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Sensitivity analysis for the manufacturing of thermoplastic e-preforms for active textile reinforced thermoplastic composites

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Abstract

Active fibre-reinforced thermoplastic composites offer a high application potential for lightweight structures capable for series production. By the integration of functional components like material-embedded piezoceramic actuators or sensors the structural behaviour becomes actively controllable and manipulable. Currently, a wide application of such adaptive structures is mainly restricted by the lack of robust manufacture technologies. Therefore, these investigations are performed to develop and realise a novel robust and efficient manufacture process capable for series production. This process bases on a material and actuator adapted hot pressing technique. In this context, special regard is given to the sub process e-preforming. There a thermoplastic film is assembled with thermoplastic compatible piezoceramic modules and the necessary conductive paths. By the development of a special e-preforming unit and the corresponding parameter investigations an adapted manufacture of so called e-preforms can be realised.

Selection and peer-review under responsibility of Conference organizers (MSE-Symposium B6).

Keywords: active composites; piezoceramic modules; fiber reinforced thermoplastic composites; e-preform

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1. Introduction

Due to the worldwide shortage of resources as well as the function-integrative lightweight engineering in multi material design cross-industry demands for key technologies in the development of modern high-tech-products with high sustainability arise. In this context, fibre-reinforced composites based on thermoplastic matrix systems exhibit a high application potential for lightweight structures ready for series production. These materials offer outstanding specific mechanical properties in combination with a high freedom of design and the possibility to realise reproducible as well as economic manufacturing processes. Moreover, the integration of additional functional components such as piezoceramic actuators or sensors in these thermoplastic based lightweight structures enables an active manipulation of the dynamic and vibro-acoustic structural behaviour [Crawley et al. 1987; Gibson 2010 and Nuffer et al. 2009]. Besides the function integration for structural applications e.g. for morphing structures and compliant mechanisms [Daynes et al. 2011; Hufenbach et al. 2006; Gude 2008; Modler 2008; Arrieta 2001] further functionalities like quality monitoring, energy harvesting or active vibration and noise control are also possible [Adhikari et al.; 2006; Edery-Azulay and Abramovich 2006; Moro and Benasciutti 2010; Tang et al. 2011; Viswamurthy and Ganguli 2007]. Nevertheless, the state of the art manufacture of adaptive lightweight components is predominantly characterized by the detached manufacture of the composite structure and the piezoceramic modules attended by extensive manually bonding processes [Wilkie 2003; Wilkie and Bryant 2008, Williams et al. 2004]. The adhesive bonding of the function module to the composite structure as well as the additional adhesive film between the fibre-reinforced polymer structure and the module leads to a deformation transfer loss and to an inefficient use of the sensory and operating potentials [Hufenbach et al. 2001]. In regard to a high volume production of active lightweight structures, a transition from these assembly-oriented to technology-oriented actuator integration processes is necessary [Heber 2011; Hufenbach, Gude and Heber 2009; Hufenbach et al. 2009]. In a first development process, novel piezoceramic modules, adapted to the fibre-reinforced thermoplastic composites have been designed [Heber 2011] and in a further process they will have to be integrated into the composite structure (see Figure 1).

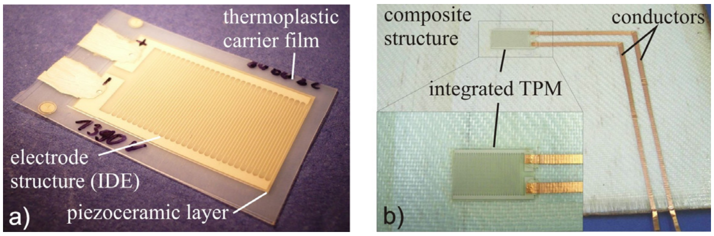

Figure 1: a) Thermoplastic compatible piezoceramic module (TPM); b) Active composite structure with integrated TPM

In regard to a series capable manufacture of these active composites a material and actuator adapted process based on a hot pressing technology is developed. This process is divided in three main sub processes, which means in detail the so called e-preforming, the assembly of the composite lay-up, and the hot pressing with an accompanied online polarization process (Figure 2). There the first manufacture step is to assemble a thermoplastic film with TPM and conductors to a so called e-preform. This e-preform will be transferred to a material store where it will be dried and furthermore picked by a robotic handling system to the next process step. There, the e-preform is first positioned into the pressing die. After this, the structural composite lay-up, consisting of several composite sheets and thermoplastic films, if necessary, are assembled and fixed in a special picker-stacking tool. This tool guarantees a continuous tension of the lay-up through the whole processing. After the assembly, the mounted picker-stacking tool is transferred by a robotic handling system into a preheating station. There the composite structure is heated over melting temperature for a defined dwell time and afterwards transferred into the press. Subsequently the press closes and the e-preform melts into the composite lay-up to one structural component. Hence, the active elements are integrated into the surface of the part. During the press process an online-polarization for the functionalizing of the piezoceramic modules is implemented. Therefore, the relatively high temperatures and the moderate pressure load support the polarization process of the TPM, so that the polarization voltage and time can be reduced [Hufenbach et al. 2011]. Finally an active composite part can be removed of the press.

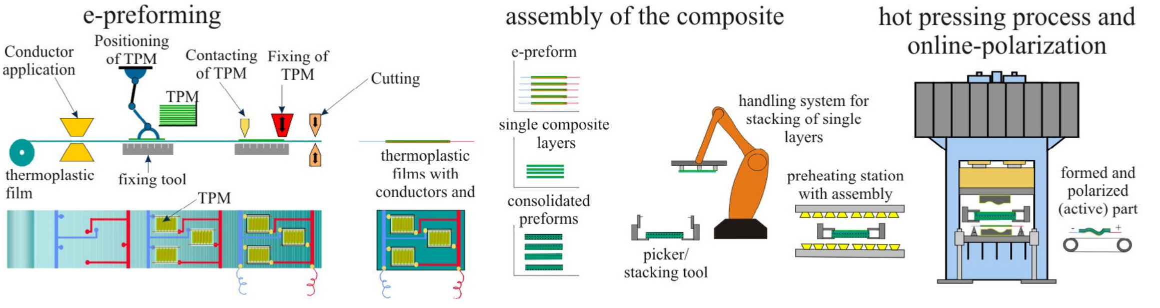

Figure 2: Schematic manufacture process for active fibre-reinforced composites based on thermoplastic matrices

The investigations suggested in this paper are performed for the development and verification of the e-preforming process. Therefore, intensive investigations are carried out in regard to determine appropriate fixing parameters for the single components to the thermoplastic film.

2. E-preforming process

Based on preliminary investigations for the assembling of conductive paths and thermoplastic based modules with a thermoplastic film a special e-preforming unit was developed (see Figure 3).

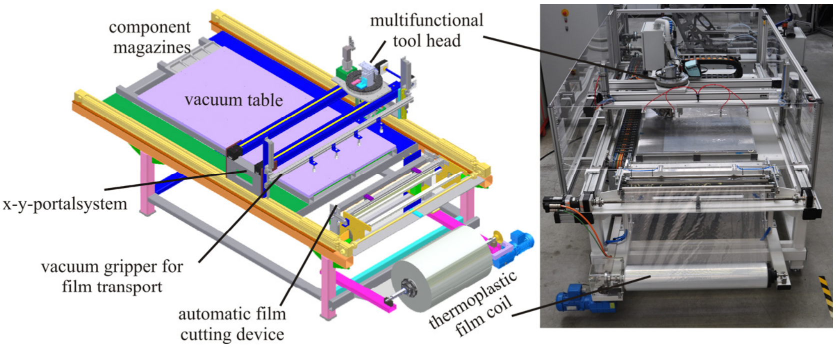

Figure 3: E-preforming-unit; left: Concept; right: Testing plant

The e-preforming unit consists of a vacuum table for the fixation of the film during the assembling process. Additionally, the film transfer to the table is realized by a controlled roll-off device for the thermoplastic film coil and a line of vacuum grippers which grip and pull the film over the desk. The cutting of the film to a predefined length is realized by an automatic cutting device. For the application of the TPM and conductive paths a multifunctional tool head is developed. It includes a thermal as well as an ultrasonic welding device, a conductor application unit, and a vacuum gripper for the transport of the TPM. The tool head is positioned on a x-y-portal system, so that it is movable in two directions and it is additionally rotatable from -180° up to 180°. The integrated ultrasonic welding station shows adapted parameters for the welding of polymeric components. It is operated by an electricity of 500 W and 35 kHz.

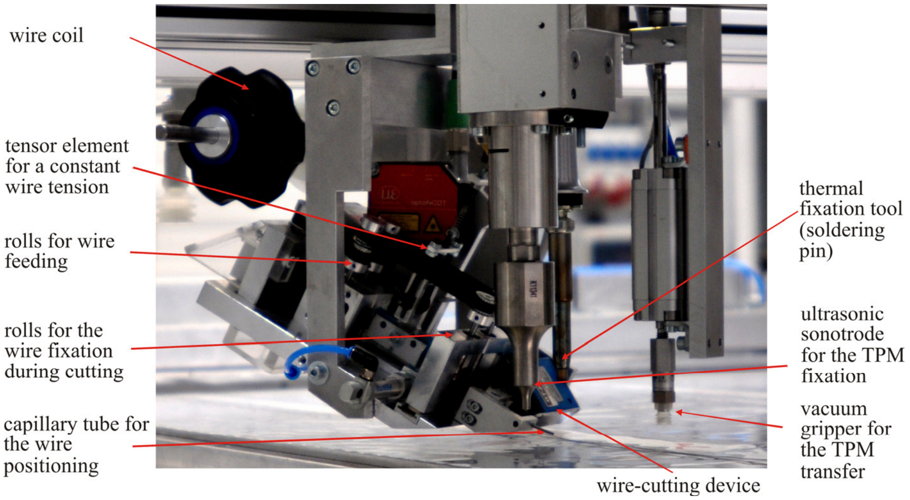

Figure 4: Multifunctional tool head

Basic components of the conductor application unit are the wire coil, several clamping rolls for the wire feeding, a tensor element coupled with an optical senor, a cutting device, and a capillary tube for the wire positioning. In this context, the conductors are rolled up, positioned to the fixing tool, and cut automatically.

Initial investigations show that the fixation by thermal stapling via soldering pin has a high application potential for the conductor as well as for the TPM fixation to the thermoplastic film. However, adapted parameters for a series capable process have to be determined. Furthermore ultrasonic welding can only be used for the TPM application. In regard to the performed studies, the two methods are investigated to realise a proper fixation of the functional elements to the thermoplastic film.

3. Experimental investigations

The investigations in regard to the TPM application are split into two test series. On the one hand the thermal fixation by soldering pin and on the other hand the fixation by ultrasonic welding. Therefore, dummy TPM (see Figure 5) are used. They consist of equal thermoplastic material and show the same thickness compared to the series TPM.

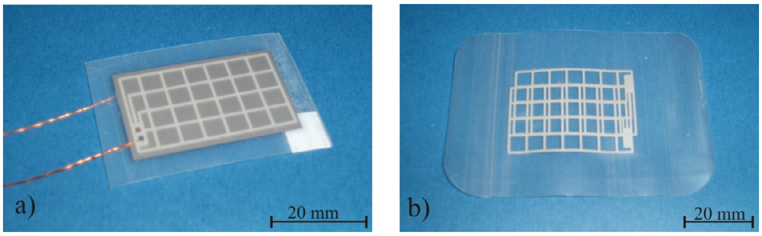

Figure 5: a) TPM; b) Dummy TPM

In the case of thermal fixation the influence of the fixation temperature and the dwell time was investigated with regard to a reproducible process. Therefore, the temperatures of the soldering pin are varied in the range of 400 °C up to 450 °C in 10 °C steps. Furthermore dwell times from 1 s to 10 s are investigated (see also Table 1).

Table 1: Parameter configuration for the thermal fixation of TPM

Properties/Parameter	**values**
Thermoplastic material of the TPM	PA 6
TPM film thickness [µm]	200
Thermoplastic carrier film thickness [µm]	100
Thermal fixation parameters	
Temperatures [°C]	400 – 450
Temperature variation steps [°C]	10
Dwell time [s]	1-10
Dwell time variation steps [s]	1

The fixation of the TPM by ultrasonic welding was performed with two different contact pressures of the sonotrode end face to the thermoplastic films (2.4 bar and 5.8 bar). Furthermore, dwell times from 1 s to 6 s and post dwell times between 1 s and 10 s are investigated (see Table 2).

Table 2: Parameter configuration for the ultrasonic fixation of TPM

Properties/Parameter	**values**
Thermoplastic material of the TPM	PA 6
TPM film thickness [µm]	200
Thermoplastic carrier film thickness [µm]	100
Ultrasonic welding parameters	
Contact pressure [bar]	2.4; 5.8
Dwell times [s]	1 - 6
Dwell time variation steps [s]	1
Post dwell time [s]	1-10
Post dwell time variation steps [s]	1

In regard to the conductor fixation three different conductor configurations are used. Therefore, two tin-coated wires with diameters of 0.35 mm and 0.21 mm as well as a hybrid yarn made of carbon fibres (type T 300, 67 tex) and PEEK filaments (49 tex) were selected. The fixation temperatures are varied in the range of 380 °C up to 450 °C in steps of 10 °C. Furthermore the dwell times are modified from 1 s to 10 s (see Table 3).

Table 3: Parameter configuration for the thermal fixation of conductors

Properties/Parameter	**Copper wire (tin-coated)**	**Copper wire (tin-coated)**	**Hybrid yarn**
Material nomenclature	SWG 35	SWG 29	Multiple twisted yarn, carbon fiber-PEEK (CF: T 300, 67 tex; PEEK: 49 tex)
Diameter [mm]	0.21	0.35	-
Thermal fixation parameters			
Temperature range [°C]	380 – 440	400 - 450	390 - 450
Temperature variation steps [°C]	10	10	10
Dwell time [s]	1 - 10	1 - 10	1 - 10
Dwell time variation steps [s]	1	1	1

4. Results

The application of the TPM by thermal stapling shows applicable results for temperatures above 410 °C. Nevertheless, a guaranteed fixation success was realized for a parameter configuration of a minimum temperature of 430 °C and 5 s dwell time (see Figure 6a, b). At elevated temperatures above 450 °C and longer dwell times (> 8 s) the thermoplastic material is damaged by burning a whole through the TPM and the carrier film (see Figure 6c).

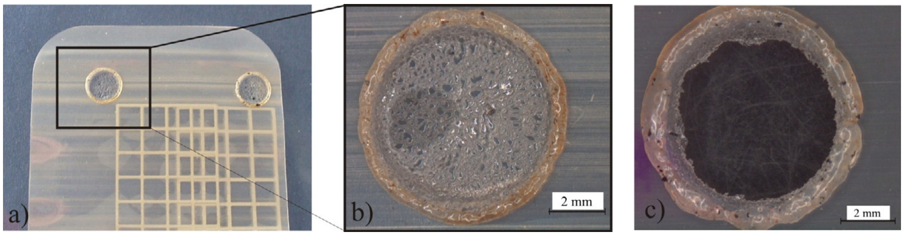

Figure 6: a) and b) Well executed thermal fixation point of a dummy TPM to the thermoplastic film; c) Burned fixation point

Furthermore, the TPM have to be very even and positioned flat on the thermoplastic carrier film. Otherwise the soldering pin will melt a hole in the TPM before the pressure will be exposed to the joining zone. In this case a robust fixation of the TPM is not possible.

With respect to the fixation by ultrasonic welding, the thermoplastic TPM and the carrier film are properly joined with a contact pressure of 2.4 bar, 6 s dwell time and 4 s post dwell time. Figure 7 shows an ultrasonic welding point, where both thermoplastic films are joined across the whole sonotrode end face area. Furthermore, the welding tests with lower contact pressures show by trend better fixation results than the fixation tests with higher pressure (5.8 bar).

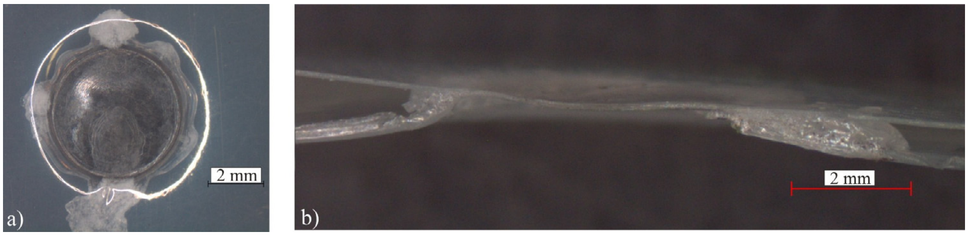

Figure 7: a) Ultrasonic-welded fixation point; b) Cross section of an ultrasonic-welded fixation point

In general, the ultrasonic welding shows a more manageable application for the joining of the TPM to the thermoplastic film compared to the thermal fixation. The thermoplastic material will not be burned, so that further fixation points will not be affected by contaminations. Furthermore the ultrasonic welding quality is not influenced by the distance between the thermoplastic film and the TPM. One reason for this is that the sonotrode end face will expose the contact pressure to the films at first and after that the welding process will start. In the case of the thermal fixation the TPM film will be melted thoroughly when there is a gap between the TPM and the thermoplastic carrier film.

The investigations for the conductor fixation show that all conductor configurations are well fixable by the thermal stapling via soldering pin. Table 4 shows the results for a reproducible application of the conductors.

Table 4: Adapted parameters for the thermal conductor fixation

Properties/Parameter	**Copper wire (ø 0.21 mm)**	**Copper wire (ø 0.35 mm)**	**Hybrid yarn**
Minimum temperature for 100 % fixation success	420 °C	430 °C	410 °C
Minimum dwell time for 100 % fixation success	5 s	5 s	5 s

The thinner tin-coated copper wire (ø 0.21 mm) can be proper fixed by setting the soldering pin temperature at 420 °C. Furthermore, the adapted fixation temperature rises up to 430 °C in regard to the 0.35 mm copper wire and for the hybrid yarn only 410 °C are needed to set reliable bonds. For all configurations dwell times of 5 s show the best results. A fixed hybrid yarn lay-out for an e-preform is shown in Figure 8.

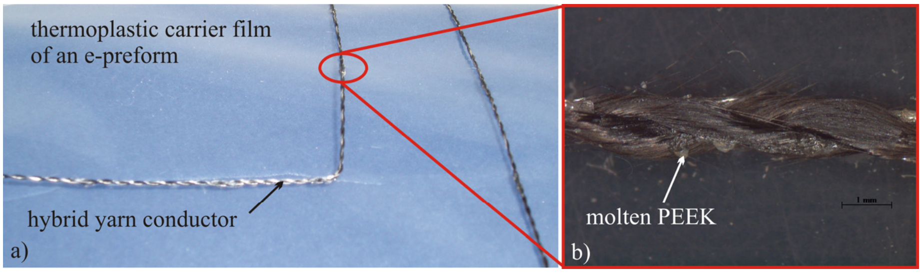

Figure 8: a) Applied hybrid yarn conductor on a thermoplastic film; b) Detail of a hybrid yarn fixation point

The PEEK component of the hybrid yarn melts and fixes the yarn to the thermoplastic carrier film. This will be an advantage in the further processing of the e-preform. So the thermoplastic PA6 film will melt in the hot pressing process, the conductors will be embedded into the cover layer of the composite structure and the lay-out will stay relatively unaffected because of the higher melting temperature of the PEEK component. By this technology a wide design range of lay-outs is applicable. Even sharp edges can be realized because of the flexibility of the yarn.

In regard of the copper wires, selected fixation points are shown in Figure 9. These conductors are particularly embedded into the thermoplastic film of the TPM. The fixation points on the carrier film of the e-preform look a little bit different. There, the wires are not completely embedded into the thermoplastic film. Due to the hot soldering pin and the pressure load, the conductor is heated up and the thermoplastic material underneath it will melt, so that the wire is pressed into the molten material. After the removal of the soldering pin the conductor sticks on the film by adhesion.

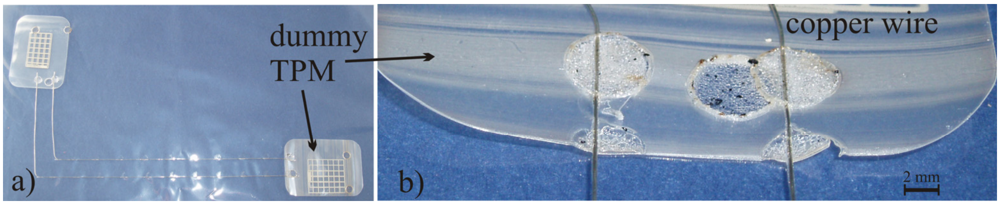

Figure 9: E-preform - Applied copper wires on a thermoplastic film: a) Rectangular lay-out; b) Selected thermal fixation points of the wire

5. Conclusions

By the use of adapted manufacturing technologies for novel active fibre-reinforced thermoplastic composites with embedded piezoceramic modules a high potential for processes capable for series production arises. Therefore, the developed hot-pressing process combined with the necessary process steps e-preforming and composite assembly offer a base technology for these structures. The focus of the presented investigations is on the development of an assembling process for so called e-preforms. Therefore, the determination of joining parameters for the fixation of thermoplastic TPM and several conductor materials to a thermoplastic carrier film is carried out in parameter studies. It is shown that the adapted parameters for the thermal stapling of the conductors and for the ultrasonic welding of the TPM to the carrier film achieve reproducible and applicable results. Further investigations will have to be carried out to research suitable assembly strategies in regard to realise short cycle times. This means in detail the verification of the movement speed of the portal during conductor application, definition of suitable conductor lay-outs (especially radii), and the investigation of adapted working sequences for the processing of defined lay-outs.

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