FUNCTION INTEGRATION FOR INJECTION MOULDED STRUCTURES USING FIBRE-REINFORCED GRIDS

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Abstract

Multiaxial textile grids made of hybrid yarn rovings can be incorporated into injection moulded components to improve their mechanical properties. The reinforcement grid can furthermore be functionalised by wiring for supplying electronic components serving as electrical function integration. To connect the electronic components to the wires, various contact methods, like conductive soldering, ultrasonic soldering, crimping and bonding with conductive adhesives, were tested. In four-terminal sensing tests the contact resistances of connected specimen has been determined. It has been found, that ultrasonic soldering is the most reliable connection method with the lowest achievable contact resistances. In application tests, the technology is used to connect function carriers with functionalised grids. The measured contact resistances are in the range of the contact tests.

1. Introduction

Thermoplastic composites are predestined for the efficient manufacturing of lightweight structures with high mechanical properties. Due to the thermoplastic matrix, such composite structures can be efficiently functionalised by additional substructures like ribs using injection moulding technology. Since the textile architecture of state of the art reinforcements implies high roving densities, most thermoplastic composites can only be applied at the surface of the moulded component. An alternative is the use of textile grids made from hybrid yarns. With their open space between warp and weft roving (see Fig. 8c), these grids enable a full three-dimensional integration into the injection moulded part [5].

In addition to the mechanical reinforcement, the grids can also be used to provide wires for electrical function integration into the moulded part. Common methods for electrical contacting are insert moulding [1], moulded interconnected devices (MID) [2] or integrated polymer metal injection moulding (IKMS) [3]. For insert moulding pre-shaped sheet metal structures are used. Their cross-sectional area can vary in a wide range and is chosen after the transmitted electric power (see Fig. 1a). For MID, injection moulded parts from polymers with metal oxide fillers are manufactured first. Afterwards the surface is partially activated by laser radiation, enabling a subsequent selective metallisation. With MID, the low achievable layer thicknesses only permit the transmission of small electric powers like sensor signals (see Fig. 1b). IKMS bases on a two-component injection moulding process. In a first step the polymer component is manufactured. Afterwards the part is transferred into a second cavity and locally overmoulded with a low-melting metallic to create the electric paths. Hereby it is possible to adjust the cross-sections of these paths, depending on the electric power to be transmitted (see Fig. 1c).

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Figure 1. Injection moulded parts with electrical function integration: a) insert moulding, b) moulded interconnected devices, c) polymer metal injection moulding.

For the described methods, additional parts, process steps or more complex mould technologies are necessary for functionalising the part. In the manufacturing process proposed here, the wires are integrated into the reinforcement grids during their fabrication (see Fig. 2a). Afterwards, the functionalised textile grids are heated up and preformed in a three dimensional shape using a pressing mould, to be adjusted to the cavity of the injection mould (see Fig. 2b). Adjacently the functional elements are placed to a function carrier adapting the individual contact zones to the grid. This assembly is placed and connected to the preformed grid. (see Fig. 2c). Finally, the functionalised preform is transferred into the injection mould and overmoulded to form the fibre-reinforced part with additional electric functions (see Fig. 2d).

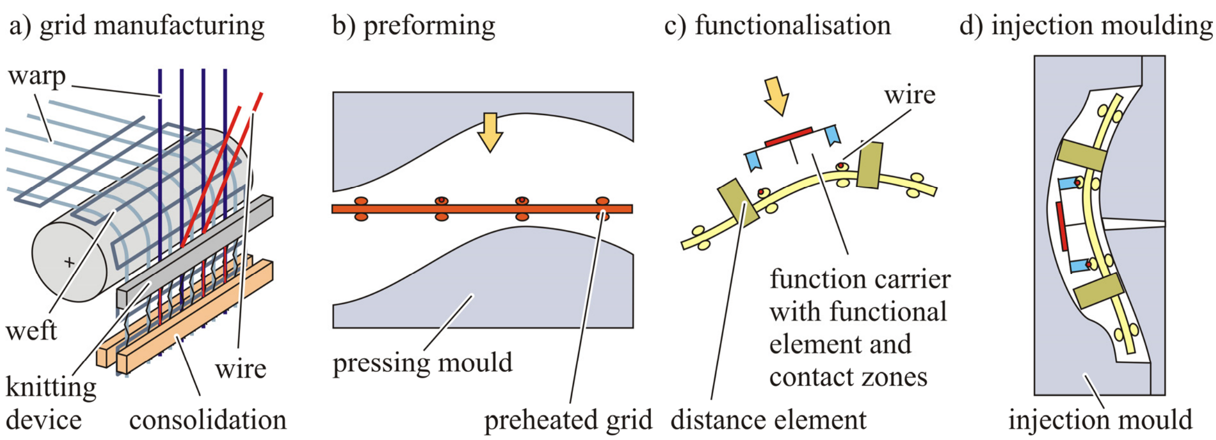

Figure 2. Manufacturing process for grid-reinforced injection moulded structures.

In this paper different contacting techniques between the wire in the grids and the function carriers are elaborated and discussed. For this purpose, four electric joining methods are specified and applied to the test specimens. The contact resistances of the different samples are measured and classified. Afterwards the technology with the lowest contact resistance and the highest contact reliability is used to join function carriers to the functionalised grids.

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2. Contact partners

For the specification of possible contact technologies, the characteristics of the contact partners have to be considered. The first contact partner is a wire, embedded inside the rovings of the textile grid. In this work a TWINTEX® 1870 tex comingled hybrid yarn containing polypropylene filaments and glass fibres with a glass weight content of 60 % is used. The integrated wires for data transfer and energy supply are made from copper with a tinned surface for a better connectivity especially for soldering. During the grid manufacturing process on the warp knitting (Stitch-bonding) machine MALIMO 14022 (Karl Mayer Technische Textilien GmbH) both materials are tied together by a 7.6 tex polyester stitching yarn. After the knitting process, the functionalised grid is pre-consolidated using an infrared radiation device and a pair of rollers, with one rubber coated. The resulting position of the wire can be inside or at the surface of the roving.
The second partner is a solder point at the function carrier. In this work, the function carriers are printed circuit boards (PCB) with a thickness of 0.5 mm and the solder points are squared copper pads with an edge length of 5 mm and a tinned surface (see Fig. 3).

Figure 3. Developed function carriers with functional elements and electric contacts.

For consistent testing conditions, a specimen configuration with simplified contact partners is used. The manufacturing process of the first contact partner is based on the production process of the textile grids [5]. A tinned copper wire with a diameter (*D*) of 0.35 mm is tied to the hybrid yarn roving by a polyester yarn and a double lockstitch sewing machine (see Fig. 4a). Afterwards, the functionalised roving is pre-consolidated with a forming tool in a laboratory press to ensure a defined thickness of the roving (see Fig. 4b). The specimen of the first contact partner has the same shape like the functionalised textile grid (see Fig. 4c).

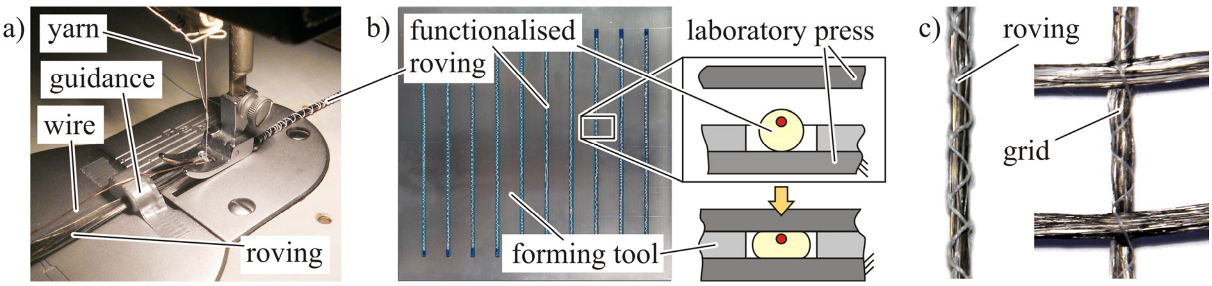

Figure 4. Manufacturing of the functionalised roving: a) assembling with sewing machine, b) pre-consolidation, c) comparison of roving and grid.

The second contact partner is a copper strip with a width (*W*) of 3.5 mm, a thickness (*T*) of 0.1 mm and a length of 30 mm which is perforated at one end. The hole with a diameter of 2 mm and the burr on the edge of the hole is helpful to concentrate solder at the end of the strip (see Fig. 5a and b). STANNOL® HS10 is used as solder.

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3. Contact tests

The first tested contact method is soldering using a soldering iron, as it is well known for assembling electric elements on PCB [7]. In case of a hidden wire within the roving the soldering process can be difficult. But with the support of ultrasonic vibration and a moderate pressing force in an ultrasonic soldering process the matrix in the roving is melted and the glass filaments pushed sideways. The roving is flattened to the same thickness of the uncovered solid wire (see Fig. 6 V2) [6]. Another possibility to contact the hidden wire is to penetrate the roving with an additional contact element. By installing a crimping element [7] the free edges of the contact zone can penetrate the roving while it is enclosed in the same time (see Fig 6 V3). This is selected as the third method to be investigated. According to the diameter of the functionalised roving a MOLEX 02-06-2103 crimping element is used as the second contact partner for this test (see Fig. 5c).

Figure 5. Different second contact partners: a) copper strip, b) tinned copper strip, c) crimping element

On a closer examination of the functionalised roving it is revealed, that there is no closed surface after pre-consolidation (see Fig. 4c). It can be an option to infiltrate the roving partly with a liquid conductive adhesive for establishing an electric contact to the hidden wire (see Fig. 6 V4). Hence, the fourth method under investigation is bonding with silver-epoxy adhesive [8]. The described contact technologies are listed in Tab. 1. To increase the reliability of the connection methods, also selected combinations are investigated in the configurations V5 to V8.

Table 1. Investigated contact configurations.

Configuration	V1	V2	V3	V4	V5	V6	V7	V8
Contact technology								
Soldering	x				x	x		
Ultrasonic soldering		x			x			x
Crimping			x			x	x	
Silver-epoxy bonding				x			x	x
Contact partner 1								
Tinned copper wire	x	x	x	x	x	x	x	x
Contact partner 2								
Copper strip	x	x		x	x			x
Crimping pin			x			x	x	

For each test configuration 12 specimens are connected. The contact partners are placed perpendicularly and joined at the crossing zone (see Fig. 7, left). For the soldering joint (see Fig. 6 V1) the first contact partner is placed on a heat resistant base. The second contact partner is located above the roving with the tinned side down. Then, a pre-heated soldering iron (temperature T=195 °C) is manually placed on top with low force. Due to the heat transfer through the copper, both the solder and some of the thermoplastic filaments in the roving are molten. A connection is established, when the solder reaches the wire and cooling down after the soldering iron is removed.

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For the ultrasonic-supported soldering a hand-guided welder (BRANSON® Palm Grip HT-350) is used (see Fig. 6 V2). The horn has a square transfer zone with an edge length of 8 mm. The contact partners are placed above another with the copper strip on the ground and the tinned side up. The horn is placed on top of the contact partners and the soldering procedure is performed manually with moderate pressure. After initialization of the ultrasonic vibration (frequency f=30 kHz, amplitude w=100 µm), the roving is flattened and the solder is heated up and connects the wire with the copper strip. During this process a lateral movement of the hand-guided welder and the wire is observed. After the end of the vibration (approx. 2 s) the pressure force is retained until the solder cools down and the contact partners are joined.
For the crimping connection (see Fig. 6 V3) the tip of the crimping pin is bended for a better accessibility to the crimping zone. The functionalised roving is placed inside and the joint is made with a crimping plier suitable to the size of the crimping pin.
The adhesive connection (see Fig 6 V4) is made with CircuitWorks® CV2400 conductive epoxy filled with silver particles (weight content 18 %). First, the contact partners are cleaned using propanone. Then a copper strip without solder is placed on the bottom and wetted with a small amount of the adhesive. Afterwards the first contact partner is placed above and fixed by low manual pressure.

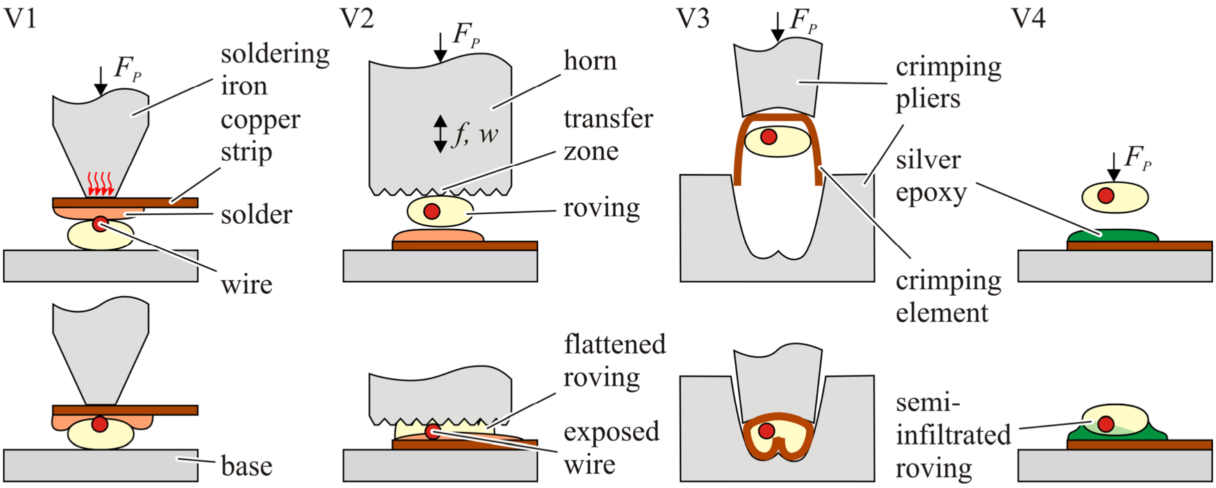

Figure 6. Set-up of the basic joining methods: V1) soldering, V2) ultrasonic soldering, V3) crimping, V4) silver-epoxy bonding

For investigating combined techniques the ultrasonic process is prefixed to the soldering step in configuration V5 to expose the wire and spread the solder in the contact zone. With the subsequently introduced heat from the soldering iron and a moderate manual pressure, the solder is molten again to get a better distribution. To improve the reliability of the crimping joint, in configuration V6 a piece of solder is placed aside the roving in the crimping element. After the crimping step the pre-heated soldering iron is placed on the surface of the crimping element to melt the solder and get a better distribution in the contact zone. In a further tested configuration V7, the conductive adhesive is used to improve the crimping connection by placing it around the roving at the end of the crimping pin. Compared to the setup in Fig. 6 V2, the tested configuration V8 is conducted with silver epoxy instead of solder.

With the manufactured contact specimens the resistance measurements are performed. Four-terminal sensing is used, as it is common for measurement of small resistances [4]. The test setup is shown in Fig. 7 left. The specimens are connected with kelvin clamps and the measurement of current and voltage is done internally by a multimeter Agilent U3606A. The determined resistance R between the clamps is shown directly on the display.

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It comprises the individual resistances of the contact partners 1 (R_1) and 2 (R_2), and the contact resistance R_C in the form

$$R = R_1 + R_2 + R_C. \tag{1}$$

To determine the contact resistance, the individual resistances from the contact partners are calculated with the known specific electrical resistance ρ of the materials (copper for both contact partners [7]), the defined geometrical dimensions W, T and D and the measured distances between kelvin clamp and contact L_1 and L_2 from the contact partners with

$$R_1 = \rho \frac{L_1}{WT}; \quad R_2 = \rho \frac{4L_2}{\pi D^2}; \quad \rho = 1.75 \cdot 10^{-2} \frac{\Omega mm^2}{m}. \tag{2}$$

So, R_C is calculated with

$$R_C = R - \rho \left(\frac{L_1}{WT} + \frac{4L_2}{\pi D^2} \right). \tag{3}$$

The results are summarised in Fig. 7 right. If a certain resistance is measured, the electrical joint is specified as successfully established. The ratio between the successful connections and the number of specimens manufactured is a measure for the method reliability and is drawn with grey bars in the diagram in Fig 7 right.

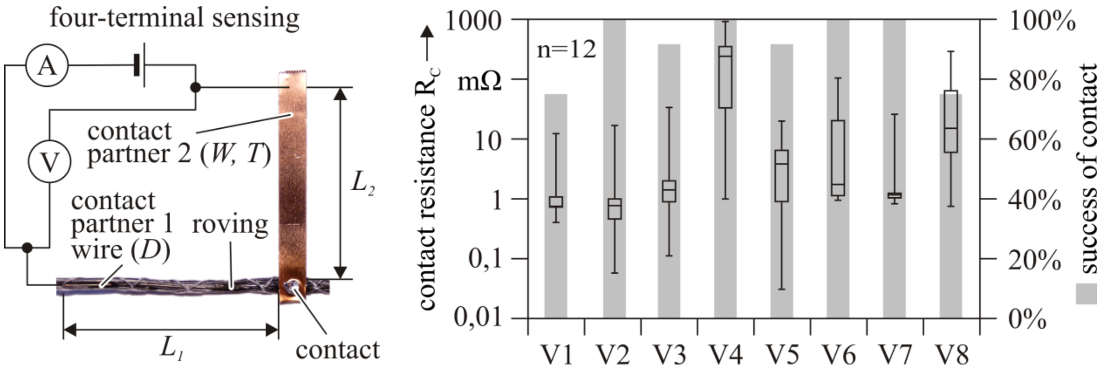

Figure 7. Determination of the contact resistances: left) measurement setup, right) derived values.

Here, a method is taken to be suitable for the connection between functionalised grids and function carriers, if a reliability of 100 % and low contact resistances are achieved. Here, the configurations V2, V4, V6 and V7 are reaching a reliability of 100 %. In comparison with usual contact resistances at soldered joints on PCB's between 0.1 and 10 mΩ [7], the median values are in the same range, apart from V4. Since also the scattering of the values is a criterion for the reliability, a spread of more than one decade is set as exclusion criterion for data transfer or energy supply. Hence, only ultrasonic soldering (V2) and crimping combined with conductive adhesive (V7) seem to be appropriate for application.

5. Application test

Due to comparably simple contact zones on the function carriers and no need of additional elements like crimping pins, ultrasonic soldering (V2) is chosen for joining functionalised grids with contact carriers in an application test. For the test, function integration elements with a plug connector are used (see Fig. 3, 7b and d). The carrier is a PCB with copper soldering pads. The distance of the pads is equal to the warp-roving distance in the textile grid. In contrast to the contact tests on single contact specimens in this case a group of contacts has to be connected repeatable. To prevent the observed lateral movement of the wire during the contact process in section 4, the uncovering of the wire is

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conducted prior to the soldering step. With the support of ultrasonic vibration and a low pressing force the matrix in the roving melts and the glass filaments can glide sideways. The roving flattens to the same thickness of the uncovered solid wire (see Fig. 6 V2). The vibration ends after 2 s but the pressure is retained. The thermoplastic polymer cools down and the wire is fixed in the exposed situation. Afterwards the hand-held welder is removed from the joining zone (see Fig. 8a). This step is repeated for each wire. Subsequently the carrier is placed on a basis with the tinned solder pads upward (see Fig. 8b). Then, the grid is positioned on the solder pads with the exposed wires downwards and the connection is established as described above for each wire until the complete carrier is mounted (see Fig. 8c, d).

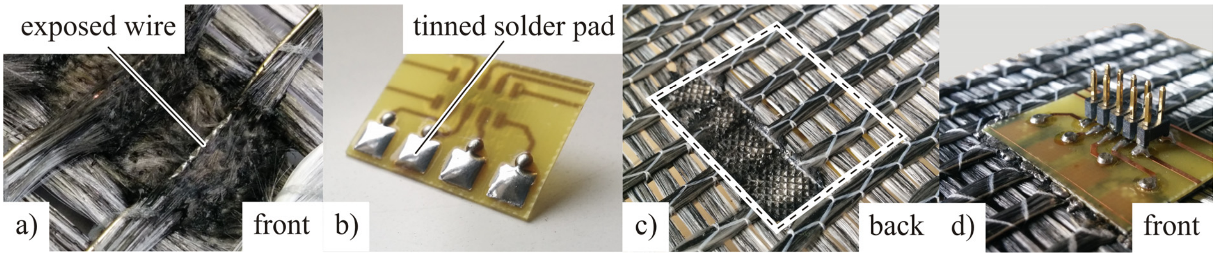

Figure 8. Electrical joint between wires and carrier with ultrasonic soldering: a) exposing the wires, b) application of solder on the soldering pads, c) soldering process, d) mounted function carrier.

The contact resistances of two mounted carriers with eight copper pads are determined according to section 4. The results, shown in Tab 2, are comparable to the results of the specimens contact tests. Unfortunately two joints show no electric contact, which is caused by larger lateral deviations of the wires during the recovering step, so that no connection is established. Furthermore two adjacent soldering pads were unintentionally interconnected because of distributed molten solder.

Table 2. Results from application test

n=8	Lower Extreme	Lower Quartile	Median	Upper Quartile	Upper Extreme	Success of contact
Contact resistance	0.8 mΩ	1.7 mΩ	2.8 mΩ	5.6 mΩ	23.9 mΩ	75%

5. Conclusion

Different approaches to contact a copper wire enclosed in a hybrid yarn roving to a PCB are evaluated. For this, the four electric joining methods soldering, ultrasonic soldering, crimping and bonding with conductive adhesives are tested. The resistance of connected specimens is measured with four-terminal sensing and the contact resistances are determined. The results show, that ultrasonic soldering is the most reliable connection method with the lowest achievable contact resistances. In further tests, this method is evaluated to mount function carriers on biaxial grids made from hybrid yarns with integrated wires. It has been found, that low contact resistances are reachable, but the reliability and repeatability of the process still needs to be improved. A first possibility for optimisation is a better guidance of the ultrasonic device to prevent lateral deviations of the rovings during the recovering step. Secondly by optimising of the applied amount of solder and the use of an ultrasonic horn with a smaller contact zone the welding zone should be kept smaller, eliminating unintentionally interconnection of adjacent soldering pads. Another possibility is a wider distance between the soldering pads.

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