micro-deformation of the piezoceramic fibres due to the textile structure's waviness. Here the waviness of the textile structure strongly depends on the fibre refinement and thus on the textile grammage.

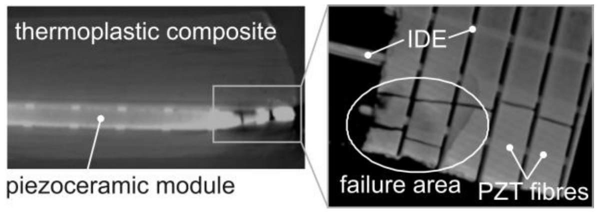

Fig. 5. Failure of piezoceramic fibres

Rys. 5. Uszkodzenia włókien piezoceramicznych

For the determination of the micro-deformation influence of different grammages of glass and carbon fibre fabrics on the fracture sensitivity of the piezoceramic material press tests with a laboratory press tool were carried out. Due to these tests the feasible pressure loads for the manufacture of the fibre-reinforced structure with embedded piezoceramic modules are determined.

In a first step piezoceramic wafers were used instead of TPM. The wafers were positioned symmetrically between the fabrics. These lay-ups were pressed at ambient temperature in the press tool to determine the failure pressure load. The used loads have been increased stepwise from 0.1 MPa up to the pressure where the piezoceramic wafer was damaged. This value was than specified as the failure compression load. Figure 6 shows the used glass and carbon fibre fabrics and the experimental verified failure compression loads for the press tests of the piezoceramic wafers. For all fabrics grammages higher than 300 g/m^2 lead to a premature failure of the ceramic wafer. Contrary to expectations the results show an early ceramic failure for lower grammages (less than 200 g/m^2) as well. This can be explained by lower material qualities for these fabrics, what means that the failure is not due to the grammage but to unforeseen material inhomogeneities like flaws or contaminations.

A second test series was carried out to analyse the behaviour of the composite during the press process. The lay-ups with thermoplastic films and piezoceramic wafers were pressed with an adapted compression load under increasing temperatures up to the melting point of the thermoplastic films. The first composites were heated under a predefined compression load of 0.6 MPa which ensures a good consolidation of the fibre-reinforcement. The piezoceramic wafer was damaged before the thermo-

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plastic matrix was molten (Fig. 7 left). Further composites were loaded with a low contact load of 0.001 MPa during the heating phase up to the melting temperature of the thermoplastic films and than loaded with the consolidation pressure. These composites show no damages of the piezoceramic wafers (Fig. 7 right).

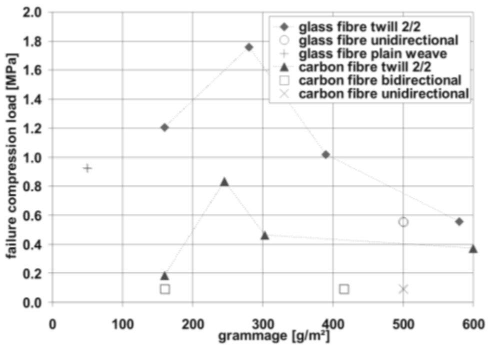

Fig. 6. Comparison of failure compression loads of PZT-wafers embedded in textile fabrics

Rys. 6. Porównanie wartości obciążenia ściskającego elementów PZT osadzonych w płytach kompozytowych

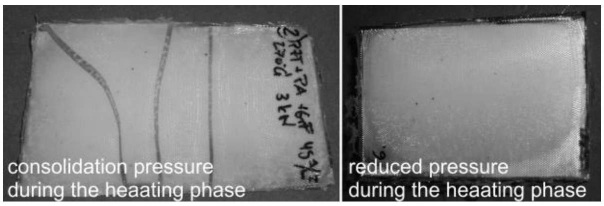

Fig. 7. Embedded piezoceramic wafers manufactured under different compression loads

Fig. 7. Osadzone elementy piezoceramiczne wykonane przy różnym obciążeniu ściskającym

The investigations show that during the heating phase only significantly reduced compression loads have to be used. This is reasoned by the different coefficients of thermal expansion (CTE) between the thermoplastic and piezoceramic material, the micro-deformation caused by the textile structure as well as the brittleness of the piezoceramic wafer. During the heating phase the expansion of the thermoplastic film is significantly higher than the expansion of the piezoceramic material, what causes failure critical tension loads in the ceramic. Figure 8 shows the temperature-dependent CTE of PA6 and PEEK, determined by means of dilatometric analysis. For comparison, the CTE of non-polarized PZT ceramic is about $2x10^{-6}$ K^{-1}.

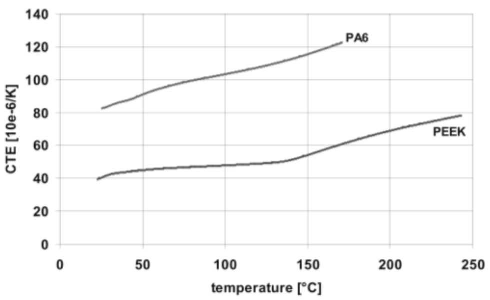

Fig. 8. Temperature-dependent CTE of PA6 and PEEK

Rys. 8. Wykres CTE zależności temperaturowej PA6 i PEEK

In order to specify the actuator performance of an embedded piezoceramic module and to determine the influence of the anisotropic cover layers further functionality tests were performed. Therefore a composite with unidirectional (UD) glass fibre-reinforcement and an integrated piezoceramic wafer contacted with planar electrodes were used. The embedded piezoceramic wafer was polarized and the in-plane expansions of the active composite structure were determined by use of the optical gray image correlation method. The strain results in x- and y-direction dependent on the operation voltage are shown in Figure 9.

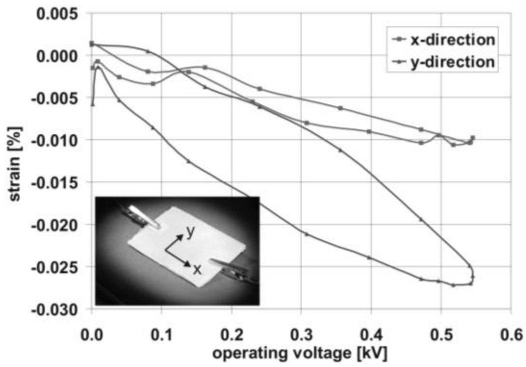

Fig. 9. Expansion of an UD-composite with an embedded piezoceramic module

Rys. 9. Odkształcenie płyki kompozytowej z osadzonym modułem piezoceramicznym

Due to the unidirectional reinforcement the strain in fibre direction (x-direction) is very small compared to the strain perpendicular to the fibres (y-direction). The high stiffness of the fibres prevents the strain in x-direction. Perpendicular to the fibres the thermoplastic matrix dominates the stiffness and consequently allows higher strains.

Analytical and numerical simulations according to the experimental embedding tests were carried out to define an adjusted material thickness referring to the actuators bending performance [14]. The basic model is designed like a bimetal beam consisting of a polyamide based TPM (thickness 0.28 mm) on the top and a composite structure on the bottom (Fig. 10). The considered composite structures are composed of glass or carbon fibre-reinforced PA6 and PEEK, respectively. Each composite has a fibre volume fraction of 50 % and a balanced fibre orientation.

A comparison of the beams absolute deflection related to the different material thicknesses and composite varieties is shown in Figure 10.

The analytic results show a very good correlation to the FEM solutions and the influence of the reinforcement's stiffness is well identifiable. Due to the higher Young's modulus of the carbon fibre-reinforcement these composites enable higher bending amplitudes compared to the glass fibre reinforcements whereas the influence of the matrix type (PA6 or PEEK) is of negligible importance. The optimum material thickness for the actua-

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tor integration is reflected in the maximum of the deflection curves. It is recognizable that the thickness for carbon fibre-reinforced structures needs to be even thinner than for the glass fibre-reinforced composites.

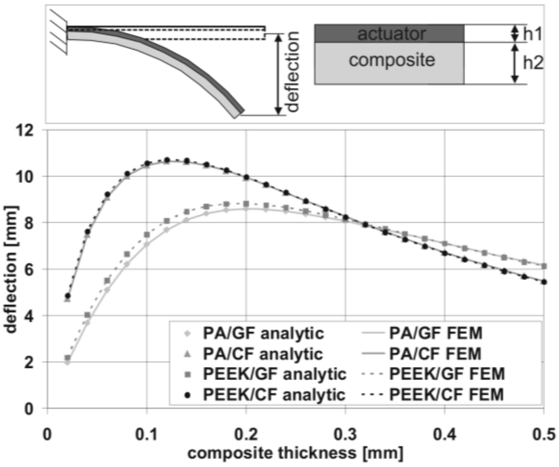

Fig. 10. Structural deflection of multilayer beam model referring to the material thickness

Rys. 10. Wykres ugięcia modelu wielowarstwowej belki w zależności od grubości materiału

In summary the calculated material thicknesses are very thin so that in practice compromises have to be found between the composites thickness and the actuators bending performance.

CONCLUSIONS

New fibre-reinforced thermoplastic composites with embedded novel thermoplastic compatible piezoceramic modules (TPM) offer specific advantages for new active structures. Investigations for a new efficient manufacture process on the basis of a material- and actuator-adapted hot-pressing technology were carried out. The possibility for a robust serial manufacture of active thermoplastic composites is shown and adapted design and process parameters are provided.

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