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DETECTION OF MATERIAL INTEGRATED CONDUCTORS FOR CONNECTIVE RIVETING OF FUNCTION-INTEGRATIVE TEXTILE-REINFORCED THERMOPLASTIC COMPOSITES

Due to their highly-specific mechanical properties as well as ease of design combined with economic and reproducible manufacturing processes, textile-reinforced composites based on thermoplastic matrix systems exhibit great potential for application in lightweight structures ready for mass production. Moreover, the integration of additional functional networks composed of sensors, actuators, and electric components in thermoplastic lightweight structures enables operational-dependent control and adaptation of the structural behaviour with regard to health monitoring or active vibration and noise control. For the creation of complex structures, the use of material-adapted joining techniques is necessary.

This publication is a contribution to the development of material- and application-adapted rivetting technology for the joining and electrical contacting of textile-reinforced composite parts with integrated conductors. In particular, different materials and methods for the generation of conductive paths are assessed. For accurate placement of a contacting rivet, various methods for the detection and localization of the conductors after integration, are investigated. Especially X-ray technology demonstrates good performance with regard to a high volume process chain. Furthermore, the studies show the ability to use printed conductors and carbon fibres as well as conventional wires for integration in textile-reinforced composites, suitable for mass production.

Keywords: thermoplastic composites, non-destructive testing, function integration, joining technology

DETEKCJA ZINTEGROWANYCH MATERIAŁÓW POŁĄCZEŃ NITOWYCH INTEGRACYJNEJ FUNKCJI KOMPOZYTÓW TERMOPLASTYCZNYCH WZMOCNIONYCH WŁÓKNEM TEKSTYLNYM

Ze względu na bardzo dobre własności mechaniczne oraz swobodę projektowania w połączeniu z ekonomicznymi i powtarzalnymi procesami wytwórczymi kompozyty włókniste o osnowie termoplastycznej posiadają ogromny potencjał, szczególnie do wykorzystania w produkcji seryjnej konstrukcji lekkich. Ponadto, integracja dodatkowych funkcji w postaci czujników, wzbudników i elementów elektrycznych w termoplastycznych konstrukcjach lekkich pozwala na kontrolę oraz adaptację zachowań projektowanych struktur. Przykładem mogą być urządzenia do monitorowania funkcji życiowych, aktywnego tłumienia drgań oraz kontroli natężenia hałasu. Do wykonania takich złożonych struktur kompozytowych niezbędne jest jednak użycie odpowiednio zaadaptowanych technik łączenia.

Niniejsza publikacja wnosi wkład w rozwój technik nitowania i połączeń elektrycznych dostosowanych do elementów z kompozytów włóknistych ze zintegrowanymi przewodnikami. W szczególności, ocenie poddane zostały różne materiały i metody przeznaczone do wytwarzania ścieżek przewodzących, przetestowano ponadto dokładne pozycjonowanie nitów oraz metody lokalizacji przewodników po procesie integracji. W tym przypadku bardzo dobre wyniki pokazała technologia rentgenowska X-ray, szczególnie w wysoko wydajnych liniach produkcyjnych. Ponadto przedstawiono perspektywy integracji przewodników drukowanych, włókien węglowych oraz tradycyjnych przewodów elektrycznych w strukturach kompozytów włóknistych wytwarzanych seryjnie.

Słowa kluczowe: kompozyty o osnowie termoplastycznej, badania bezinwazyjne, integracja funkcji, techniki łączenia

INTRODUCTION

Due to their highly-specific mechanical characteristics and versatile design possibilities in combination with economic and reproducible manufacturing processes, textile-reinforced polymers with thermoplastic matrix systems exhibit great potential for application in the mass production of lightweight structures [1-4]. Textile-reinforced thermoplastic composites, developed in the frame of Collaborative Research Centre SFB 639, show the possibility for material functionalization e.g. through textile engineering based on the integration of conductive hybrid yarns and sensor networks [5-9]. This enables the transmission of electric energy inside the composite part without additional electrical components outside the structure. For the signal- and energy transfer between such functionalized structures, specially adapted interfaces are necessary (Fig. 1). With regard to thermo-mechanical compatibility, these interfaces also have to fulfil special requirements of modern multi-material designs, such as robustness, the compensation of different coefficients of thermal expansion, and the avoidance of contact corrosion.

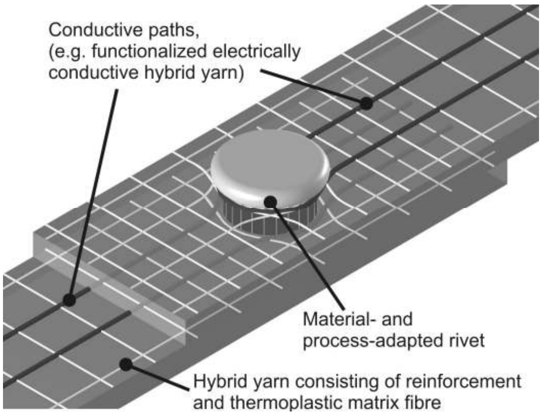

Fig. 1. Schematic illustration of combined structural and electrical interface of joined functionalized thermoplastic composites

Rys. 1. Schematyczne przedstawienie połączonej powierzchni przylegania elementów elekrycznych ze strukturą kompozytów termoplastycznych

For the development of these functional interfaces, suitable concepts for point- and line-shaped as well as plane connections have to be developed, technologically realized, and verified by experiments. Figure 2 shows recently developed concepts for function-adapted joining of composite parts [10-13]. The concepts make a contribution to the transmission of mechanical loads as well as to the electric conductivity from part to part, realized by the joining element.

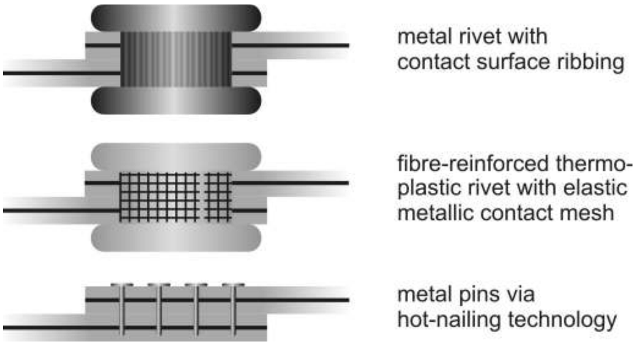

Fig. 2. Joining concepts with regard to transmission of mechanic loads and electric signals

Rys. 2. Połączenie koncepcji dotyczącej jednoczesnego przenoszenia obciążeń mechanicznych i przekazywania sygnałów elektrycznych

Besides the development of adapted riveting technologies, appropriate materials and technologies for the generation, integration, and detection of conductive paths need to be evaluated. The following studies show the investigation of material-embedded conductors and mainly concentrate on the non-destructive detection and localization of the conductors by different methods, which is necessary for subsequent accurate placement of a contacting rivet.

CONDUCTIVE PATH GENERATION

The transmission of electrical power and signals takes place along conductive paths, which are embedded in the textile-reinforced thermoplastic structure. For the identification of qualified methods for a material adapted realization of conductive paths, fundamental experimental studies with regard to a structured conductor application on thermoplastic composite layers were conducted. The application of conductive paths composed of copper wire, copper film, carbon fibres, and silver paste was investigated by means of different technologies in particular.

Fixing of the structures using ultrasonic welding turned out to be possible, but led to local destruction of the conductors. Thus, purposeful adjustment of the welding parameters to improve connection quality is necessary. The feasibility of thermal fixing has been proved by contact heating. Furthermore, conductive paths designed as copper film tapes were bonded and carbon fibre rovings as well as copper wires were applied on thermoplastic carrier layers by means of stitching technology (Fig. 3 left).

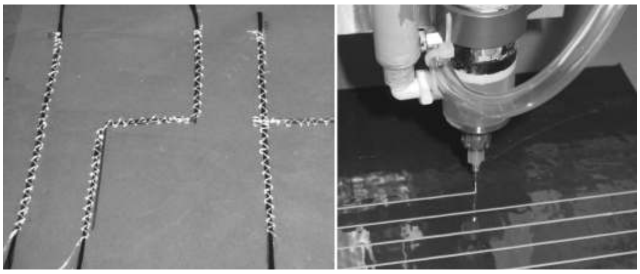

Fig. 3. Stitched carbon fibre conductors (left) and printed silver conductors (right) on thermoplastic carrier layer

Rys. 3. Obszyte przewodniki z włókna węglowego (z lewej) i drukowane przewodniki srebrne (z prawej) na termoplastycznej warstwie nośnej

With regard to a conductor generation suitable for mass production, the automated application of conductive silver paste (here DuPont 5028) by a pneumatic metering system, consisting of a metering valve, cartridge, and control unit, was investigated (Fig. 3 right). Under successive adaptation of the process parameters, favourable results for the realization of continuous and steady conductive paths could be achieved; the final parameters leading to the desired results were a needle diameter of 0.33 mm, a needle distance of 0.3 mm, a feed rate of 5 mm/s, and 2 bar metering pressure.

After application on the thermoplastic or textile carrier layers, the conductive structures were integrated in the textile-reinforced thermoplastic composite structures by means of hot-pressing technology. The realized investigations demonstrate robust processing behaviour of the conductor structures of copper wire, metal film, and carbon fibres as well as combinations like hybrid yarns of reinforcement fibres and metal fibres. Even after the consolidation process under high pressure (up to 20 bar) and temperature (up to 400°C), good resistance against process induced damage and displacement was observed. The automated printing of conductive paths exhibits a fast and cost-effective alternative; whereupon, precise adjustment of the consolidation parameters is required to avoid damage as a result of flowage in the composite lay-up.

For the succeeding evaluation of the appropriate detection methods, an exemplary arrangement of conductors of different thicknesses (0.25, 0.5, 0.8, 1 and 1.3 mm in diameter) and placement geometry (straight lines and loops) was configured and positioned between four single layers of different types of two-dimensional textile preforms. For the first studies, copper wires were used exemplarily; other conductor materials are considered in further investigations. Figure 4 shows the exemplary composition for a knitted textile structure of glass fibre-polypropylene hybrid yarns. After consolidation, the entire composition results in a non-transparent textile-reinforced thermoplastic composite plate with a thickness of 2.2 mm; whereupon, the positions of the integrated wires are not able to be estimated by visual inspection.

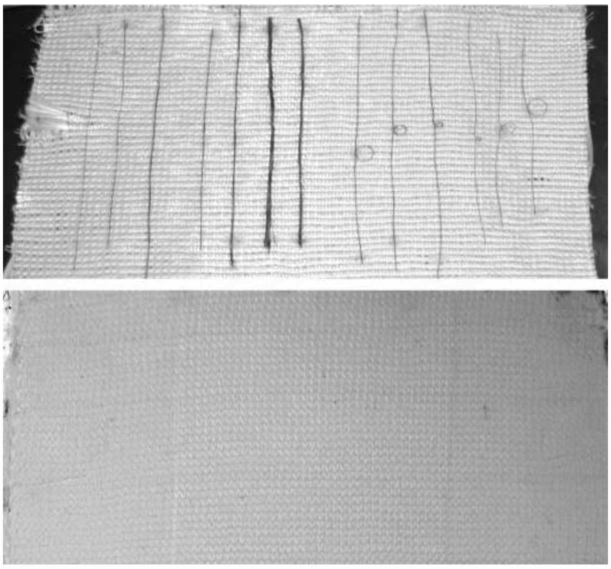

Fig. 4. Exemplary wire arrangement in textile-reinforced thermoplastic structure before (top) and after consolidation (bottom)

Rys. 4. Przykładowe rozmieszczenie przewodów w strukturze termoplastycznej wzmocnionej włóknami przed (na górze) i po procesie konsolidacji (na dole)

EVALUATION OF DETECTION METHODS

The electrical contact of adjacent parts is supposed to occur through the connection of integrated conductors e.g. via electrical conductive rivets. Due to the fact that the conductors are normally not visible from the outside, their position has to be determined before exact part and rivet positioning can be performed. For this reason, different detection methods were tested and evaluated with regard to their usability in high volume processes.

In the first step, detection of the integrated wires by means of ultrasonic analysis was tested. Hence, the set-up of an x-y-ultrasonic system with air coupling was used, which allows automated two-dimensional scanning of thin-walled structures by sound transmission. Figure 5 shows the test set-up with the C-scan of the composite structure with the embedded wire arrangement.

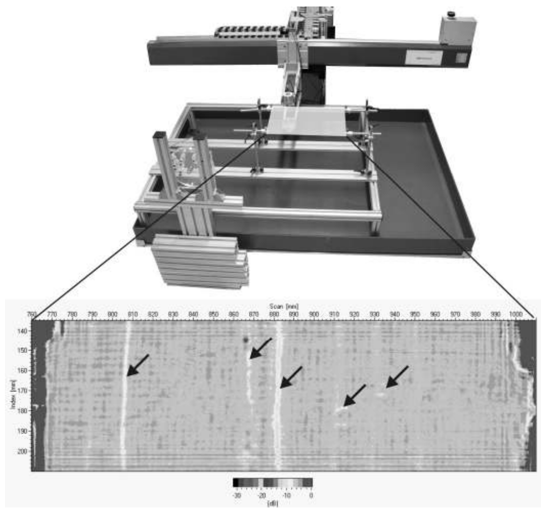

Fig. 5. Air coupling based ultrasonic analysis system with C-scan of test structure (excitation with 65 dB, resolution: 125 μm)

Rys. 5. System do analizy ultradźwiękowej ze sprzężeniem powietrznym wraz z wynikami badań struktury (wzbudzenie przy 65 dB, rozdzielczość: 125 μm)

While performing the ultrasonic analysis, it was not possible to adjust the preferences in such a way as to detect the entire wire arrangement. Just single components of the arrangement in Figure 4, marked with black arrows in Figure 5, could be visualized. Thus, the detection of integrated conductive paths by ultrasonic analysis is suitable only to a limited extent for in-process detection, e.g. for defined and previously tested components.

Further studies were carried out using X-ray technology. The test structures were radiographed by means of a computer tomography scanner with a 180 kV micro focus tube, a 12 bit flat detector with 2300 x 2300 pixel, and a pixel size of 50 x 50 μm. Figure 6 displays the X-ray result of the textile-reinforced thermoplastic plate with the embedded wire arrangement (compare to Fig. 4).

The complete wire arrangement can accurately be detected and localized by this non-destructive testing method. Similar results were achieved for other tested conductors, made of conductive silver paste, copper film, and carbon fibres. Notwithstanding, X-ray technology, due to its installation complexity and high safety requirements, demands a higher investment effort compared to other technologies.

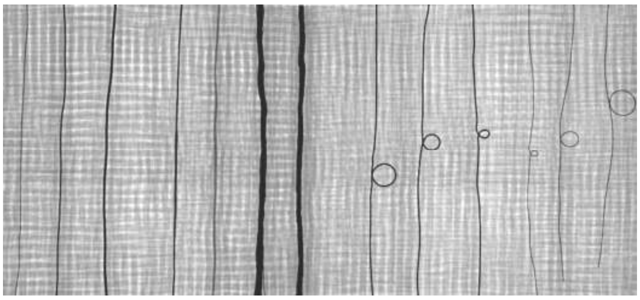

Fig. 6. X-ray analysis of composite structure with embedded wires (voltage: 80 kV, current: 100 μA, resolution: 50 μm)

Rys. 6. Wyniki analizy rentgenowskiej struktury kompozytu z wbudowanymi przewodnikami (napięcie: 80 kV, prąd: 100 μA, rozdzielczość: 50 μm)

A more cost effective method is thermal imaging analysis. Hence, a thermography set-up, consisting of a lock-in thermography camera system with a spectral range of 1÷5.5 μm, a thermal resolution of 2 mK, and a 1000 W halogen spot light for excitation was installed as the reflexion arrangement. This technology allows the detection of various inhomogeneities, due to their individual absorption and emission behaviour, which is usually different from that of the remaining structure. In order to reach high emissivity, the test structure surface had to be prepared with graphite spray. Even after extensive studies under systematic parameter adaptation, the measured results, exemplary presented in Figure 7, exhibit a limited possibility for the detection of embedded conductors, similar to the ultrasonic method.

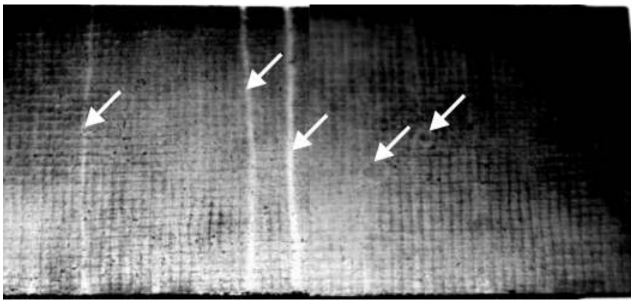

Fig. 7. Lock-in thermography of composite test structure with embedded wires (5 measuring cycles, sinusoidal excitation over 10 s, recording frequency: 5 Hz)

Rys. 7. Wyniki analizy termograficznej struktury kompozytu z wbudowanymi przewodnikami (5 cykli pomiarowych, pobudzenie sinusoidalne ponad 10 s, częstotliwość: 5 Hz)

In order to enhance the detection quality, different strategies for purposeful detection support were evaluated. Due to the fact that the conductors need to be continuous in the later composite structure, the application of an electric current, aiming at the purposeful use of resistance heating, turned out to be possible. Therefore, additional composite plates, similar to the ones previously explained, with adapted wire arrangements were manufactured. The wires were positioned parallel to each other under alternating connections of free wire endings so that the wires result in one meandering conductor.

For detection of the heat generated by resistance heating owing to the electric current, a thermal imaging system, different from the previous one, was used, which features a spectral range of 7.5÷14 μm and a thermal resolution of 80 mK. Compared to the lock-in thermography system, this thermography camera measures the temperature allocation independent from the excitation source. Figure 8 shows a selected measuring cycle with a current of 1 A, which was switched on at the time of 0 s and switched off right after optimum visibility at 70 s. The maximum observed temperature difference is about 1 K.

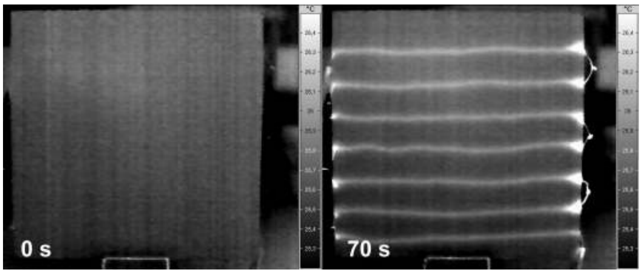

Fig. 8. Thermal imaging analysis with resistance heating of integrated conductors (current: 1 A, electric power: 960 mW, duty cycle: 70 s)

Rys. 8. Analiza termiczna płyty kompozytowej z zintegrowanymi przewodnikami podgrzewanymi rezystancyjnie (prąd: 1 A, zasilanie elektryczne: 960 mW, cykl pracy: 70 s)

By trend, increasing detection quality with rising current intensity can be noticed. Nevertheless, this procedure is not always applicable; it is restricted to composite structures with continuous conductors and dedicated electric components that have the ability to withstand electric current for resistance heating over a short period of time. In the case of non-continuous conductors, especially if the conductors end in a piezoceramic sensor or actuator, this current-assisted thermal imaging method is unfeasible. A further condition for this method, which is not easy to fulfil due to technological reasons, is to provide free conductor endings for the connection with an external current source. Beside these restrictions, the thermal imaging method has got the major advantage of a fast and cost effective procedure, which offers the ability for online conductor detection and localization within a high volume production process.

Table 1 shows the compilation of the tested non-destructive detection methods and their evaluation with regard to their compatibility ready for mass production.

In comparison to each other, the X-ray analysis exhibits the best detection results and the highest test speed, but it is also the technology with the highest investment cost. Nevertheless, it is well qualified for fast online conductor detection in a high volume production process. The final method of choice depends on the individual application. In a mass production process, where just a few defined conductor materials are utilized, it might be possible to specifically adapt the preferences of lock-in thermography to achieve recurring good detection quality. Hence, cost-effective conductor detection isochronous to the remaining process steps becomes possible.

TABLE 1. **Evaluation overview of tested conductor detection methods**

TABELA 1. **Ocena przebadanych metod wykrywania przewodników w strukturze kompozytu**

	Ultrasonic analysis	X-ray analysis	Lock-in thermography	Current supported thermography
test range	arbitrary, here 110 x 250 mm	depending on detector, here max. 200 x 300 mm	depending on objective, here 110 x 250 mm	depending on objective, here 300 x 300 mm
test speed	8 h for used test range and resolution of 125 μm	< 10 s	10 s for each test cycle, here 5 cycles	≈ 60 s
test result	insufficient	good	insufficient	sufficient
ability for automation	limited	good	good	good

CONCLUSIONS

Novel manufacture processes for textile-reinforced thermoplastic composites offer the possibility of defined integration of functional components and material adapted riveting of neighbouring parts; whereupon, the rivet contributes to the mechanical and electrical connection simultaneously. Against this background, various methods for the realization of embedded conductors and appropriate technologies for non-destructive conductor detection were investigated and evaluated with regard to the suitability for mass production. X-ray technology, in particular, showed the best results and turned out to be a promising method provided that it is specifically adapted to the process chain for high volume production.

In addition to conductor detection, an intelligent image interpretation method for defined conductor localization is needed as input for the part positioning and riveting process. Thus, current and future studies should concentrate on the development of a continuous riveting process chain and automated connection of single process steps.

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