Intrinsic fibre heating: a novel approach for automated dry fibre placement

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Abstract. The present study deals with a novel binder activation approach for automated dry fibre placement. Via application of an electrical current within carbon fibre tows, ohmic heating is used for activation of binder systems. The working principle of intrinsic fibre heating is demonstrated within two prototype devices: A handheld tape laying device for the manual application of pre-bindered carbon fibre tows is introduced. Furthermore the automation potential of intrinsic fibre heating is demonstrated within a unique fibre laying approach: the Advanced Ply Placement (APP).

1. Introduction

Modern production technologies for carbon fibre reinforced plastic components, such as Automated Tape Laying (ATL) and Automated Fibre Placement (AFP) have been established as standard manufacturing processes in commercial aircraft production and the automotive industry. These state-of-the-art large-scale industrial fibre placement processes mainly utilize pre-impregnated unidirectional fibre materials for the manufacturing of preforms with low scrap-rates. Main goal is the production of load-path optimized lightweight components with minimal utilization of reinforcement fibers. A near net shape geometry is the target to reduce cutoff waste and therefore minimize material and manufacturing costs. Compared to a prepreg process chain, preforms made from dry carbon fibres offer substantial potential to reduce lead time and costs. The almost unrestricted processing time of dry fibres allows the production of large parts without restricting layup rates.

The dry carbon fibres utilized in this paper are prepared with a binder system that is necessary for the tack between fibre and the mold or in-between the different fibre layers. The automated placement methods for dry fibres commonly utilize infrared (IR) radiators or diode lasers for binder activation during the layup process. Thereby, heat is generated on top of the carbon fibre tow in order to activate the binder systems. However, diode lasers involve high costs and IR radiators generally heat up the surrounding environment, resulting in a loss of efficiency.

For that reason, a new approach for binder activation during fibre layup is investigated in the scope of this paper. The electrical properties of carbon fibres are being utilized and due to the application of an electric current ohmic heat is generated and subsequently binder systems can be activated.

2. State of the Art and Fundamentals

The following chapter describes the necessary fundamentals for understanding the principle of the intrinsic fibre heating approach described in this paper.

2.1. Binder Systems

Binder systems are auxiliaries in a fibre-reinforced preform to achieve structural and / or geometrical fixation [1]. The binding effect depends on the adhesion of the binder system with the fabrics' and fibres' surface and its cohesion. For the stabilization of rovings, fabrics as well as semi-finished products and subsequent use and fixation in textile processes, different binder systems are commercially available and can be distinguished in powder, veil and hot-melt binder systems. The melting range of binder systems lies between 75°C and 200°C, the majority however is found within 100°C and 130°C.

Powder binder systems consisting of thermoplastic or thermoset powders vary in different particle sizes between 32 µm and 250 µm. Different particle sizes can result in varying preform permeability, due to blocking of flow channels by small particles. Large particles however can increase preform permeability by increasing distance between layers. After binder application onto the semi-finished product, the binder needs to be activated via heat input. The activation process melts the binder and after cool-down and solidification subsequent layers are bonded together.

Binder veils consist of thermoplastic threads or mats, with or without any preferred orientation. Various binder veils are commercially available and vary in polymer composition and areal weight. Typical areal weights can be found in the area between 4 g/m^2 and 50 g/m^2. They are generally composed of co-polymers. The binder veil usually is placed between the reinforcement layers. Subsequently the preform is activated via heat input and consolidation (e.g. thermoforming, calender processes, etc.).

Binder activation can be distinguished in four different operating principles [2]: Heat transfer, radiation, mechanical activation and electrical activation, as it can be seen in Figure 1.
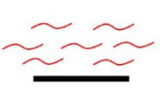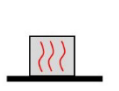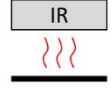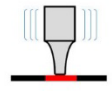

Heat Transfer		Radiation		Mechanical	Electrical	
Convection	Conduction	Absorption		Friction		
Hot Gas	Heated Tooling	Infrared	Laser	Ultrasonic	Direct Resistive	Induction

Figure 1. Binder activation methods

Among the different principles, some binder activation approaches are more commonly used in fibre placement machinery due to better controllability, integrability and lower complexity. Binder activation via infrared radiation (IR) is mostly used. State of the art AFP and ATL machinery utilize this approach due to long time experience, good controllability and efficient IR radiators. However, additional periphery at the lay-up head is necessary and efficiency is lost due to heat convection into the surrounding environment. Another commonly used process is the heat transfer via hot gas. A hot gas torch is pointed towards the nip point of the lay-up head and hot compressed air activates the binder system just before compaction. The disadvantages of this approach are the additional gas pipes and the additional periphery attached to the lay-up head, resulting in lesser flexibility during the lay-up process. Furthermore introduces the gas flow kinetic energy that causes fibre misalignment, especially before initial touchdown of the fibre tape. Ultrasonic (US) vibrations and the subsequent mechanical friction can also be used for binder activation. However, cost-intensive generators and sonotrodes, special end-effectors and the additional periphery prevent US binder activation from extensive use. Furthermore the ultrasonic vibrations might lead to fibre breakage and tool damage, if welding parameters are not set accurately. However, the local binder activation opens new possibilities for fast preform manufacturing with adjustable draping properties.

In the scope of this paper, special focus is paid on the electrical operating principle. Intrinsic fibre heating is based on ohmic heating of electrical conductive carbon fibres. This approach allows fast, efficient and local binder activation.

2.2. Joule Heating

Resistive heating, also known as ohmic heating or joule heating, describes the heat generation if an electric current passes through a conductor. Joule's first law states that the power P of generated heat is proportional to the product of its resistance R and the square of the current I ($P \sim R * I^2$). Joule heating can be described as follows: A voltage difference between two points of a conductor (in this case two electrodes connected to the conductive carbon fibres) creates an electric field that accelerates charge carriers (electrons) in the direction of the electric field, giving them kinetic energy. If electrons are colliding with ions in the conductive material, the kinetic energy is converted into thermal energy.

Generally known, carbon fibres have a good electrical conductivity. The specific electrical resistance lies between ρ = 8 Ωmm²/m (HM-fibres) and 20 Ωmm²/m (HT-fibres) [3]. This means, resistive heating of laminates due to electric currents is possible and is widely used in heated composite tools. Selected layers of carbon fibres are electrically contacted before lamination. After part consolidation an electric current can be applied and the tool can be used for part curing.

2.3. Advanced Ply Placement

State of the art AFP processes depend on small tape widths, leading to various abutting tape edges. Therefore, requirements concerning tape width are demanding for avoiding effects like gaps or overlaps [4]. Double curved surfaces require varying roving lengths within one tape to equalize length deviations between adjacent fibres. For that reason wide tapes in combination with complex part geometries usually lead to wrinkling and buckling defects. Therefore ATL processes are mainly used for large geometries with little complexity.

The Advanced Ply Placement (APP) process avoids these problems due to a unique forming approach. By allowing longitudinal tape shearing it allows draping of wide unidirectional tapes over double curved and complex surfaces.
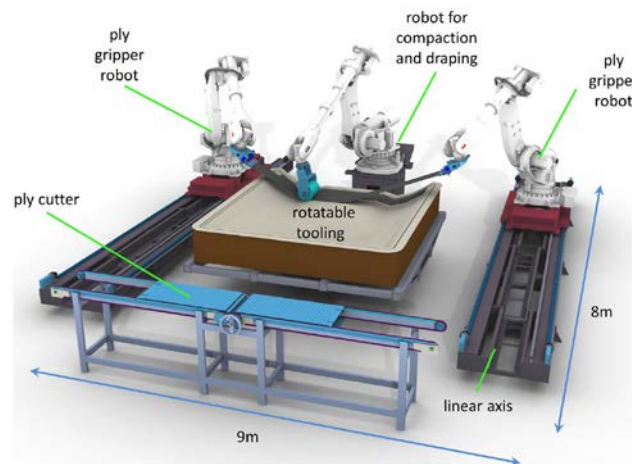

Figure 2. APP process scheme [5]

The APP production cell consists of two ply gripper robots on linear axes, a stationary draping / roller robot, a heated mould on a rotary axis and a ply cutting and pick-up station that can be adapted to different ply lengths. The APP process scheme can be seen in Figure 2. During part production, the two ply gripper robots move to the ply cutter and pick up the tape. The two coordinated robots move parallel to the designated placement position. At the same time the mould rotates to the defined angle for the required fibre orientation of the current ply. Having reached the placement position, the draping robot pushes the ply towards the mould surface applying a pretension that evens out present wrinkles. After initial touchdown of the tape, one gripping robot relaxes the tape, while the roller robot moves along the mould surface towards the gripping robot. Subsequently, the roller robot moves back to the initial point

of touchdown and repeats the same procedure towards the second ply gripper robot. This process is repeated until the designated preform is completed.

One key element of this unique draping approach are segmented gripping units at the two ply gripper robots. Various clamping fingers can move independently and allow tape shearing at predefined tape tension, allowing compensation of tape length differences.

The second key element is the segmented compaction roller that applies a defined compaction pressure onto the tape during fibre layup. The self-adjusting roller geometry is able to adapt to the mould surface ensuring constant and equal pressure over the whole contact surface between compaction roller and mould surface. This ensures tape adhesion and preform consolidation.
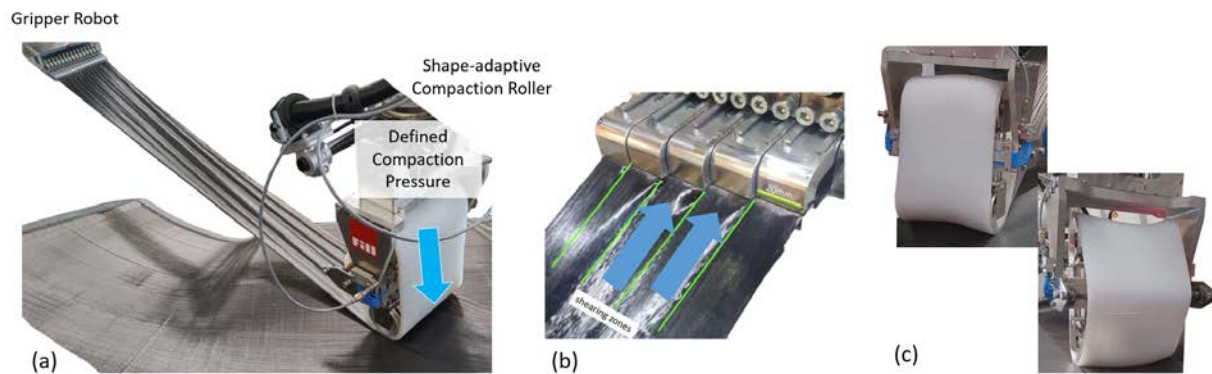

Figure 3. Working principle APP. (a) Wrinkle compensation (b) Tape shearing (c) Shape-adaptive compaction roller [4]

3. Intrinsic Fibre Heating

Intrinsic fibre heating is no new development, since joule heating is a widely used principle for heat generation. In the scope of the CFRP part production it is already used in heated composite tooling. However, there is no widespread use in automated tape laying devices. Cost intensive diode lasers or IR radiators are still state of the art for ATL and AFP processes. Most binder activation systems require additional periphery that limits the operating space of the layup head (radiators, spotlights, hot gas torches, etc.). Furthermore additional piping and generators need to be installed.

The intrinsic fibre heating approach grants several advantages compared to other binder activation systems, allowing local binder activation. Since the heat is generated directly within the carbon fibres, there is no significant efficiency loss due to convection. The overall process is well controllable due to proven equipment like adjustable power supply, etc. By disconnecting the power supply, fibre heating is instantly turned off without any delay. The electrodes can be integrated into the robotic end-effector. And at last, no special equipment needs to be provided, since potent power supply is already available (presumed the layup-head is integrated into a robotic production cell).

3.1. Relation between Power Input and Heat Generation

Carbon fibres can be described as NTC (negative temperature coefficient thermistors). This means, with increasing fibre temperature the electrical resistance decreases [6]. If carbon fibres are heated and a constant current is applied, the heating power P will increase as the resistance decreases. If the fibres are attached to a constant voltage source U, the thermal output will increase successively due to the thermistor behaviour.

Figure 4 shows the relation between fabric temperature T and the applied power input P. A unidirectional (UD) fabric with TENAX-E-HTS40 F13 12 k fibres has been used. Different tape widths are investigated (16 mm, 27,5 mm and 40 mm). A controllable laboratory power supply (VOLTCRAFT PS 2403 Pro) has been attached to the fabric and the temperature is measured with a thermal imaging

camera (FLIR Systems Thermovision A 40). The graph shows the increasing temperature with increasing input power. Furthermore, it can be seen that wider tapes require increased power input.
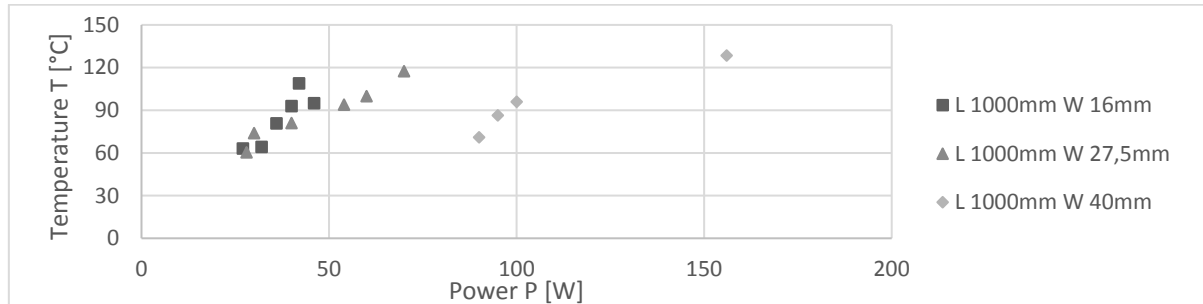

Figure 4. Relation temperature T and power input P

3.2. Electrical Contacting

In terms of electrical conductivity, silver and copper are the superior conductive metallic materials (silver: $61 * 10^6$ S/m; copper: $58 * 10^6$ S/m). Considering material costs, copper is the preferred electrode material. To use carbon fibres for resistive / ohmic heating with a homogeneous heat distribution, the transition resistance at the contact points should be as low as possible. For joule heating of carbon fibres, preferably low voltages and high currents (> 50 A) are used [6]. A higher transition resistance will subsequently lead to excessive heating at the contact points. State of the art carbon fibre contacting in tool making is mostly realized via metallic sleeves or integration of metallic knitting threads. Adhesion of the thermoplastic fraction of the semi-finished product and power dissipation at the contact points needs to be minimized. Lowest contact resistance can be achieved via large contacting areas and high electrical conductivity of the electrodes' material. The goal therefore needs to be the implementation of an optimal power introduction, as well as detachable and cost efficient contacting approaches.

Generally speaking, contact partners do not touch each other at the maximal possible area. Waviness, roughness and impurities especially in fabrics made from carbon fibres caused by knitting yarns, weave style and textile behaviour of fibres results in several contact areas. Forceless contact will only result in contact of outer peaks. With increasing contact pressure, elastic and plastic changes of waviness will occur, resulting in increased bearing surface. This leads to power transmission via a variety of small areas. The number, distribution and its size depends on several factors: contact force, contact shape, temperature, material properties and surface structure. The resulting effective contact surface results from the actual bearing surface minus the surface fractions covered with impurity layers (thermoplastic binder, knitting threads, etc.) [6] At these many, but small, contact areas power bottlenecks are created at which a higher current density has to pass, leading to excessive heat generation and hot spots. This so called constriction resistance can be reduced with higher compaction forces resulting in higher contact areas, as well as increasing electrical conductivity.
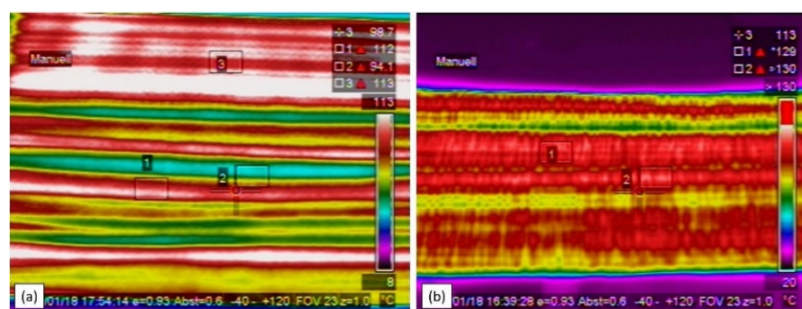

Figure 5. Effects of varying contact pressure during intrinsic fibre heating. (a) Insufficient pressure – Uneven heat distribution (b) Sufficient pressure – More even heat distribution

Furthermore, filaments that are not perfectly aligned in tape length will also cause misleading of currents and the creation of hot spots, since electrical currents always go along the path with the least resistance. These cross-currents have to be prevented. One approach is the segmentation of contact surfaces, in a manner that only few rovings are heated by one electrode-pair at a time. Several parallel aligned electrodes along the tape width result in an even heat generation.

Figure 5 shows the effect of varying contact forces during intrinsic fibre heating. In the left picture (a) various overheated areas can be seen, while at the same time colder fibres are occurring. The right picture (b) shows a sufficiently contacted carbon fibre semi-finished product with a more even heat distribution. The fabric had a width of 300 mm and was manufactured with TENAX-E-HTS40 F13 12 k fibres. However, the increasing contact pressure, in combination with rigid copper contact elements and the created heat can lead to undesired deformations in the semi-finished product.

Most of the fibre contacting is done via mechanical clamping with copper elements (sleeves, plates, profiles, etc.). This is state of the art and well experienced. However, the rigid copper contact element cannot adapt to varying mould surfaces and the waviness of textile semi-finished products.

One approach for better contacting is the achievement of electrical conductive silicones that can be manufactured as blocks, membranes, etc. With good electrical conductivity and the resilience and stretchability of silicones, adequate contacting due to sufficient bearing surfaces can be achieved at lower contact forces and local hot spots can be avoided.

There are few electrical conductive silicones available, eg. ELASTOSIL LR 3162 [7]. To achieve electrical conductive silicones, it is possible to add conductive additives to silicones. For achieving contact between the added particles and therefore formation of a current path, additives must be added in high quantities. However, high concentrations will affect the composition of the silicone. The percolation curve describes the relation between electric conductivity and additive concentration. Increasing the weight-fraction of conductive particles will result in touching of the particles. Above a critical point K_c, further increasing of additive concentration will only achieve little improvement of conductivity, while the consistency of the silicone will change [8]. If the fraction of added particles is only little compared to the overall mass, electron transport happens via tunnel-effect [9]. If the distance between conductive particles is large compared to the atomic dimensions, the silicone's resistance is dominant. Decreasing the distance (< 10 nm), the electrons are able to penetrate the silicone.

In the scope of this paper various additives are investigated. The commercial silicone ELASTOSIL VARIO 15 / CAT PT is used as base material. Subsequently, different additives have been added with increasing weight fractions, increasing in steps of 5 %w. One approach was the addition of a graphite powder (GraphCOND 15/98). Another approach was the adding of silver coated additives, like glass flakes (ECKART eConduct Glass 35200), copper (ECKART eConduct Copper 12200) and aluminium balls (ECKART eConduct Aluminium 202000). Different industrial carbon black pigments have also been investigated (Co. PyroPowder; Printex XE-2B), as well as copper and iron powder.
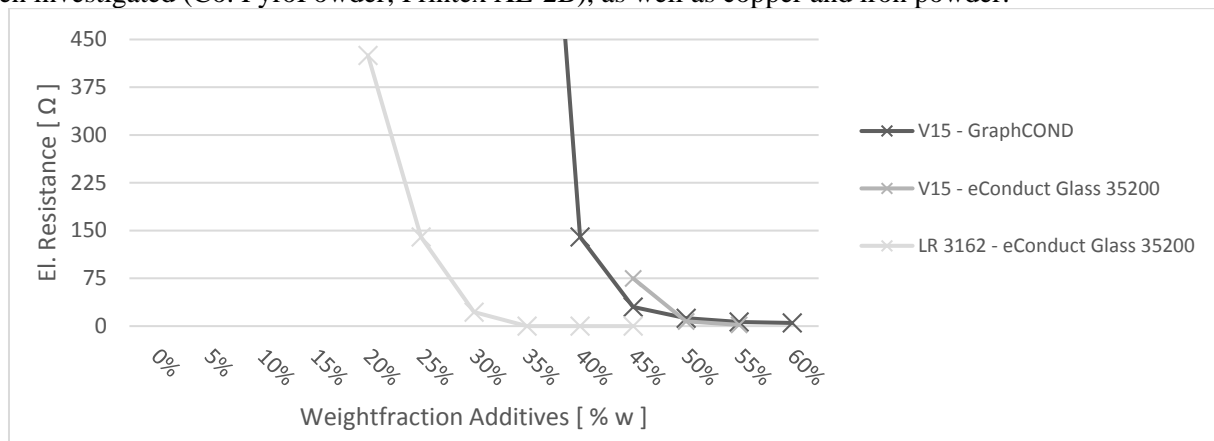

Figure 6. Electrical resistance of silicones

Successful establishment of conductivity has only been realized with two additives: GraphCOND 15/98 and ECKART eConduct Glass 35200). Figure 6 shows the development of resistance with increasing weight fractions. As it can be seen, the electric resistance decreases with increasing additive fraction. Especially the ELASTOSIL LR3162 in combination with silver-coated glass flakes looks promising, since already low weight fractions of the glass flakes results in acceptable conductivity. Different series of experiments have been showing, that increasing the additive weight fraction beyond 30 %w results in severe impacts of the silicone texture. Up to 30 %w the VARI 15 has its silicone-like consistency. By further adding of additives the consistency became more porous and fragile. Going beyond 50 %w the silicone did not cure properly and maintained a dough-like consistency. Similar results have been observed by Schüler [9].

3.3. Effects of Intrinsic Fibre Heating on Carbon Fibres

As described earlier, insufficient contacting can lead to power bottlenecks, at which higher current density has to pass, which subsequently will lead to increased heat generation (hot spots). Figure 7 shows a hot spot in the area of electrical contacting with burned knitting yarns, binder system and possibly damaged fibres. Insufficient contact pressure during power application has been applied and electric arcs have been observed. Increasing pressure or flexible electrode materials can resolve this problem.
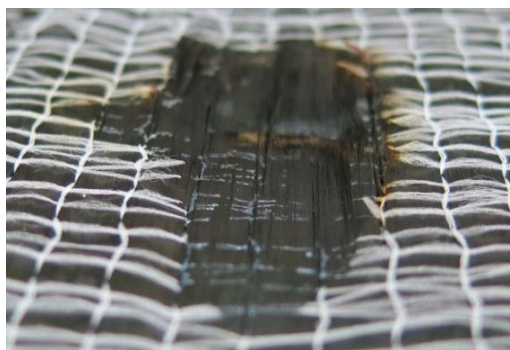

Figure 7. Hotspot; local melting of knitting yarns

4. Handheld Tape Laying Device

In the scope of this work a prototype-device for manual layup of dry carbon fibres has been developed, see Figure 8 a. Main focus was put on using ohmic heating for fast and efficient binder activation. A lightweight and small construction is necessary for one-handed use and sufficient flexibility.

The fibres are stored on a coil on the upper end of the device. Fibre separation is realized via a cutting mechanism. The mechanism can be released either via compressed air or CO_2 cartridges. Cartridges offer the benefit of greater mobility, since pneumatic hoses are not necessary. However, the maximum number of releases is limited to approx. 60 cuts. A quick reload mechanism allows fast replacement of empty cartridges for minimization of downtime.

Electrical power can be supplied by a power supply unit or lithium polymer batteries. For greater mobility and flexibility the lithium polymer accumulators are preferred since additional wiring can be avoided. A commercial model making battery (SLS XTRON 3200 mAh 3S1P 11,1V 20C+/40C) has been installed, due to its light weight and efficient characteristics.

The handheld tape laying device allows one handed tape layup of varying tape widths and different binder systems [10]. In this case a spread tape of 20 mm, equipped with the EPIKOTE TRAC 06720 powder binder has been use for tape layup, see Figure 8 b. The activation temperature of 120°C has been achieved with the lithium polymer accumulator. An overall power input of about 40 W has been measured for successful binder activation and tape layup onto a glass fabric.

The tape is led from the fibre storage coil via a feeding mechanism into the cutting section. For fibre cutting only the trigger at the handle needs to be released and the compressed air will then release the cutting mechanism. After the cutting section, the first electrical contact is installed before the tape reaches a silicone compaction roller. The second electrode is placed shortly after the nip point, the point at which the compaction roller applies pressure onto the tape and attaches it to the substrate. With this constellation, the tape is being contacted and joule heat generated during pressure application, ensuring sufficient binder activation and optimal adhesion.
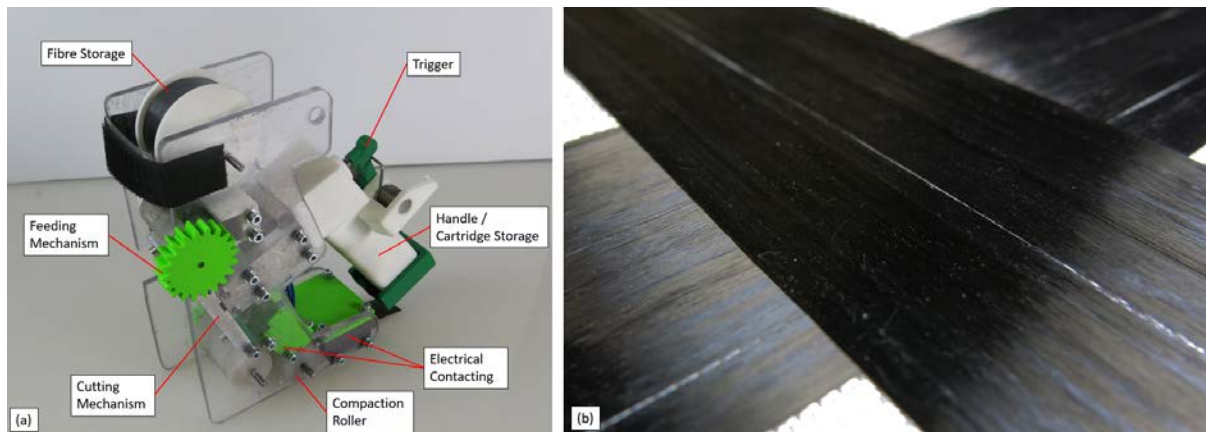

Figure 8. Handheld tape laying device prototype (a); Manual tape layup (b)

5. Automation Potential

To demonstrate the automation potential of the intrinsic fibre heating approach, a unique end-effector for the APP production cell has been designed and constructed (Figure 9 a). Goal is the manufacturing of omega-shaped stiffener elements in various lengths. The two gripping robots maintain their original functionality. The compaction roller however is replaced with the new end-effector.
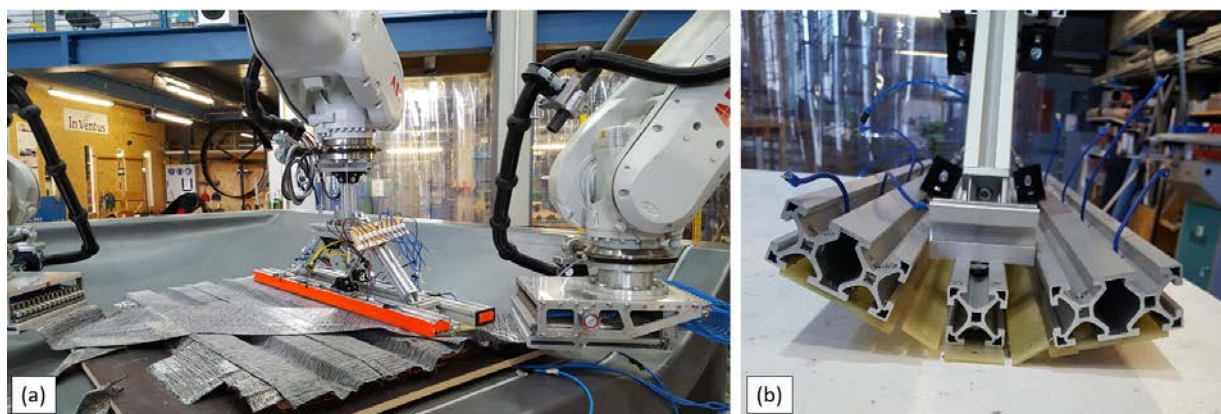

Figure 9. Automated omega stringer production using APP periphery and intrinsic fibre heating approach (a); Side view of end-effector

The end-effector consists of five segments (Figure 9 b) and imitates the manual draping process of omega stiffener elements. Meaning that initially the fabric will be consolidated at the lowest point of the omega. Subsequently, the lateral surfaces and upper flanges are pressed against the mould. For manipulation of the draping mechanism, pneumatic cylinders are installed. The automated end-effector can reach two positions. In the first position, the flanges are lifted up, preventing fibre friction and damage during initial contact and layup. In the second position, the end-effector already pushes the

fibres at the bottom segment against the surface of the mould. The pneumatic cylinders are then activated and pressure is build up, so that the lateral surfaces and flanges are pressed against the mould and consolidation is achieved.

The electrical contacting is realized via copper plates, integrated into the surfaces of the five segments. The applied pressure of the pneumatic cylinders also ensure proper contacting pressure. As soon as sufficient consolidation is achieved, the power supply is connected and the binder can be activated via intrinsic fibre heating. Depending on the fibre angle of the various layers, different contacts located in tooling and end-effector have to be connected to the power supply unit for binder activation.

6. Discussion and Conclusion

As shown in the scope of this paper, intrinsic fibre heating can be used for automated placement of dry carbon fibres. The application of a power supply in combination with the electrical properties of carbon fibres is used for ohmic heat generation within the fibres. The direct heating of carbon fibres allows fast, efficient and local binder activation during fibre layup.

In two prototype end-effectors the fundamental functionality of intrinsic fibre heating in the operational environment have been demonstrated. Intrinsic fibre heating can be used for AFP and ATL processes for dry carbon fibres. Furthermore integration in the APP process has been shown.

Fibre contacting is an ongoing field of research. Insufficient contacting due to missing compaction force will lead to electric arcs and local overheating. This leads to possible fibre damaging and melting of knitting yarns. Effects concerning mechanical properties on the final part have to be validated. Further work will include optimization and automation of the handheld tape laying device and possible benchmarking against state of the art AFP processes. Moreover tests with conductive silicones will be performed, since this is a crucial factor in optimization of the intrinsic fibre heating process.

Acknowledgments

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