Layer-for-Layer Precision plus High Performance

Thermoplastic Tapes Require New Processing Technologies

The first processes for manufacturing of thermoplastic composite components with organic sheets have reached the series production stage. Further developments are now focused on solutions for thermoplastic tapes reinforced with glass and carbon fibers. Engel – the injection molding machine maker and systems supplier – also gathered the necessary experience in the manufacture of own products. For example, some of their own robots series are fitted with a lightweight carbon rotational axis. Heart of the production line is a tape laying cell that is based on the pick-and-place principle.

A video-optical measuring system has been integrated to determine the actual position of the tapes on the laying head of the experimental setup (© Engel)

The technical basis for processing thermoplastic fiber composites is expanding continuously. Meanwhile, organic sheet has adopted a predominant role in the automotive and sporting goods industries, where series products are manufactured in large numbers. In the field of tape laying, thermoset processing shows the way. Here, pre-impregnated, rolled, and unidirectionally reinforced fiber composites supplied as prepregs have become established. Thermoplastic tape versions with matrices made of PA, PP, PE, PC+ABS, PPS, and PEEK have only recently gained in importance. They can be processed faster, but require an entirely different processing technology, which in turn exhibits clear parallels to organic sheet processing [1].

Organic sheets contain one or more fabric layers and are available as water jet cut blanks that are already adapted to the respective product. For further processing, the organic sheets must only be subjected to controlled heating up in an IR oven and inserted into the injection mold, where they are formed, consolidated and functionalized by means of injection molding. Challenges arise during handling and clamping the hot, pliable organic sheet. Moreover, processing conditions must be found that ensure adequate bonding between the components.

In the form of single layers, carbon and glass-fiber-reinforced tapes have a thickness of just 0.14 to 0.30 mm. However, a single tape layer is inadequate for most applications. In practice, layups consisting of several, sometimes up to 20 tape layers, are built up. In this way, components made of carbon tapes can reach wall thicknesses of about 3 mm.

Layup design is part of the design procedure of the part. The aim here is firstly to obtain the highest performance with a minimum amount of material, and secondly, to design the layup so that as little scrap as possible is produced, and the number of tapes is kept low. An ideal combination of lightweight design and economy is not always possible. While the optimum structural-mechanical design results in a layup with many small tapes, the number of tapes and their load-optimized arrangement must be limited to a practical amount for reasons of economy.

Consequently, considerations regarding overall productivity of the production cell are made during development of the process. The expected component weight as well as an estimate of the proportion of tapes in the finished component (**Fig. 1**) are a guide for the performance required from the tape laying cell. The laying cell's output must be matched to the production cycle of the processing machine. If tape laying requires far more time than the processing stage, this working step will be the limiting factor for the entire production chain. To ensure efficient operation of the entire production cell, the number of laying operations must be appropriately limited, and minimum tape formats must be defined. What's more, if an appreciable weight reduction is to be achieved, it should be taken into account that a

Component weight [g]	100			250			500			1000		
Proportion of tape [%]	40	60	80	40	60	80	40	60	80	40	60	80
Format 300 × 450 [mm]	1.4	2.2	2.9	4	5	7	7	11	14	14	22	29
Format 200 × 300 [mm]	3.3	5	7	8	12	16	16	24	33	33	49	65
Format 140 × 210 [mm]	7	10	13	17	25	33	33	50	67	67	100	133
Format 100 × 150 [mm]	13	20	26	33	49	65	65	98	130	130	196	261
Format 60 × 100 [mm]	33	49	65	82	122	163	163	245	326	326	489	652

Laying process (3 s per laying operation): <1.0 min; 1.0 up to 3.0 min; 3.0 up to 5.0 min; >5.0 min

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Fig. 1. The number of laying operations for producing a tape layup (tape: PA-CF; thickness: 0.14 mm; density: 1.46 g/cm³) can be estimated by means of component weight, the proportion of tape, and the tape format (source: Engel)

substantial part of the overall component structure must consist of tapes.

With a component weight of e.g. 250 g, the tape blanks should have a mean surface area of at least 300 cm². This is necessary to ensure that some 20 to 30 laying operations are enough to produce a layup weighing 100 to 200 g. This in turn corresponds to a proportion of 40 to 80 % of total component weight for the tapes.

Tape Layups Synchronized with Processing

With an assumed cycle time of about 60 s for the injection molding stage, the central requirement for the tape laying cell is that one of the tapes with dimensions up to approx. 300 x 450 mm must be laid and spot welded together every three seconds. The conceptional approach adopted by Engel Austria GmbH that meets these requirements, is based on the pick-and-place principle.

The manner in which the tapes are prepared for laying is determined by technical and economical criteria. The decisive design parameters are:

- Minimum scrap,
- the largest possible tape blanks, and
- the most favorable structurally-mechanical arrangement of the tapes in the layup.

The preparation stages are readily automated and implemented as integral parts of the tape laying cell. Similarly, ready-cut tapes can be fed to the cell.

Tape blanks can also be prepared in previous steps – e.g. angled or straight cutting from the tape roll, punching with curved end contours or practically any other shape, as well as cutting the tapes with an ultrasonic knife, whereby the finished tape blanks can be stored in magazines or are processed immediately.

Carbon Tapes for Rotational Axis

Engel's e-pic robots come in two versions: as a pick-and-place unit (type: e-pic Z) and as a sprue picker (type: e-pic B). The former are modified linear robots with a conventional z-axis for moving between mold and stacking position above the injection molder. The sprue picker on the other hand, has a rotational axis instead of a z-axis, with which it is able to reach down behind the machine. On both versions, the y-axis, along which the robots move downwards into the mold or into the stacking position, is also a conventional linear axis. The special feature of the e-pic series lies in the x-axis, which was designed as a rotational axis with coupling rod (**Fig. 2**).

An important advantage of this system is the extremely low space requirement, which is particularly useful with smaller processing machines. During development of the robots, a major challenge involved the reduction of robot arm weight, thereby improving its performance data even more. This was made possible by the pick-and-place procedure developed by Engel for tape processing. Due to the innovative manufacturing technique, a 37 % weight reduction of the robot's rotational axis »

Fig. 2. Instead of a conventional x-axis, type e-pic robots have a rotational axis, which also ensures that the system requires minimum space (© Engel)

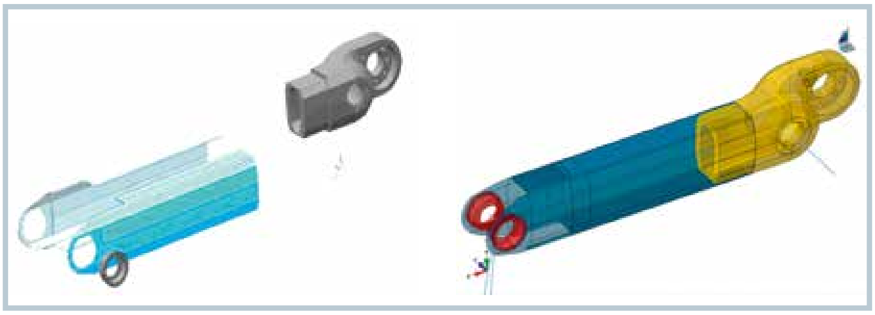

Fig. 3. The rotational axis was designed with an assembled profile of carbon tapes and a stub of die-cast aluminum for connecting to the servo motor (© Engel)

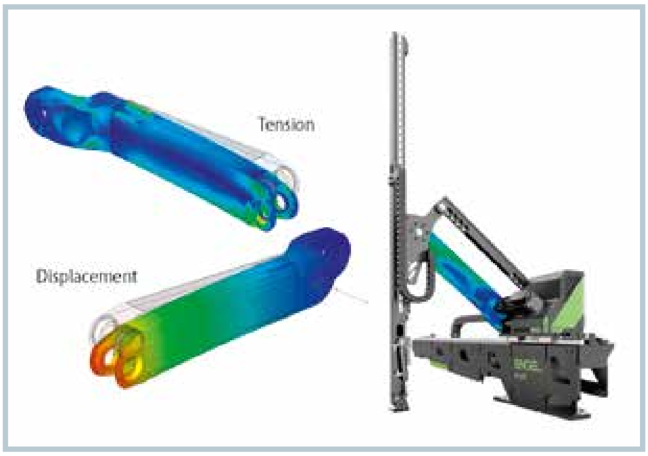

Fig. 4. The load-optimized design of the rotational axis is based on FEM calculations (© Prime aerostructures)

was achieved. In this way, the robot's movements can be significantly faster, and require less energy.

Load-Optimized Component Design

While designing the rotational axis, the aim was to achieve a lightweight mechanical structure, while keeping mold complexity as low as possible. The developers opted for a concept in which the component consists of two identical tape-reinforced half shells, which create a closed profile during final assembly. Engel only uses a die-cast aluminum component for the connection to the servo-motor, as the component's geometry is highly complex, and rotational speeds in this area are low, due to the distance from the pivotal point (**Fig. 3**).

To meet the high demand on stiffness, the majority of tapes are inserted in the longitudinal direction of the rotational axis. In addition, several tape layers are introduced at angles of ±45° and 90° to the longitudinal axis. With the help of FEM calculations (**Fig. 4**), Prime aerostructures GmbH determined the most favorable design considering the different initial conceptional prerequisites and taking into account the required load conditions. The results of this design work were recorded in the so-called Ply-book, which serves as a guide for the layers of the tape layup.

Other project partners were Celanese GmbH, who supplied the carbon tapes, and Schöfer GmbH, who provided a forming device and the assembly equipment. Apart from the tape laying step, the multi-stage process for manufacturing the rotational axes also includes a consolidation step, the subsequent heating up and forming of the prepared tape layup, plus cutting and joining operations (**Fig. 5**).

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References & Digital Version

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Precise Laying Operation without Matrix Channels

Four different tape formats are required for the rotational axis. Every half shell consists of 32 individual and unidirectionally reinforced tapes. To obtain the required high dynamics during the laying operation, a fast articulated arm robot is used (type: Agilus KR 6; manufacturer: Kuka Roboter GmbH). Demand-oriented removal of the tapes from the magazines is done independently of the actual laying operation, so that the robot's laying speed is not reduced by slow removal movements.

Layup quality depends mainly on the accuracy of the positioning of the tapes. If tapes overlap, severe fiber shifting occurs during consolidation, i.e. the fibers slip sideways in order to compensate local deviations in the tape layup thickness. If the tapes are laid with spaces, linear areas without fibers are created during consolidation, resulting in reduced stiffness and strength. Different to thermoset tape layups, the gaps between the tapes are frequently not closed completely during consolidation, because the viscosity of the thermoplastic matrix is several decades higher than e.g. with epoxy resin. Therefore, it is essential that the tapes are laid precisely even at high laying speeds. Often, laying accuracies with gap widths of max. 1.0 mm are demanded, sometimes even below 0.5 mm.

The dimensional deviations during tape laying are partially due to inaccuracies of the blanks or the punching operation. Moreover, the tape stacks cannot be aligned perfectly precisely in the magazines, and the handling operations during tape removal or the take-up by the laying head can lead to additional positioning errors. In particular, dimensional deviations of the blanks cannot be compensated even by utmost precision. Therefore, the equipment must be able to detect and correct faults as far as possible, to ensure that the tapes are laid exactly parallel to each other. Hereby, obtaining minimum gap widths or overlaps has a higher priority than an accurate outer contour of the tape layup.

Fig. 5. The integrated process for manufacturing rotational axes with carbon tapes involves six working steps (© Engel)

Fig. 6. Investigating direct and indirect illumination during imaging: Illumination is a key factor for exact edge detection (© Engel)

Optical Measurement Technology for High Precision

Laying accuracy of the individual tapes can be considerably improved with the help of a fast and high-resolution optical measuring system (**Title figure**). Either the tape position at the take-up location (i.e. after separating a single tape) or the position on the laying head has to be determined. For this purpose, reference points must be provided at the take-up location or on the laying head, whose position is known precisely with reference to the robot's coordinate system. A digital image of the tape is taken that is converted by means of a threshold value method that subdividing the picture's contents into segments, whereby the Otsu method is applied [2]. Additional calculations provide information e.g. about the edges and the tape's center of area with respect to the reference coordinate sytem.

These measurements permit correcting values for the position and the angle that need to be determined separately for every tape. These values then are transmitted to the robot control system, which takes them into account during laying. One of the key factors for precise edge detection is appropriate illumination while taking the image (**Fig. 6**).

The first tape layer is kept in position on the laying table by vacuum. Succeeding layers are spot welded to the respective lower layer. The tapes can be bonded by means of ultrasonic sonotrodes as well as with electric heating dies within just 0.2 s. The main advantage of the heating die lies in its far more compact design, which also permits several heating dies to be mounted on a laying head.

Summary

Tape laying with optical image processing and using the pick-and-place procedure is flexible in application and is not limited to specific tape widths. In fact, tape blanks can be used with practically any contour. Image processing is used to detect and effectively correct deviations resulting e.g. from tape production or cutting operations, so that a high-quality tape layup is produced for further processing. If the tape layup, which has been created parallel to the injection molder's cycle time using the pick-and-place procedure, matches precisely the component geometry, subsequent processing steps such as consolidation, heating up in the IR oven, plus forming and functionalization in the injection mold can be carried out immediately without any intermeditate or additional trimming. ■