ZSK STICKMASCHINEN

White Paper

THE DAWN OF THE COMPOSITE ERA?

How an alternative approach to tailored fibre placement could bring composite materials to the mainstream

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TABLE OF CONTENTS

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Composite materials have long been heralded as the future for a wide variety of manufacturing applications. They offer an unparalleled strength-to-weight ratio that has attractive benefits for everything from spacecraft to sports equipment. However, outside of a few low-volume applications, the reality is that composite manufacturing has struggled with high costs, considerable material wastage, low productivity and complex labour-intensive processes.

Fig.: ZSK Technical Embroidery System with up to 15 laying heads.

When tailored fibre placement (TFP) was developed in the early 1990s, it raised the prospect of a more efficient, cost-effective means of producing composite parts, featuring low scrap rates and the potential for a high degree of automation. The theory was sound, but the required know-how did not exist to productionize it at the time.

Now, however, a series of innovations is helping to unlock the vast potential of TFP. This paper examines the factors that are driving the technique's adoption. In particular, it looks at the pioneering concepts introduced by technical embroidery specialist ZSK STICKMASCHINEN and how these have the potential to bring TFP to the mainstream.

The fundamental benefits of using composite materials remain as compelling as ever. Carbon fibre reinforced polymers (CFRP), for example, can be 10 times stronger than steel yet just a fifth of the weight [1]. There are applications in almost any industry where this combination has the potential to bring huge benefits.

The lightweight properties of composite materials are particularly applicable to transportation, where any additional mass adds to the vehicle's energy consumption and hence its carbon footprint. For road vehicles, studies indicate that a 10 per cent reduction in weight can result in a 6 to 8 per cent improvement in fuel economy [2].

A similar principle applies to air transport. Easy Jet, for instance, recently stated that every kilo taken from its fleet of aircraft saves the company around $20,000 US per year [3]. With increasingly stringent emissions targets for both automotive and aerospace manufacturers, the emphasis on so-called lightweighting has never been stronger.

Composite materials such as CFRP provide the ideal solution. However, there are significant obstacles when it comes to large-scale production with conventional processes. Chief among these is cost, with carbon fibre parts produced with traditional techniques potentially 20 times the price of the equivalent steel item [4]. Other issues can include a slow, labour-intensive production process with scope for human error and indeed fundamental constraints on the part's design and geometry.

TFP has the potential to overcome these obstacles. It also raises the prospect of new opportunities that could broaden the scope of composite materials to new applications.

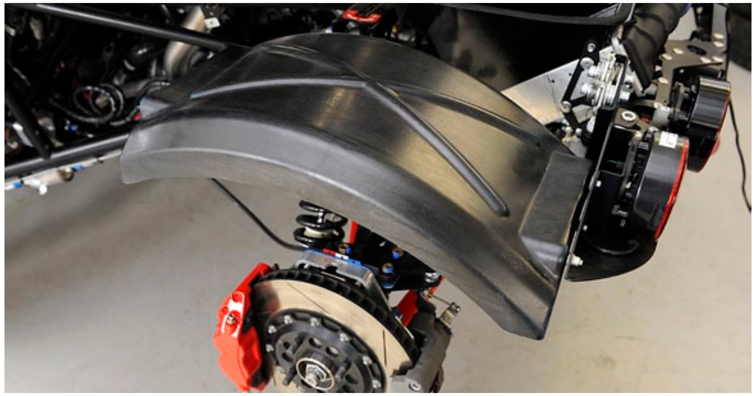

Fig.: Inner wheelarch constructed as TFP component manufactured by SHAPE for the Elemental Motor Company

LIMITATIONS OF TRADITIONAL TECHNIQUES

Before examining the benefits of TFP, it is worth pausing to consider the drawbacks of traditional composite techniques. Carbon fibre generally starts life as woven pre-impregnated (prepreg) sheets with fibres running at a set orientation (usually at 0 and 90 degrees or -45 and +45 degrees). These fibres are immensely strong when a force is applied directly along their length, but away from that axis, their physical properties rapidly begin to deteriorate. As such, a series of layers are generally applied at different angles to build up the component's strength in multiple directions.

Complex shapes – or parts with complex force paths – can be challenging to design as it is not always possible to satisfy the full range of loading conditions with fixed fibre orientations. Even though multiple layers can be built up to provide a good approximation of the appropriate fibre orientation, they are still separate sheets rather than one continuous fibre. Similarly, the fibre orientation within these layers (or plies) is two dimensional without any reinforcement in the Z-axis.

Each of these plies has to be cut from a sheet of prepreg, resulting in a substantial amount of waste material in the form of off-cuts. In some cases, as much as 40 per cent of the carbon fibre that goes into the part is wasted in this manner [5]. That adds a significant amount of time and cost to the process. Furthermore, due to the thermoset resin materials that are typically used in prepreg sheets, the scrap material can be extremely difficult to recycle, as can the finished part when it reaches its end of life.

There are numerous other challenges involved with prepreg materials. For a start, they must be kept at low temperatures to prevent the thermoset resin from ageing. Likewise, the cutting technology required to 'nest' multiple plies efficiently on a single sheet of carbon fibre can be complex and costly. Once in service, the thermoset polymers are very strong, but they can also be very brittle, limiting their impact resistance [6].

Prepreg sheets are also an inherently expensive form of the carbon fibre. Much of the cost of these woven materials actually comes from the resins used to impregnate them. While prepreg sheets can be hundreds of dollars a kilo the more basic forms of the material can be as little as $15 USD per kilo [7].

Perhaps the biggest issue with traditional prepreg methods, however, is that they are very labour intensive, limiting the scope for mass production and elevating the price of the finished products. Hand laying composite laminates is a complex process and one that is open to human error. What's more, such mistakes do not necessarily come to light until the part is complete and in service.

TFP offers a fundamentally different approach to composites production, drawing on embroidery techniques developed for the textile industry. Unlike prepreg methods, it begins with the reinforcement material in its strongest (and generally cheapest) form: dry fibres.

There are no plies to prepare or cut out before work begins on the preform. As such, the time and resources normally spent on these stages with prepreg production can be eliminated, lowering costs and reducing the total manufacturing time. In particular, waste material is kept to a bare minimum by sewing the fibres (known as rovings or tows) directly onto the base layer. Unlike prepreg processes, where a substantial proportion of the material can end up being trimmed off during the course of manufacturing, the scrap rate on a TFP part is in the region of one to two per cent.

Here, the fibre is embroidered onto a base material as one continuous fibre string, using a series of stitches. Often, the matrix material is commingled with the structural fibre, so the two materials are effectively deposited as a single fibre string. This results in a uniform distribution of resin right across the part, without the drawbacks of using a prepreg material. However, it is also possible to stitch the matrix material as a separate fibre layer in defined areas.

One of the fundamental advantages of TFP is that the individual fibres can be placed exactly as required, without the need for multiple plies, giving the designer almost limitless freedom to optimise the structure based on the forces acting upon it. This is particularly useful for multiaxial loads, as the process allows fibres (and resin) to be laid in the Z plane. Similarly, it allows holes or inserts to be included in the part without any breaks or joins in the fibre.

This ability to dictate the position and orientation of the reinforcement material opens up new options when it comes to optimising the part's geometry. It allows designers to employ concepts such as topology optimisation – where a software package automatically iterates through potential geometries – and biomimetics – where designers seek inspiration from the lightweight structures found in nature [8].

A particularly apt example comes from the structure of plants and trees, which feature an arrangement of cellulose fibres, bound together by lignin. The angle of these fibres confers different properties to different parts of the structure. Likewise, it has been shown that spiders can dramatically alter the properties of their silk fibres by using different braiding techniques. Increasingly flexible production methods, such as TFP, are essential to harnessing these principles from the natural world.

Almost by definition, TFP is a highly mechanised process. It requires very little manual input once the layout of the rovings has been designed. As a result, it provides excellent repeatability, minimising the variations in dimensions, density and fibre position; all of which are critical factors for ensuring consistent structural performance across a large production batch of components.

The rovings are deposited using a fixed stitching head, while the base material is moved around in X and Y direction beneath it on a pantograph system. Although the base material's primary function is to anchor the rovings it can also play a significant role in the part's physical properties. For instance, a common choice is the use of a nylon sheet, which can then form part of the thermoplastic matrix.

Although the part is still essentially two-dimensional at this stage, it can be built up with successive layers of fibres to create three-dimensional surface features. The system developed by ZSK STICKMASCHINEN is capable of depositing up to eight layers in one process, which represents a height of 7 to 8 mm. Multiple preforms can then be stacked on top of each other if greater thickness is required (this still dramatically reduces the number of layers compared to laying up sheets of prepreg).

Another important distinction of the TFP process is that layers of fibres can be deposited without stitching them on to the base material at regular intervals. Instead, they can simply be anchored at a few key points to maintain position. This means that the preform is able to deform into quite complex three-dimensional shapes when it is pressed into the mould, resulting in geometries that would be hard to achieve with other automated methods.

Once this near-net shape preform is ready, it is cut from the base material and placed into a heated press, where it is shaped into the finished geometry and cured. Although there is a small amount of tooling expense involved in the press, the apparatus required to do this is considerably simpler and cheaper than the autoclaves required for traditional carbon fibre processes. What's more, TFP requires no tooling investment whatsoever up to the preform stage, which results in an inherently flexible manufacturing process.

Fig.: ZSK W-Head: Embroidery Technology to lay fibres, wires and tubes.

REFINING THE TFP PROCESS

While TFP offers compelling advantages, early iterations of the process also suffered from a number of drawbacks. In particular, they struggled to deliver the productivity levels required to break into the mainstream. The key to solving this issue has been a series of refinements that have increased the speed, reliability and scalability of the process.

Perhaps the most fundamental changes have come in the way that the rovings are deposited. ZSK STICKMASCHINEN has developed a patented variable stitching technique, known as Fast Fibre Laying. This allows the intermediate layers of fibres to be laid down very quickly with a relatively small number of stitches – focusing on anchoring the fibre at key points, such as changes of thread orientation. The top layer is then anchored more securely to provide a cap, which holds all the material in place. This can dramatically increase the speed of the process when compared to stitching every layer through to the base at regular intervals.

Similarly, the latest generation of TFP machines can intelligently vary the speed at which the fibre is deposited. For instance, the machine will speed up when the rovings are being laid in a straight line and then automatically slow down for more complex areas. Likewise, machine settings, such as the presser foot height and the zig zag swing can all be automatically controlled; speeding up the process and reducing the scope for human error.

State of the art control and monitoring systems have also helped to reduce downtime. Drawing on the principles of Industry 4.0, it is possible to check the productivity and status of a connected TFP machine from anywhere in the world. Functions such as switching between two fibres or changing under thread bobbins can now be fully automated.

Hardware developments also play an important role. One example of this is the pneumatic cutting systems that are used to sever the fibres in TFP production; ZSK STICKMASCHINEN has collaborated with knife makers from Solingen to create an enhanced blade design, which retains its sharpness for extended periods. This reduces the frequency of time-consuming knife changes and also helps to improve quality control by ensuring a clean cut, which prevents fraying or snagging.

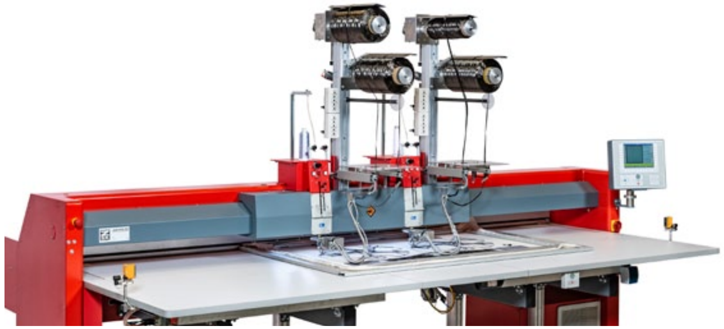

Fig.: Hardware developments like the the twin active wire/fibre feeding system increase the speed, reliability and scalability of the process.

Viewed in isolation, these are all incremental improvements, but they add up to a step change in the productivity of each TFP head. The next major consideration is scalability: Each ZSK STICKMASCHINEN head can lay between 1 and 3 kilograms of preform per hour and can handle two rovings of up to 60,000 fibres each. However, the machines can be scaled up with additional heads to create multiple parts concurrently, slashing the overall cycle time.

The practical limit to this so far has been found to be a machine with eight heads, with a laying area of 900x1.900mm per head, which is the largest system that will fit into a single shipping container. This can process parts at eight times the rate of a single head machine and it still represents a very cost effective option, with simple TFP systems often costing less than a typical automotive sheet metal forming tool.

ZSK STICKMASCHINEN has recently developed a twin active wire/fibre feeding system, which allows to either feed two fibre bundles on top of each other for high volume laying or to feed and lay the fibres one after the other. Or for instance a carbon fibre on the bottom and a thermoplastic fibre on top.

An additional new development is the laying of two or more parallel strings of fibres in one go. This possibility in combination with the “fast fibre laying” will bring the brake trough in laying speed. This technology will almost increase the laying speed by four times.

With the twin active wire/fibre feeding system it is also possible to stitch in an embedded component, such as electrical wiring, heating elements, strain gauges or antennae. This means that smart textiles can be created, embedded with elements such as RFID components. It’s even possible to overlap wires in three dimensions to create complex wiring [9].

These hardware and software innovations have played a major role in refining TFP into a viable production process. They have also simplified the procedures, greatly reducing the amount of manual input. However, successfully designing for TFP still requires specialist training, even for an experienced composites engineer. For a start, designers need to be aware of where to add or remove material to ensure that the two-dimensional preform will successfully press into a three dimensional structure. Similarly, it’s important to understand how and where to apply the stitches – potentially leaving intermediate layers of thread free to distort in certain areas. This has led ZSK STICKMASCHINEN to establish dedicated research and training centres in Europe and Seattle, enabling engineers to familiarise themselves with the technique and the opportunities that it brings.

The TFP process works with a wide variety of materials. Almost any fibre can be used as the reinforcement material, including carbon fibre, glass fibre, basalt fibre and stainless steel. In place of the thermoset resins found in prepreg carbon fibre, the co-mingled matrix materials used for TFP are nowadays more and more thermoplastics. This brings a number of key benefits. For a start, thermoplastics can be kept at room temperature, while thermoset resins typically have to be refrigerated to prevent them from ageing. Thermoplastics can also be up to 10 times tougher than thermoset resins [10], resulting in improved impact resistance.

Another major benefit of using a thermoplastic resin is that they are typically far easier to recycle when the component reaches its end of life [11].

Broadly speaking, all that is required is to heat the component to a sufficient temperature – around 200 to 300 degrees – and the fibres will separate out from the matrix. In contrast, the thermoset resins found in traditional prepreg materials make it far harder to separate out the various constituents.

Recycled carbon fibre in nonwoven sheet form can also be used as the base material for the TFP process. This material is not especially strong in its raw state, but once combined with TFP fibre rovings it can provide an exceptionally good strength-to-weight ratio with a reduced environmental impact.

Fig.1: Carbon preform with additional thickness and curvilinear placement of carbon around the holes.

Fig.2: “Attaché Case” made of natural fibre flax in a preform optimized TFP process for demonstrational purposes.

The recent refinements to the TFP process have the potential to bring composite materials to semi-mainstream markets, such as premium automotive, where they were previously considered prohibitively expensive.

The technique is ideally suited to small-to-medium size carbon fibre components, with individual preforms of up to 2 by 1.8 metres in size. Due to the virtually limitless freedom it offers in fibre placement, this technique is compatible with a wide range of different geometries, including complex curves and spirals. No other composite technology offers the same combination of design flexibility, continuous fibre strength and automation.

TFP can be used to create a variety of lightweight parts, including suspension components, body elements, mounting brackets and other structural and semi-structural items. In many cases, it is likely that the carbon fibre items would be replacing parts previously made in steel or aluminium, resulting in substantial weight savings.

The use of TFP also has the potential to open up new options – enabling designers to utilise composite materials in ways that were not previously possible. For example, one ZSK STICKMASCHINEN customer used the TFP process to create an inner wheel arch liner for a high performance sports car. Not only would the compound curves required on this type of part be a challenge with conventional carbon fibre processes, but there is also the very real danger that the material would shatter if stones or other debris were flicked up by the tyres.

Thanks to the thermoplastic resins that can be used with TFP, however, the manufacturer was able to achieve a much higher degree of impact resistance. What's more, drawing upon the excellent strength-to-weight ratio of carbon fibre, the manufacturer was able to make the component freestanding, while most inner wheel arch liners would need to be hung off a separate structure. Such was the strength and rigidity that the designers were able to mount other components on to the inner wheel arch. This included the rear wing, with all the aerodynamic loads that it would produce.

Other application areas include aerospace, defence, medical, clean energy, smart clothing and sports equipment. In fact, almost any structure requiring a combination of high strength and low weight has the potential to benefit from the use of TFP.

CONCLUSION

In order to broaden the scope of composite materials into more mainstream applications it will be necessary to reduce cost. TFP has always shown great promise in this regard, with low up-front investment, minimal wastage and a high degree of automation. Other benefits include low energy consumption, excellent recyclability and the flexibility to change product design without re-tooling.

Recent innovations in TFP have reduced cycle times and improved productivity. As a result, it is now possible to apply the technique in applications where traditional methods may have been deemed too costly, too labour intensive or simply incapable of providing the required geometry. As such, current TFP technology represents a major step forward in the quest to bring composite materials to the mainstream.

Fig.: ZSK Technical Embroidery Systems increase the speed, reliability and scalability of the process to bring composites to the mainstream.

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ABOUT

ZSK Technical Embroidery Systems is a division of ZSK Stickmaschinen GmbH, the leading German manufacturer of industrial embroidery machines „Made in Germany“.

ZSK STICKMASCHINEN is the leading brand for industrial embroidery machines and technical embroidery systems MADE IN GERMANY.

The application of unusual material like fibers, wire, tubes or even LED to ZSK STICKMASCHINEN‘s approved embroidery technology opened a wide scope of products, applications and methodical procedures.

Today companies from diverse branches develop and manufacture functional products, fashion, advanced composites or wearables with the embroidery solutions of ZSK TECHNICAL EMBROIDERY SYSTEMS.

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