The advanced ply placement process – an innovative direct 3D placement technology for plies and tapes

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Abstract Breaking down the cost structure of state-of-the-art CFRP part shows that a major share of the costs is caused by labor and equipment as well as process energy consumption. Therefore, the main goal of the EU funded FP7 project LOWFLIP (Low Cost Flexible Integrated Composite Process) has been the reduction of these costs by introducing new technologies into CFRP production processes. The LOWFLIP concept focuses on three main aspects:

• Development of a new out-of-autoclave (OOA) prepreg system with snap cure capabilities.
• Development of a direct 3D placement technology for plies and tapes.
• Development of energy efficient and fast heating toolings.

The main content of this paper is detailed information on a novel direct 3D prepreg layup process for automated production of large-scale fiber reinforced parts of small and medium lot sizes. The advanced ply placement process, which is able to drape and compact unidirectional prepreg tapes with currently up to 300 mm ply width directly into a double curved tooling, is being introduced. Two large-scale demonstrator parts from the transport and aerospace sector will be presented. Experiences gained during prototype manufacturing will be reflected and benchmarks of the equipment are presented.

Keywords Ply placement, Tape placement, Draping, Automated preforming

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Introduction

In the past decades, there has been a significant progress in the development of automated production technologies for carbon fiber reinforced parts (CFRP). However, the application of these technologies for mass production has not been achieved by now for different reasons. Until today, high investment cost for equipment, complex, and unreliable machinery or low process flexibility prevent a wide use of the developed technologies.

The main motivation behind the research work conducted in the EU funded program LOWFLIP is the introduction of new materials and production methods in order to enable widespread use of automated composite manufacturing technologies.

Different studies show that 33–67% of the costs of state-of-the-art CFRP parts are caused by labor and equipment as well as process energy consumption. The remaining share is resulting from material costs, as it can be seen in Fig. 1. Also it can be found that by application of automated processes in CFRP production a decrease in overall part costs can be achieved.

Since material costs are mainly driven by resource and energy prices, they cannot be influenced directly by the components manufacturer. However, the material efficiency can be increased using automated processes, while usually the expenses for manual labor will decrease. The expenses for equipment increase when automated processes are
being introduced into production. Therefore, it is absolutely necessary to get the costs down for automated preforming equipment and at the same time maintain or even increase part quality. Reducing energy consumption and cycle time of production processes can further decrease part expenses. The newly developed APP production process is a direct 3D placement technology for plies and tapes that has been developed for the production of mid to large-sized shell-like CFRP parts for transportation industry and general machine building applications. The aimed cycle time for the intended application is 45 min per cured part representing a mid-volume production cycle of up to 5000 parts per year in two shift production process. The laminate quality is required to be in the range of typical prepreg processes e.g. fiber volume content of 55–60%, porosity lower than 2%.

In order to reduce energy consumption and to achieve faster curing cycles, novel tooling solutions have been developed. Compared to state-of-the-art-tooling solutions, they show superior performance in terms of minimal thermal capacity and achievable heating/cooling rates.

This article is focusing on the results of the APP production process development. Detailed information on the developed prepreg material and tooling solutions are given in the sources stated below and will not be presented in this paper.
Development of the advanced ply placement process (APP)

State of the Art fiber placement processes

Most of today's commercially available advanced tape placement (ATL) systems are gantry type machines suitable for the production of large-sized parts with flat or single curved surfaces, e.g. wing skins or fuselage panels. ATL machines usually process UD prepreg tapes between 75 and 350 mm width. While working predominantly on flat preforms ATL machines reach theoretical layup rates up to 100 kg/h mainly depending on the material width and fiber areal weight. The actual layup rate is often comparably lower due to downtimes caused by spool changes and cleaning operations of the fiber guiding elements, e.g. 25–50 kg/h for simple full ply geometries down to 12 kg/h for more complex preforms. Since these machines have limitations to work on highly double curved molds due to the missing capability to equalize path length deviations inside a tape it is necessary to transfer the preform from the preforming tool to the curing tool after the layup has been completed. This transfer leads to extra process time and may damage the preform. The huge envelope of the placement head (diameter of up to 2 m) makes it impossible to address dents or buckles in the parts to be produced. Scrap rates strongly depend on the tape length / width ratio as well as the outlines' shape of the part and typically range from 2 to 10%. Known manufacturers of ATL machines are Forest Liné (France), MTorres (Spain), and Cincinnati (USA).

Typical advanced fiber placement machines (AFP) nowadays process 1-32 prepreg or dry fiber tapes slit to an exact width between 3.175 and 12.7 mm. The placement head is able to move on double curved surfaces and independently start, stop, and cut single tows. The tapes are transferred to the head from an external creel rack or transported within the placement head. The placement head is usually driven by a robot for production of smaller parts or by gantry system for large parts. The theoretical movement speed can be up to 60 m/min leading to a layup rate of up to 40 kg/h. Due to acceleration / deceleration and slow movement in difficult areas the layup rate can decrease down to 5.5 kg/h. The AFP placement head usually has a smaller envelope then an ATL machine head enabling it to manufacture highly curved parts such as stringer profiles at the cost of sacrificing layup speed. The achievable scrap rates can be very low down to 2% using the near net shape layup capabilities. But due to its very complex head architecture these system are prone to imperfections of the slit tapes used leading to downtimes for maintenance and cleaning. Fiber placement technologies have in common that they require a specified type of textile material with high quality and low tolerances making it very expensive. Furthermore, it limits the flexibility of the process to adapt to different fiber types due to availability issues. For high...
been assessed in several publications and will also be investigated by the authors. However, poor width tolerances or uneven impregnation of the UD prepreg material should not crucially affect the layup process. In order to efficiently use the raw material and to be competitive, the scrap rate will be targeted in the range of 5% of the total material being used.

Further focus has been the reduction of the complexity of sub-components used for the machinery to a necessary minimum to achieve a reliable and stable process. The APP process is aiming for applications in general mechanical engineering and transport industry. The reduced component complexity and the kit-based architecture using standard components results in a more robust layup process as well as lower equipment investments compared to state-of-the-art ATL or AFP technologies. The kit-based customization of the end-effector to the parts geometry potentially enables small and medium-sized enterprises (SME) to introduce automated production technologies into their portfolio.

SME have to deal with different part sizes and geometries. For that reason the APP equipment has been designed in a modular concept, resulting in an easy adaption to changes in parts size and geometry at reasonable expenses.

It is difficult to produce small and complex parts as well as large, less complex parts efficiently using only one machine set-up. Therefore, the APP process combines different end effectors with different tooling approaches and materials to work as efficient as possible. All components can work as stand-alone solutions as well, if they have to be integrated into existing equipment lines. In summary, the main features of the APP process are:

- Fully automated production of large CFRP components (dimensions of 3 by 3 m) at small to medium volumes.
- Use of out-of-autoclave materials such as prepreg, especially unidirectional plies.
- Direct 3D placement into a double curved mold without further draping steps.
- Simple sub-components requiring low investment costs.
- High flexibility (varying ply width, use of different materials).

Manufacturing equipment for large-sized parts

General design features of the advanced ply placement cell

The APP production cell for large parts is based on several industry robots and interchangeable sub-components. Therefore, it is possible to adapt the size of the accessible

Figure 5 Ply tension equalization

Figure 6 LOWFLIP draping mechanism

Figure 7 Ply bridging effect
area, changing only single components at reasonable time and cost investment. The current demonstrator cell has a size of 8 m x 9 m and can be reduced in size. A reasonable minimum size for parts manufactured using APP is not smaller than 1 m edge length.

The basic machine concept consists of two robots carrying one gripper unit each to pick up a pre-cut ply of UD prepreg material from a cutting table next to the placement system. Both robots are mounted on a linear axis on both sides of the tool. A third robot is mounted in front of the tool and is operating the compaction roller for the layup consolidation. The use of three robots is causing higher invest cost than AFP single robotic solutions, but is less expensive than a gantry solution. Also the robot programming effort is bigger with APP compared to SoA AFP. The standard ply width is 300 mm, and can be changed to smaller width down to 20 mm with no setup changes. A larger width is possible, but would require a redesign of gripper and compaction roller assemblies. The minimum ply length using the actual compaction roller is 0.5 m, resulting from the envelope of the compaction roller, which has to fit between the two gripper units. Shortest ply length for AFP/ATL systems is 100 mm. For APP, a reasonable minimum ply length is 1 m to achieve sufficient productivity. The auxiliary process time will increase with shorter ply length and therefore reduce productivity. The mold itself is mounted on a rotatable tool tray, allowing the deposition of material in any direction. The tool can be electrically heated by an integrated carbon fiber direct heating close to the surface. It is used for preforming and curing of the part. For that reason a transfer of the preform from a layup tool to a curing tool is not necessary, giving an advantage of the APP process against ATL state-of-the-art processes. Of course this means additional off-time for the tooling during the curing phase depending on the resin systems curing time. An approach to solve this issue would be to use multiple toolings instead of one to decrease downtime at the drawback of higher invest.

The demonstrator part is a truck trailer front wall with a size of 2.5 m x 2.8 m and double-curved surface. The structure is a CFRP monolithic part with a thickness of 2.4 mm and additional 1.6 mm local reinforcements in the highly loaded lower area of the part. The ply architecture is [0/90/45/−45]s for the constant thickness part and [0/90]s for the local reinforcement in the lower part of the shell. The minimum concave radius of the surface is 45 mm located in a corner blend area. This corner blend cannot be addressed with the current compaction roller design, which is limited to radii of 50 mm and above. This smaller radius was implemented on purpose, to investigate how the equipment performs beyond its systems boundaries.

A second demonstrator, a double-curved part from the outer skin of an A320 class passenger aircraft was selected (size 1 m x 1.2 m). It is a monolithic skin stiffened with stringer profiles. This demonstrator was selected to investigate the equipment’s capabilities to place a skin directly on the pre-manufactured T-shaped stiffener profiles in an automated process.

Draping state-of-the-art
The process of draping textiles usually refers to placing the textile material onto a double-curved mold surface without wrinkles by allowing the adjacent fibers inside the ply to move by shearing. In the picture the shape changes of a rectangular UD ply is visualized when draping it on a half dome geometry. The projected width decreases in comparison to the flat state, while the edges rectangular to the fiber direction transform from a straight line into a curve. The same ply plan formed over a straight edge of a prismatic body would not influence its width and outline curvature, because its surface is fully developable into flat state. This small experiment is representing the main difference between draping and plan forming of textiles.

During the draping process there is the inherent danger of creating gaps between the fibers inside a ply caused by unevenly distributed friction forces resulting in areas of large local shear distortion. This can be influenced by temporarily selective fixation of the endangered areas, e.g. with stamps or compaction rollers. In order to avoid creases it is essential to equalize length deviations between adjacent fibers in a ply caused by the non-uniform track lengths of parallel cross...
sections along the shape of the mold. With AFP processes this equalization is normally done by steering the single tows at different speeds to achieve the desired tape length on every section of the layup path.

When using ATL it is more difficult to achieve wrinkle free laminates on 3D surfaces. Most ATL machines have to do a flat layup first, since wider tapes in the range of 75–350 mm are being used and they are not able to manipulate the material's inner fiber architecture. After the 2D layup usually a transforming step into the final 3D geometry is necessary. In most cases this is realized via a press or diaphragm process. While the preform stack is being heated and transformed, the fibers in the stack will move from the 2D into the 3D architecture following the tooling's curvature. The fiber movement is hardly reproducible due to various complex boundary conditions like internal friction, material grade, temperature, etc. and often results in wrinkles or gaps inside the preform.

**Details on the APP layup process**

The APP process allows a direct and controlled draping of UD prepreg material directly into the 3D mold.

The main sub-components responsible for in-line draping are the segmented grippers holding the outer edges of the ply, as well as the flexible compaction roller. The newly developed gripper units are divided into segments which are able to individually move parallel to the UD fiber direction. The width of the gripper segments has to be adjusted to the curvature of the targeted application. The current set-up is set to 20 mm segment width. The ply itself is taken up from the ply cutter using the grippers and subsequently transferred into a pre-layup position slightly above the mold. Therefore both gripper robots perform a parallel movement above the mold. The tape is being held under a defined tension to prevent undesirable movements. The force to apply sufficient tension is depending on the tape length and weight, during the prototype manufacturing it was set to 120 N per gripper side at a maximum ply length of 3.5 m. Tension can be measured and controlled using proportional valves. The compaction roller assembly is a highly adaptive device to attach and pre-compact the prepreg tape to the mold surface. It incorporates several segmented pneumatic cylinders which move independently. Every cylinder guides a pair of rollers. All rollers are surrounded by a single, highly flexible polymeric belt. The belt is flexible enough to fully adapt to a minimum radius of 50 mm in roller direction.

Perpendicular to the roller the applicable minimum radius for convex and concave curvatures is 200 mm. By adjusting the pressure of the cylinders it is possible to raise the compaction pressure, which is slightly varying due to the changing position of the downforce axis of the roller in relation to the surface of the tool. The feasible minimum width of a corrugation at the tool is 200 mm at a depth of 100 mm.

The compaction roller starts to attach and compact the tape to the surface of the mold at the designated starting position, which varies for each ply and can be anywhere between the two grippers. The roller area of contact to the tool is approximately 0.016 m². A maximum compaction pressure of 6.1 N/mm² can be applied, representing the maximum downforce of the robot of 100 kg. The roller moves toward one of the grippers first. After returning to the starting point, it compacts the second half of the tape to the tool.

As long as there is no curvature perpendicular to the UD plies’ 0° direction, all fibers in the ply have the same length between compaction roller and gripper. This is the case for flat parts of the mold in every placement direction (no draping effects) or in single-curved areas of the mold in the case of placing the ply in direction of the single curvature.

If the compaction roller reaches a double-curved area or if it does not move perpendicularly to the curve direction on a single-curved area of the mold, the track length of adjacent fibers between roller and gripper is not equal anymore. This also results in varying tension in the UD tape between roller and gripper. These differences in length and tension inside the ply lead to wrinkles in the lead-in area of the compaction roller. If not corrected, the roller will overrun the wrinkled tape areas and compact them as creases onto the tool.

The gripper segments keep the tension within a ply at a constant level, even if there is a local distance variation between roller and gripper. Due to the gripper segmentation, the single gripper units are able to move adjacent fibers relatively to each other by shear movement. The pneumatic system is working passively and the tension of the fibers can be adjusted. As soon as length or tension deviations caused by the draping process appear, the gripper elements pull the fibers until the tension is equalized. Tensioned fibers will prevent further movement of the related gripper segments. The compaction roller is pressing down the tape onto the tool and prevents the already placed tape behind the roller from being peeled off the tool. In this way, the ply is always tensioned across the whole width, while the compaction roller moves along its programmed path on the mold. The force needed for equalizing the tension deviations within the ply is mainly depending on the matrix viscosity and the UD material quality. The necessary tension force for equalization can be reduced by pre-cutting of the plies (in fiber direction) in critical areas. The equalization movement between adjacent fibers is dominated by the viscosity of the resin between single fibers. The force necessary for reasonable draping can also be reduced by increasing the tape temperature. On the other hand, tack and shelf life of the material are also being influenced by temperature, therefore an optimum temperature considering the whole process has to be identified. During the prototype trials the SCE-79 Prepreg has been used. For this material, the optimal tool temperature for the layup of the first ply onto the composite tooling has been identified to 40 °C, which is low enough to avoid the undesired initiation of polymerization and high enough to increase the tack to a desired level. With the current equipment there is no possibility to heat the tape, while it is still in position above the tool prior to compaction. An active heating will result in faster length equalization within the ply, due to decreased viscosity of the resin. During layup a stop and go movement of the roller is necessary, allowing the wrinkles to be pulled out. As soon as wrinkles occur in front of the compaction roller, the robot has to stop for 2–5 s. The general pre-tension of each single gripper segment is set to 16 N to achieve appropriate tension of the whole tape. For de-wrinkling the force has to be increased to up to 50 N per segment, depending
on the free tape length. After the tape has reached its initial flat state, the force is decreased to the pre-tension level and layup continues.

As soon as draping of one ply is complete, length deviations along the ply can be seen at the outer borders of the tape after the gripper released the ply.

Starting with the second layer of the stacking sequence, the tool temperature can be decreased to 27 °C since the tack of the used material is sufficient to fully attach the plies to each other.

The gripper robots are able to perform a lateral movement to side shift the single plies and thus to achieve a zero gap placement. Using 6 axes of the robot, the system is able to keep the tape at equal tension and in the optimal position with reference to the compaction roller. Therefore, the gripper units have to move in lateral direction in relation to the compaction roller to match the border of the subsequent ply. Main advantage of this approach is the continuous placement of all fibers of one ply, without cutouts. One disadvantage is the deviation of the fiber direction from the intended, optimal direction, due to the curvature of the tool. Furthermore the angular deviation will accumulate from ply to ply. In highly curved parts this may lead to severe fiber distortion in the outer plies.

**Some initial benchmarks**

In the area of flat or single curved geometries the tool center point (TCP) of the compaction roller is able to move quicker than in complex doubled areas. The full potential of the APP process has not been identified yet, but layup trials were conducted with a speed of 6.5 m/min. Using a standard UD prepreg with a fiber areal weight of 300 g/m² flat specimens were produced at a layup rate of 54 kg/h including resin content.

In double curved areas the speed of the compaction roller has to be decreased, allowing sufficient time for draping. During prototype production, layup speeds of 3.6 m/min have been maintained. The equivalent layup rate, including resin, is 30.4 kg/h. When considering auxiliary processing time required for picking up the plies, turning the tool etc., an average layup rate between 15 and 20 kg/h has been achieved with the current set-up and part geometry. Using a SoA AFP system to create comparable geometries, an average layup rate of 18.38 kg/h has been achieved. The equivalent layup rate of 18.38 kg/h has been achieved.13 The direct placement of all fibers of one ply, without cutouts. One disadvantage is the deviation of the fiber direction from the intended, optimal direction, due to the curvature of the tool. Furthermore the angular deviation will accumulate from ply to ply. In highly curved parts this may lead to severe fiber distortion in the outer plies.

**Known process issues**

During prototype manufacturing some incidents have been noticed. When setting the time for de-wrinkling process described above longer than 5 s, the ply already being placed slowly starts to peel of the mold behind the compaction roller while under tension. This occurs even if the compaction roller is set to maximum compaction pressure of 0.6 bar. Obviously the friction force underneath the roller is not sufficient to prevent fiber slipping. This results in bridging effects of the ply in concave areas of the mold.

The described effect can be reduced by decreasing the de-wrinkling time. Higher tooling temperatures seem to intensify this effect. An explanation can be the reduction of the viscosity of the prepreg matrix caused by the temperature rise and the resulting decrease in friction forces under the compaction roller. Considering the current set-up, best results have been achieved at 27 °C tool temperature and 2 s de-wrinkling time. A detaching of plies from the tooling in concave areas over time caused by inner tension during layup could not be noticed.

During de-wrinkling the outer edges of the tape tend to bend in gravity direction. If not considered and prevented, risk is overlapping these areas and creating a crease.

The contraction of tapes during pick up by the gripper units is another noticeable effect. While transferring the plies to the starting position, they have to be kept under tension to prevent uncontrolled movement. During tension application, a contraction of the plies perpendicularly to the fiber direction can be observed, starting at the gripper units toward the middle of the ply. For the used UD prepreg tape, the contraction has been measured up to 2% of the initial ply width. Since the offline programming is based on an ideal rectangular ply, the shape deviation results in a gap of about 4–6 mm in the middle area of the ply. For further improvement in lay-up quality, it has to be investigated, if this contraction is reproducible and predictable. Since the contracted plies’ edges are not linear but curved, the gaps cannot be closed during layup by a simple parallel movement of the next adjacent ply. This would cause the plies to overlap at the outer ends, while the middle section would be free of gaps, or vice versa.

The only feasible way to prevent gaps at this state is the active steering of the tape to close the gap along the whole length of the tape. To reach this a measurement of the contraction prior to the layup is necessary to adapt the programming. This will of course increase the complexity and price of the system and has to be reviewed in the future. Furthermore, the tape steering will sum up deflections of the fiber orientation from ply to ply and therefore reduce the laminate properties. Another solution for low-tech applications could be to accept small gaps and overlaps in order to guarantee the

For fiber angles between 45° and 90° the use of narrow tapes should be considered to reduce scrap. For the produced prototype, the average scrap rate was within the range of 10% of the total material used. This value is not acceptable and has to be decreased by further improvements of the APP system. This could be achieved by reducing the part outline overlap via programming. Also the gripper units could be modified to be able to grip precut 45° tapes to prevent angular induced scrap.
fiber direction as required. It has to be further investigated what is the better option in order to ensure the best possible performance of the part.

A possible explanation for the tape contraction is the fact that not all of the fibers in the UD tape are perfectly aligned in tape direction. Some filaments are aligned at a slight tilt, caused by external influences during tape production. These angular filaments induce lateral forces within the ply when tension is applied. Another minor influence is the high viscosity of the resin causing friction between fibers and changing the uniaxial stress condition into a biaxial one. The influence of the viscosity could be reduced by heating of the tape. The contraction caused by misaligned fibers cannot be influenced however. Lengthwise parallel cuts could partially solve this issue, but at the cost of higher production efforts as well as new issues concerning material handling.

Summary and future prospects

Within this paper the APP, a new method for automated production of large double curved fiber reinforced parts has been presented. The technical proof of concept and the sub-components of the system have been described. Some initial benchmarks collected during the production of the first two prototype parts have been presented. Although the APP process shows promising potential, not all of the initial goal could be achieved. The overall layup speed has to be increased to be competitive to state of the art processes. An active ply gap control mechanism has to be implemented to increase laminate quality. The scrap rate has to be lowered to reach the described state of the art. Furthermore, a simulation approach will be established in order to understand the viscous draping and contraction effects observed during layup.

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