

TFP Technology As The advanced Method Of Manufacture Of 3D Reinforced Preforms From polymer Composite Materials

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Abstract: This paper contains an overview of world trends in the development of the TFP technology enabling 3D printing of carbon fiber reinforced plastics. The review of the equipment used for the automated preform patching is included. Primary factors restraining the large-scale implementation of the TFP technology in the manufacture are identified, and prospective research trends for further development of the technology are proposed.

Keywords: Tailored fiber placement, polymer composite materials, fiber preform, 3D reinforced composites, automated patching.

Introduction

The field of application of composite materials in various industries (aircraft, space industry, shipbuilding, energy, construction, mechanical engineering, etc.) is growing from year to year. Currently, 3D reinforced composites are gaining ground in the manufacture of parts and structures from polymer composite materials (PCM). They are reproduced based on 3D fiber preforms with various orientations and angles of reinforcement during the manufacture of the preform and with the complex shape ability [1-6]. In addition to netting, 3D weaving and knitting, modern methods of manufacture of 3D reinforced preforms [7-11] include the Tailored fiber placement technology (TFP), a directional fiber laying on the base material in the specified path (Figure 1) [12, 13]. Reinforcing fiber (roving) is sewn to the base material moving in the x- and y-directions to perform a zigzag stitch using an additional thread. After laying of the appropriate layers with fiber strands, the finished fiber preform is placed into the equipment and impregnated with a polymer binder, and then cured.

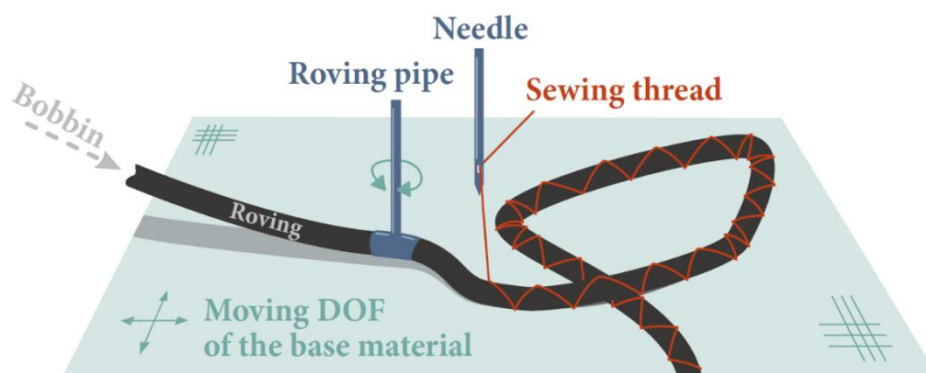


Figure1 – Scheme of the TFP-process

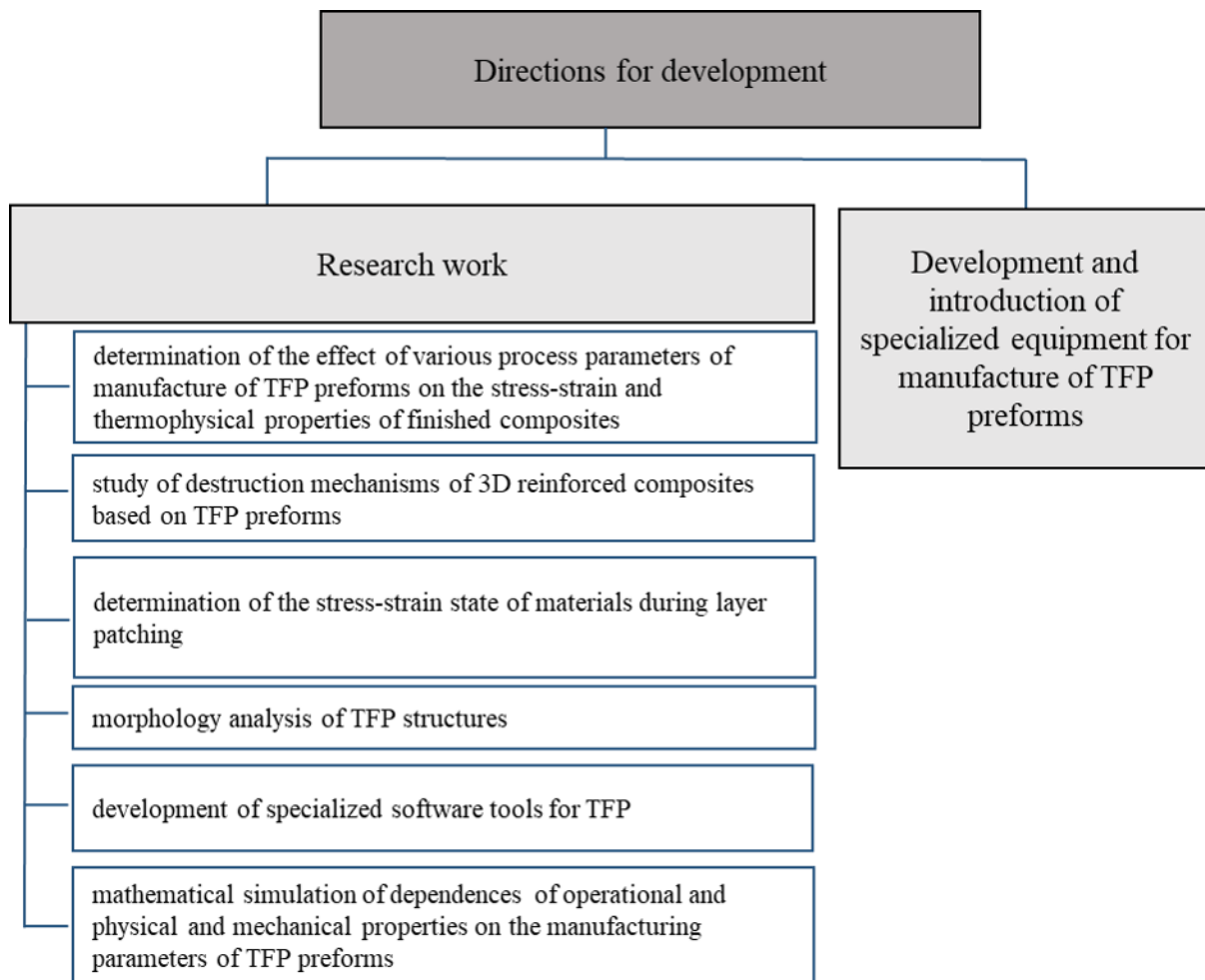


Figure 2 – Promising directions of TFP-technology development

The advantages of the method include fiberpatching based on the load distribution vectors and the possible creation of local reinforcement zones –laying of additional fiber strands can be used to form special reinforcement areas of the zones subject to a special load. Furthermore, the TFP technology enables the creation of integrated structures without auxiliary operations and the use of the material's property to the full. The highly automated manufacturing process involving several embroidery heads makes the technology attractive for the serial production of 3D reinforced blanks. TFP preforms are widely used abroad –certain companies have mastered the process and introduce it into production [14-17]. However, despite the clear advantages of directional patching, composites and products based on the TFP technology are not available in the Russian market. This can be explained by the ignorance of most researchers and developers and the poor coverage of the method in the Russian scientific and technical literature, which results in the almost complete absence of scientific research. In view of the foregoing, this paper is aimed at the review and full assessment of the state-of-the-art and systematization of the available materials in the field of manufacture of 3D reinforced composites based on TFP preforms.

Development TFP in the world

The TFP technology was developed in the Leibniz Institute of Polymer Research Dresden (Leibniz-Institut für Polymerforschung Dresden e. V. - IPF) in the 1990s [12, 18, 19]. In 1992-1998, IPF mastered and improved the method [12, 20-22]. To create curvilinear patterns, preforms were first produced by manual directional laying of the roving. This principle was further adapted and implemented for industrial embroidery machines. In 1998, Hightex Verstärkungsstrukturen (Klipphausen, Germany) involved in the manufacture of TFP preforms was created as part of IPF. FilaCon (Winterlingen, Germany) began the production of embroidery machines for the manufacture of fiber blanks using the TFP technology. Currently, FilaCon is a registered trademark of Tajima GmbH.

In 2001, Hightex jointly with Eurocopter (now Airbus Helicopters, Donauwörth, Germany) began to supply TFP preform-based spars for NH-90 helicopter to NH Industries (Aix-en-Provence, France).

From 2003 to 2007, the so-called KRAFT, EMIR and ROVING projects [18] had been developed. They were put into practice in the form of the TFP technology used for the production of window frames with Ω -shaped cross-section and Z-frames for the fuselage of Airbus Hamburg A350XWB aircraft (since 2010, window frames are in serial production).

From 2005 to 2008, IPF employees had conducted research in the field of optimization of the fiber reinforced composite material using the basics of bionics (BIOTEX project). Project developers desired to simulate the manufacture of lightweight structures from PCM using the example of various natural structures (trees, grass and bones) with the forms properly adapted to specific loads. The purpose was to achieve the maximum hardness and strength by orienting fibers in the main directions of stress. To gain the best result and uniform stress distribution with the lowest material consumption, the first computer programmes were developed for simulation and optimization of properties of the prospective composite based on the TFP technology. Cetex Institute, Daimler Chrysler AG, Herzog, SAERTEX, SINTEC, Volkswagen acted as partners.

In 2009, Q Point Composite GMBH (Dresden, Germany) was created as part of IPF. It used directional fiberlaying in serial production of parts for the aircraft industry (window frames for Airbus A350, spoilers for Airbus A330). In 2011-2012, IPF in partnership with Avana Industries, GMI AERO, IDEC, Q Point, Elektronik, Tecnaia, Tajima and others launched the EMBROIDERY project. It stipulated the development of the TFP preforms manufacturing technology for a reusable vacuum infusion heating membrane [15] and an integrated heating layer in RTM plants to ensure faster heating/cooling and lower energy consumption [16]. From 2012 to 2015, IPF employees jointly with 26 companies of the textile and composite industries had been engaged in patching of strain gauges, lighting systems and wires using the TFP technology and in the development of 3D thermoplastic composites. In 2013, IPF manufactured and tested the 17-blade rotor of the blade-integrated disk design, operating at higher rotation speeds than the aluminum analogue. By 2015, carbon fiber reinforced KUKA KR 180 RA robotic arm had been manufactured. It should be noted that the manufacture of TFP preforms mainly involves the use of carbon fibers due to their increased stress-strain properties compared to other inorganic fillers. However, other types of fiber fillers, such as glass and basalt and combinations thereof, can be used as the reinforcement material during patching.

Evolution of the support layer for tfp-preforms

Carbon or glass fabrics, thermoplastic films [24], elastomer sheets and water-soluble substrates are used as the base material (support layer) on which the first preform layer is fixed. Woven materials were originally used in the manufacture of tfp-preforms. Before the finished preform is placed into the equipment, the woven material of the base layer extending beyond the edge of the fiber blank is cut or torn off. In the first case, the support layer becomes the part of the fiber blank. It performs no functions, but increases the product weight. This is especially crucial when several fiber blanks are placed on each other. In addition, separation may occur in the area of base layers of the finished composite part. In this regard, the base material is recommended for use as an auxiliary material to be removed because of the absence of the functional load. However, another problem arises – in case of base separation, the mechanical damage to reinforcing fibers, violation of the blank integrity and geometry are highly probable. Joern Paul and Eberth Ulrich obtained the patent for the method of producing single and multilayer preforms using the TFP technology. They proposed to fix the fiber blank before the removal from the elastic and flexible base, for example, a sheet of rubber or silicone [25]. This technical solution allows to prevent unnecessary displacement of fiber strands to a significant extent. Thermoplastic powder that melts at the low temperature, curable adhesive, etc. can be used for strand fixation. The authors of [26] propose to apply a separation layer of a thin polytetrafluoroethylene film on the base layer followed by fiber patching thereon. Then a fiber blank is placed into a fixing device for melting fixing threads by heating. The separation layer of the non-adhesive material enables the easy detachment of the base layer from the fiber blank without damaging fiber strands or preform deformation. In recent years, water-soluble substrates easily removed from fiber preforms by washing have been used as the support layer [27, 28]. Water-soluble polymeric materials, for example, based on 100% polyvinyl acetate (PVA), can be used as the substrate. The solvent water is completely removed from the fiber blank by drying.

The perspective of water-soluble substrates in comparison with the currently used woven materials, elastomers and films is explained by the fact that the washout of such substrates is a simple, affordable and easily feasible technological operation, in which the integral structure of the tfp-preform with the geometry of the final product is preserved. The water-soluble substrate is removed from the fiber blank without disturbing its configuration and without causing damage to the fibers.

Stitching threads for tfp-preforms

As for the stitching thread materials, glass, poly(p-phenylene terephthalamide) (PPTA), polyamidobenzimidazole (PABI), polyamide nylon and capron fibers, high-strength and high-modulus aramid threads, etc. are currently used. Scientists conducted numerous research to study the effect of various types of threads and stitching parameters on the properties of carbon fiber reinforced plastics; obtained documents of title for the results of

intellectual activity, and gained experience in the manufacture and testing of TFP preforms-based products for the improvement of physical and mechanical characteristics. [29] specifies that reinforcing fibers are patched onto the substrate using chemically or thermally free-melting fixing threads, which are initially used for fixation of reinforcing fibers on the substrate. They are subsequently dissolved, thus not affecting the mechanical properties of the structure of the reinforcing fiber. The authors of [29] studied the effect of the type of the stitching thread on the carbon content in finished PCM samples and their mechanical properties. Unidirectional TFP blanks made of Tenax HTS 5331-24K carbon fiber were manufactured on the substrate material (fiberglass with the density of 80 g/m²) using various stitching threads to fix the roving. The fixing threads represented Grilon K85 110 dtex free-melting multifilament threads with the standard melting point of 85 °C, Transfil 56 dtex polyamide unit thread, Serafil 100 dtex polyamide thread and polyester filament typically used for manufacturing multiaxial fabrics (textured PSE 76 dtex). It should be noted that, unlike the first type of thread, the latter threads do not melt at the temperatures reached during further processing. As an additional option, Grilon K85 110 dtex reinforcing fibers were stitched on the Super Release Blue detachable fabric. Carbon fiber rovings were placed parallel to each other at the distance of 3.375 mm and fixed on the base with the zigzag stitch 4 mm long and 2 mm wide, a total of 4 unidirectional layers one above the other. Two of the reinforcing fiber structures or semi-finished products were then laid into the pattern equipment, impregnated with HexFlow RTM6 multicomponent resin (Hexcel, USA), and cured. Finished laminate panels were selected in the direction of fibers and subjected to tensile and compression tests. The comparison of physical and mechanical properties of different samples showed that the significant increase in the stress-strain properties was achieved with Grilon threads – the tensile strength is increased by 30%, compressive strength by 23%, tensile modulus by 8% and pressure modulus by 26%.

In [28, 30] authors used aramid thread Ruser-S 29,4 tex (Thermotex LLC, Mytishchi, Russia), polyamidobenzimidazole thread Armos 60 tex (Lirsot LLC, Mytishchi, Russia), poly (p-phenylene terephthalamide) Armalon 7,9 tex (Tema-M LLC, Mytishchi, Russia) as sewing threads in the manufacture of fibrous preforms. When stitching preforms aramid threads was achieved the greatest increase in shear strength of finished carbon fiber – up to 15%.

Speckenheuer et al. presented the first results of research on the possibility of using hybrid threads for the manufacture of TFP-preforms, allowing to obtain high-quality composites. The commingled yarns are made by simultaneous spinning of E-glass fibers (GF) and Polybutylterephthalat (PBT) filaments with different sizings and have increased adhesion to the matrix [31].

Thus, it should be noted that currently TFP technology applies standard threads used in the textile and chemical industries. Among them, the most promising are aramid and hybrid threads, which allow to obtain composites with increased physical and mechanical properties. Special threads for TFP have not been invented yet, so the development and use of new yarns and fibers is of considerable interest.

Physical and mechanical properties of stitched reinforced plastics

Mattheij et al. presented [32] the results of studies of the influence of orthogonal reinforcement of preforms on the physical and mechanical properties of PCM samples as well. The preforms were obtained by carbon fiber roving patch, sewn with aramid, polyethylene and polyester fibers and impregnated with a binder using vacuum assisted resin transfer moulding (VARTM). Besides, the experiments were focused on the effect of the thread tension, the distance between adjacent paths and the stitch length. The results showed that aramid fiber stitching reduces the tensile and bending strength of samples by about 3-8%. No significant increase in the impact strength was observed. In paper [31], SpinCom hybrid threads [33] consisting of glass and polybutylene terephthalate fibers were used to produce TFP preforms of thermoplastic composite samples. The possible use of hybrid threads to produce thermoplastic composites based on TFP preforms was demonstrated on the example of a bicycle saddle. The test results showed that the combination of the size-adapted SpinCom combination yarn and the Tailored Fiber Placement technology allows to obtain high-quality thermoplastic composites with the precise location and efficient use of the material. The studies of the effect of the stitch length and width and the type of thread on the degree of waviness (unevenness) of the material, the volume content of fibers, and the laminate hardness and strength were conducted in [13, 34, 35].

A great number of papers describe the studies of carbon fiber reinforced plastics with holes. For example, the use of the TFP technology for the manufacture of plates with holes and the possibility of increasing strength near the holes were studied by Crothers et al. in [22]. In [36], Gliesche et al. studied the use of the automated roving patch technology to identify the effects of additional local reinforcement near the hole. For this purpose, local carbon fiber patch was laid on the quasi-homogeneous multiaxial fabric with the hole for additional reinforcement around the hole. The experiments showed that the holes in plates made by traditional pressing reduce the tensile strength up to 61% of the strength of the holeless sample. However, additional reinforcement of the preform by patching allows to achieve the strength of samples up to 94% of the strength of the holeless sample with a slight increase in weight. El-Dessouky et al. studied the technology of manufacture of laminated plastics with the hole based on the thermoplastic binder [37]. The authors of [38] presented the results of studies of samples with holes

in tension and cyclic tests. The samples were made from multiaxial fabrics, woven preforms and using the automated roving patch method. Three different reinforcement patterns were studied. As a result of cyclic tests, three of four woven patterns were destroyed; other samples remained intact. The authors noted that the strength of samples with the laying pattern $[\pm 45^\circ]$ was lower than for holeless samples, but higher than for samples with the laying pattern $[0^\circ; 90^\circ]$ and $[+45^\circ/0^\circ/-45^\circ]$. In [39], Koricho et al. studied the effect of different roving patterns on the strength and crack resistance of samples with the hole. Samples with the hole produced by automated roving patch had a tensile strength of about 92.7% of the strength of the holeless sample, while samples with the drilled hole had a strength of 38% of the strength of the holeless sample.

Papers focused on simulation and optimization of curvilinear fiber-reinforced composites based on TFP preforms are of interest. Albers et al. [40] and Spickenheuer et al. [41] made the first attempts to separate optimization of the curvilinear fiber-reinforced composite based on the TFP technology from real numerical models in order to limit the number of required design variables and make them independent of the FEM mesh resolution. Spickenheuer et al. proposed a software system that combines a stress-strain state module and a roving patch programme module [41]. Uhlig et al. presented the results of calculation of stresses of the material structure during TFP, the uniaxial tension using the finite element method [34]. To assess the specific features of the TFP process, a mesoscale model was used according to the author's recommendations. [42] presents the concept of numerical simulation of TFP preforms – Direct Fiber Path Optimization (DFPO). Its main achievement is the local optimization of the angle and thickness of fibers at each finite element along the base mesh. A new optimization approach was demonstrated and numerically evaluated on the example of the sample with a through hole under tensile loading. DFPO is a real optimization procedure that considers not only local, but also global features of the sample. Compared to other optimization methods in which the elementary fiber orientations and thickness values are optimized without correlations caused by infinite fibers, in DFPO each fiber placement pattern covered by each optimization iteration is already easily producible and requires no further adaptation.

The significant disadvantage of TFP technology is the manufacture of preforms not thicker than 8-10 mm per process operation due to the limited technical capabilities of embroidery equipment and the needle length. Besides, the operating principle of embroidery machines stipulates the connection of each successive patch layer not only to each other, but also to the very first layer: the stitching zigzag thread in the third direction always passes through the first layer. The more layers are made, the more needle punctures each previous preform layer has. The first layer features the maximum damage to the base fiber. This adversely affects the strength properties of the finished composite due to the multiple destruction of fibers during the manufacture of the preform.

Despite this, physical and mechanical properties of stitch carbon fiber reinforced plastics correspond to the properties of traditional polymer materials and their shear strength is even higher. In addition to achieving optimal elastic-strength properties, TFP technology allows to create local reinforcements (for example, around the holes), to combine a variety of materials and reinforcement directions.

Development of TFP technology in Russia

In Russia, the TFP technology of manufacture of 3D reinforced preforms using PCM is still largely unknown, but some attempts are made in this field [43-46]. The primary and almost the only restraining factor for the large-scale introduction of TFP preforms-based composites into production not only in Russia but also abroad is the lack of specialized equipment. Currently, preform patching is carried out on industrial CNC embroidery machines used in the textile industry. For example, Hightex Verstärkungsstrukturen GmbH (Germany) uses own sewing machines (Hightex) for manufacturing TFP preforms of window frames and floor elements for Airbus A350. ShapeTex™ (Witney, Oxfordshire, England) uses ZSK Stickmaschinen embroidery machines (Germany) in its studies, and the Leibniz Institute for Polymer Research (Dresden, Germany), the Institute of Aircraft Design (IFB) (Stuttgart, Germany), and Centre of Composite Technology KNRTU-KAI (Kazan, Russia) use Tajima sewing machines (Tajima GMBH, Japan) in their developments, which are supplied by LayStitch™ (Michigan, USA) and Filacon Systems (Winterlingen, Germany). These embroidery machines were adapted for the composite industry and enable the use of carbon, glass, polyamide and aramid threads as patch materials. It should be noted that the high cost prevents the introduction of the equipment for manufacturing 3D reinforced preforms into the Russian market. For example, the simplest industrial embroidery machine Tajima TCMX – 601 (Japan) with the working area of 460x550mm costs more than \$ 16,000, a single-head embroidery machine JCW 0100-500 (ZSK Stickmaschinen, Germany) with the working area of 700x500 mm costs more than \$ 20,000. The cost of a more powerful, advanced embroidery machine adapted for patching of composite materials ZSK SGFA0112-1300 (ZSK Stickmaschinen, Germany) with a larger working area of 1300x1400mm and increased speed ranges between \$ 50,000-55,000.

Bauman Moscow State Technical University is developing an automated complex for the manufacture of tfp-preforms with less damage to the fibers. The new complex will eliminate the shortcomings of existing embroidery machines and will allow to obtain volume-reinforced preforms with a thickness of at least 50mm in one technological operation. At the same time, the improvement of technological and operational characteristics

of composites will be achieved through the use of a fundamentally new scheme of fastening the fiber to the substrate and the principle of operation.

Conclusion

The review of the scientific and technical literature suggests that currently there are wide opportunities for scientific research and technical solutions in the field of manufacture of 3D reinforced composites based on TFP preforms. Two main directions for further development of the TFP technology can be considered (Figure 2): on the one hand, development and introduction of new specialized equipment (high-tech and commercially available), on the other hand, research work, the results of which will allow to bring the TFP technology to a new level and create PCM parts and structures having high physical and mechanical properties and technical and economic performance.

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