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# Automated Fiber Placement Head for Manufacturing of Innovative Aerospace Stiffening Structures

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## Abstract

In the research project “High-performance Production of CFRP Structures” (HP CFK) a new automated fiber placement (AFP) system for laying thermoset CFRP (carbon fiber-reinforced plastic) slit tapes was developed. Its novel, modular designed laying head faces current industrial needs and challenges of prospective carbon light weight applications, e. g. future aerospace stiffening structures. Thus, its compaction unit is optimized for producing complex-curved structures. To allow approximating slopes on curved geometries, it consists of several height-adjustable rollers which, in addition, are each pressure controlled to enable an individual compacting pressure for the lay-up on materials with different compression strength (e. g. foams, metals). Furthermore, the design of the laying heads cutting unit aided the manufacturing of complex structures while being located as near as possible to the nip point to allow very short minimum placement paths. This paper introduces into the general design of the modular laying head as well as preliminary results of validation studies regarding several process limits.

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## 1. Introduction

Especially in civil aviation, CFRP becomes more and more important to achieve lighter and hence more ecological and efficient airplanes. Today, the global market leaders use CFRP to produce large airplane parts, such as the skin of fuselage and wing covers. Automated Tape Laying (ATL) and Automated Fiber Placement (AFP) are two manufacturing processes used for such parts. MTorres, Electroimpact, Coriolis, BA Composites and the Fives Group are commercial manufacturers of AFP and ATL machines. In the AFP process, small CFRP slit tapes up to 1 inch of width are placed on molds. To achieve a high production rate, AFP machines simultaneously place multiple slit tapes. Machines with up to 32 slit tapes are currently available [1]. New developments of AFP machines build upon robot-

based systems to increase flexibility and decrease the size of the production systems [2]. In addition, the costs can be reduced by using industrial robots. The laying heads of AFP production systems are highly integrated and obsolete sub units cannot easily be replaced with newly developed and more competitive ones. Therefore, a new AFP head is needed, which offers the possibility to integrate innovative units that improve the AFP process straightforward.

## 2. Requirements and constraints

To define the requirements for the AFP head, a process analysis of a series production of fuselage panels was conducted. The results show that a big fraction of process time in AFP is non-productive. The floor-to-floor time of the investigated panel is 24 h. Only 46 % of the time is spent with placing slit tapes while it takes 54 % for manually inspecting every ply and correcting placement defects, setting up or cleaning the machine etc.. Furthermore it was determined that 85 % of the placing time were spent for cutting the slit tapes, accelerating and decelerating the fiber placement head and not optimally set placement speeds.. Thus, two foci areas are identified: improving acceleration and speeding up the cutting process. Therefore, one focus is on weight reduction of the laying head especially for usage on an industrial robot and the predominate use of lightweight material such as high-strength aluminum alloys and fiber-reinforced plastics. The other focus is on maximizing the velocity the placement head is allowed to move during the cutting process. The best case is cutting at maximum laying speed of 1 m/s.

Other requirements came from a new structural design for fuselage panels developed in the research project [3]. This panel consists of a skin produced by AFP and local stiffening structures with a supporting foam core also manufactured by AFP. The surface of the structure has a three-dimensionally curved geometry (see Fig. 1). To follow the surface by the compaction unit, a roller with a flexible outer layer and adjustable positioning is necessary. As a restriction from the structural design of the local stiffening structures, the width of slit tapes is 6.35 mm (1/4 "). For the manufacturing, the stiffening structure needs short lengths of slit tapes placed by the AFP head. To insure a better adhesion on surfaces, the laying head needs a pressure control. Especially for mold materials with low compressive strength, a pressure controlled compaction unit is necessary to prevent damages of the molds (e. g. foam cores). These requirements lead to following foci in the mechanical design: flexible compaction roller, manufacturing with short lengths of slit tapes and pressure controlled compaction unit.

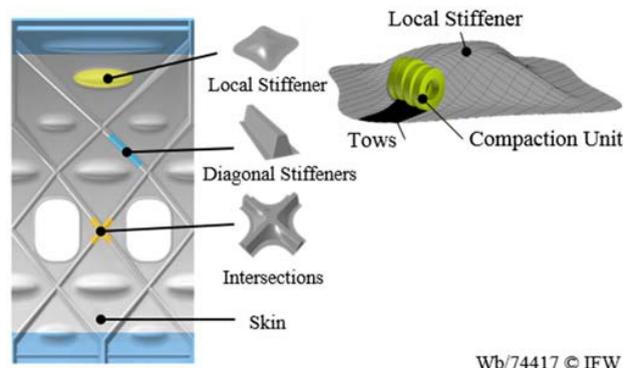


Fig. 1. Fuselage panel design developed by research project HP CFK.

Bridging is one process-induced error, which occurs especially during lay up in concavely shaped molds. It is critical because the tow detaches from the mold and creates a cavity underneath. One possibility to avoid this is to reduce laying speed or to reduce tow tension. In order to maximize the production rate and to avoid derated laying speeds, a continuous feeding synchronous to the laying speed has to be implemented to reduce tow tension during the placement process. High temperatures during the placement process cause increasing tack of slit tapes, especially in the summer with temperatures up to 30 °C. This leads to more adhesion between slit tape and parts of the laying head. For constant climate conditions in a production hall without conditioned environment, the laying head has to be encased and air-conditioned to a constant holding temperature of 21 °C.

### 3. Experimental manufacturing cell for AFP processes

For the development of innovative AFP heads, a manufacturing cell for experimental studies and processes was needed. To decrease cost and increase flexibility, the AFP machine concept is based on a six axis industrial robot with a linear positioning axis (see Fig. 2). This linear axis is also integrated in the robots positioning interpolation. To allow different end effectors for various applications, a tool changing system is applied. The robot within the manufacturing cell has two operating areas. To its right side different types of molds and other tools can be placed. To its left side a linear high-speed axis is installed, which allows maximum tow-placing speeds of up to 3 m/s and a maximum acceleration of 10 m/s<sup>2</sup>. It can optionally be equipped with a rotation axis, which is also integrated in the robots positioning interpolation and reaches up to 60 revolutions per minute. The core of the fiber placement heads control system is a Beckhoff PLC working synchronously to the KUKA robot control system by master-master communication. This control system is accessible for implementation of new components and axis and thus offers high flexibility for future applications and further developments of fiber placement applications.

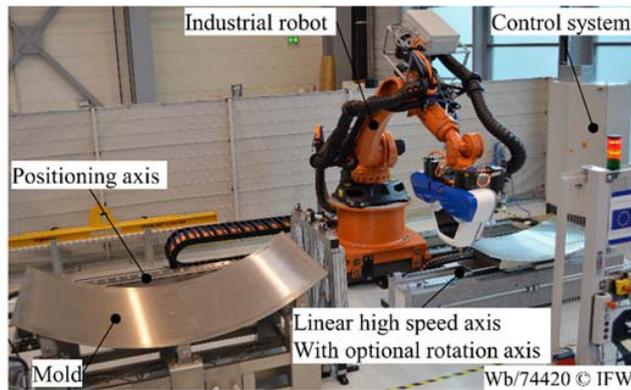


Fig. 2. Layout of the experimental manufacturing cell.

### 4. Modular AFP head

#### 4.1. General structure of the laying head

The AFP head is designed as a modular system subdivided into eight modules and mounted on an industrial robot (see Fig. 3). There are six functional modules, called air conditioning unit, material supply unit, feeding unit, cutting unit, heating unit and compaction unit, and two passive modules, called module carrier unit and tow guiding unit.

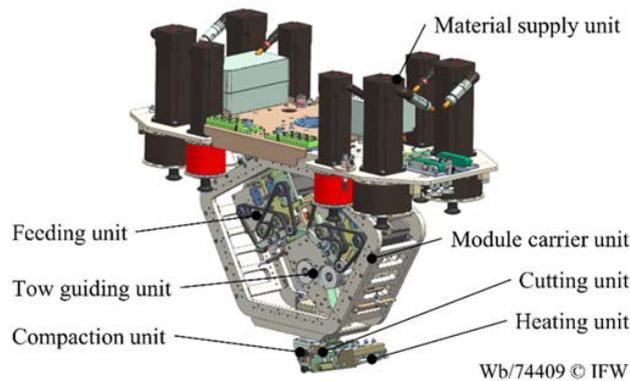


Fig. 3. Design of the modular AFP head.

Furthermore, several sensors are integrated for monitoring temperature, humidity, tow tension and approximating the amount of the material left in the supply unit. The temperature and humidity is measured and recorded during manufacturing process inside the laying head in the material supply unit and to find out the ambient conditions near the nip point. Pyrometer are used for measuring the temperature of the tow inside the laying head and for the temperature control of the heating unit. For the latter one pyrometer measures the temperature of the mold or, later, of the placed tows, and another one the temperature directly in front of the compaction roller. The tow tension is measured by pressure measurement and ultrasonic distance sensors detect the material in the supply unit. In addition, the modularity of the AFP head opens the possibility to integrate sensors for process monitoring. Fig. 4 shows e. g. an infrared camera installed on the module carrier unit. It was developed within a new project called “Therm-O-Plan” [4] and is able to monitor the placement process and to detect defects (gaps, overlaps, foreign bodies, etc.) and the position of the tows. Other sensors can be installed as well, e. g. laser line scanner for the detection of tow edges.

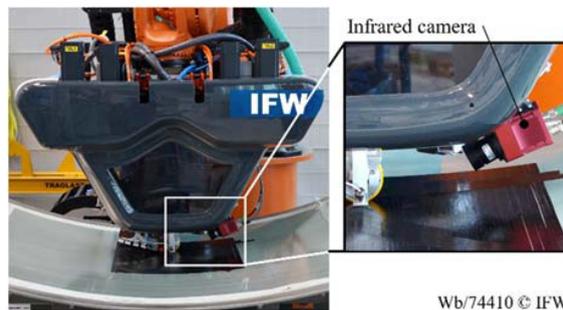


Fig. 4. Integration of an infrared camera for process monitoring.

The modular structure of the laying head makes it possible to replace existing units by newly developed ones and do reference analysis on different approaches. Commercially available machines do not offer this possibility. With this approach, it is easy to replace for example the subdivided compaction roller by a continuous compaction roller.

As mentioned before, the AFP head is primarily designed for placing four 6.35 mm wide tows. However, all units are designed to possibly extent the system to more than four tows as well as the use of wider tows in mind.

#### 4.2. Material supply unit

The first module presented in this paper is the material supply unit. It consists of two identical units with two bobbins of material each. By locating this unit directly in the laying head, the tow guiding from creel (here called

material supply unit) to compaction unit is much shorter than in designs with external creels. This reduces problems related to long distances between these two units such as fuzzball formation and twisting tows.

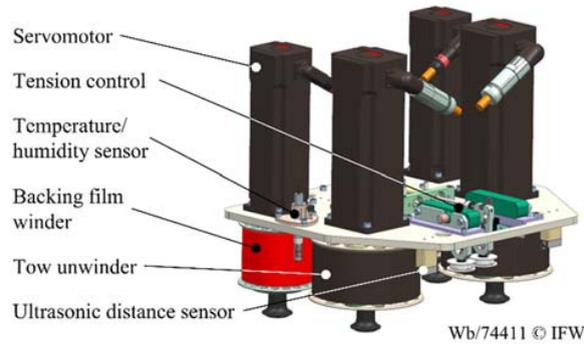


Fig. 5. Design of the material supply unit.

The current material supply unit is dimensioned for research application with a capacity of CFRP slit tapes of about 150 m per tow. This concept of material storage is, however, also possible for the usage of commercial material bobbins. The backing film of the slit tapes is removed directly after unwinding it from the bobbin. A tension control on the one hand generates the necessary tension for slit tapes and on the other hand compensates for the different dynamic behavior of the servomotors located in the AFP head (see Fig. 5). The material supply unit is designed for a maximum speed of 3 m/s and a maximum acceleration of 10 m/s<sup>2</sup>. In combination with the feeding unit, a continuous feeding of the tows is possible.

#### 4.3. Feeding unit

The feeding unit gives a continuous feed rate up to 3 m/s to the tows during the manufacturing process. Hence, the feeding unit is not only used for the restart process after cutting the tows. The continuous feeding leads to less tension in the CFRP tows before placing them on the mold. This is particularly important to prevent bridging. Between feeding and cutting unit, the tow guiding unit is located, as displayed in Fig. 6, and guarantees a direct guidance of the tows towards the nip point.

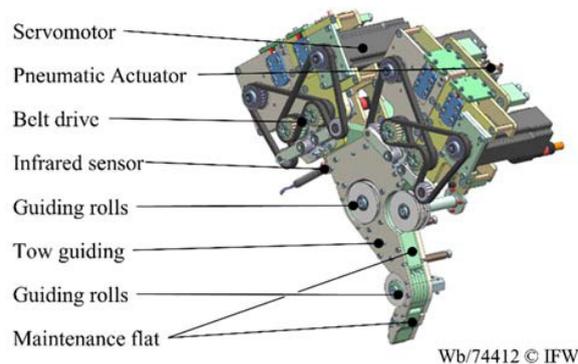


Fig. 6. Design of feeding and tow guiding unit.

#### 4.4. Cutting and heating unit

Among others, the development of the cutting unit focused on reducing the minimum length of a tow, which can be placed (minimum placement length). The cutting mechanism of the cutting unit is knife-edge cutting on an anvil (see Fig. 7a).

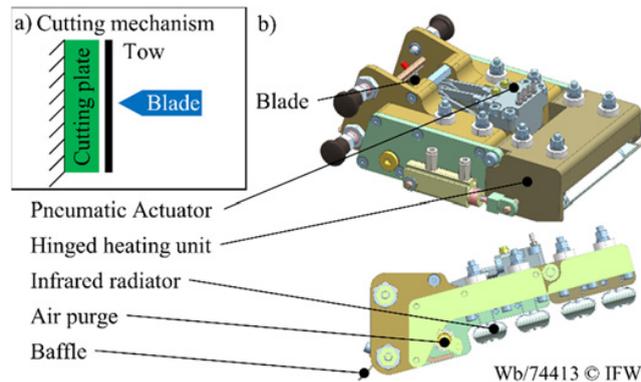


Fig. 7. (a) Cutting mechanism of the cutting process, (b) Design of the cutting unit with integrated infrared radiators.

The anvil, here called cutting plate, is made of a self-healing and flexible material. This combination guaranties a reliable cutting process. In order to describe not only straight laminate boundaries also curved and bevel boundaries, one blade for each tow is required to approximate the outer geometry. For the cutting process, pneumatic actuators actuate the blades and with fast switching valves and a short travel of the piston, the time for cutting can be reduced to a few milliseconds. In Fig. 7b, the assembly of the cutting unit is displayed.

To realize a compact design and high flexibility in the area of the nip point, the heating unit with its four infrared radiators is integrated in the cutting unit. An air purge cools the assemblies because of the thermal radiation of the infrared radiators. They heat up the mold or the already placed CFRP layers, respectively, before placing tows (see Fig. 8). Each infrared radiator has a maximum heating power of 500 W. Therefore, with four implemented infrared radiators, a heating power of 2000 W is available. This corresponds to a surface power density of 15.77 W/cm<sup>2</sup>.

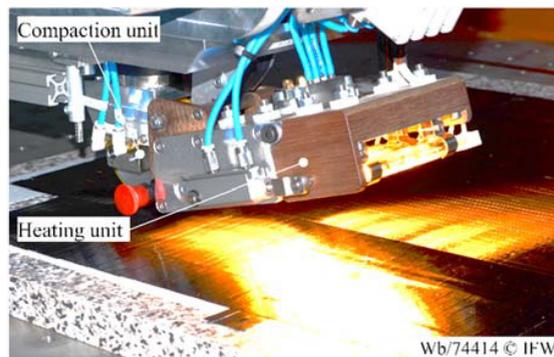


Fig. 8. Using infrared radiators in the heating process.

#### 4.5. Compaction unit

As mentioned in chapter 4.1, the compaction unit consists of four rollers, each having a width of 6.3 mm with a tolerance of +0.05 mm. By design there is a gap of 0.2 mm between the rollers. In total, the compaction roller therefore

has a width of 25.8 mm. The diameter of the rollers is 68 mm, allowing for a maximum curvature of 0.015 1/mm to be followed. Each segment of the roller is height-adjustable by 4 mm. In Fig. 9 important geometric boundary conditions are displayed. These parameters define the limits in manufacture of curved stiffening structures.

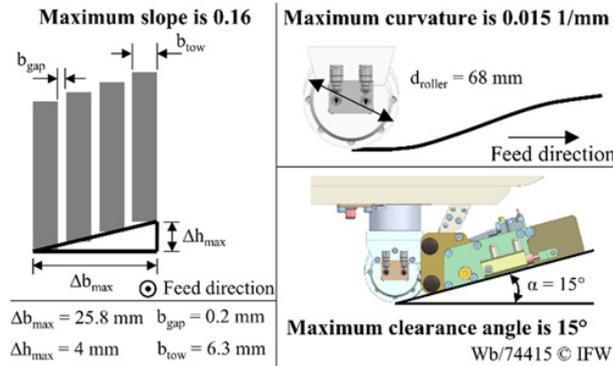


Fig. 9. Geometric boundary conditions of the AFP head.

The mechanical design of the compaction unit is shown in Fig. 10. Each of its segments consists of a roller with a flexible outer layer and a pneumatic actuator within the bearing. The actuator allows for realizing different grades of compaction and surface pressures. A force/torque sensor measures the forces and torques in the nip point and controls the pressure of the pneumatic actuators. The data from the force/torque sensor can be used to analyze the actual pressure applied by the compaction unit and estimate compaction of each placed tows.

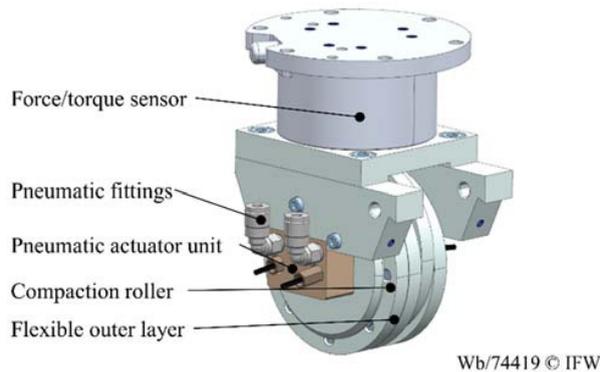


Fig. 10. Design of the compaction unit.

#### 4.6. Process monitoring

Process monitoring becomes more and more important in the manufacturing process of CFRP parts in the aerospace industry. Analyzing the fiber placement process makes direct feedback regarding process failures possible. Such monitoring of the placement process is implemented by using thermographic imaging to detect the temperature difference between the heated mold or placed CFRP layers and the slit tapes in the laying head. When placing slit tapes, the temperature of the placed slit tapes is lower than the temperature of the mold or the CFRP layers. The measured temperature differences are analyzed to detect edges as well as to determine relative positioning of the tows. Furthermore, defects and foreign bodies in or on the laminate can be detected. More information about the thermal process monitoring are published in [4].

## 5. Validation of placement quality

In first experiments to validate the requirements of the AFP head the characteristics of gaps in flat placement processes were investigated. The gap width varies between 0 mm and 0.4 mm for planar fiber placement. Due to the mechanical design, the gap between the compaction rollers is 0.2 mm. Thanks to the pressure control of the compaction roller and the high-power heating unit, good adhesion of the first ply to mold surface was achieved. While placing the second ply, the regions with low first-ply adhesion were compacted again and a perfect adhesion was reached. In Fig. 11a, the results of the first and second ply placement are displayed.

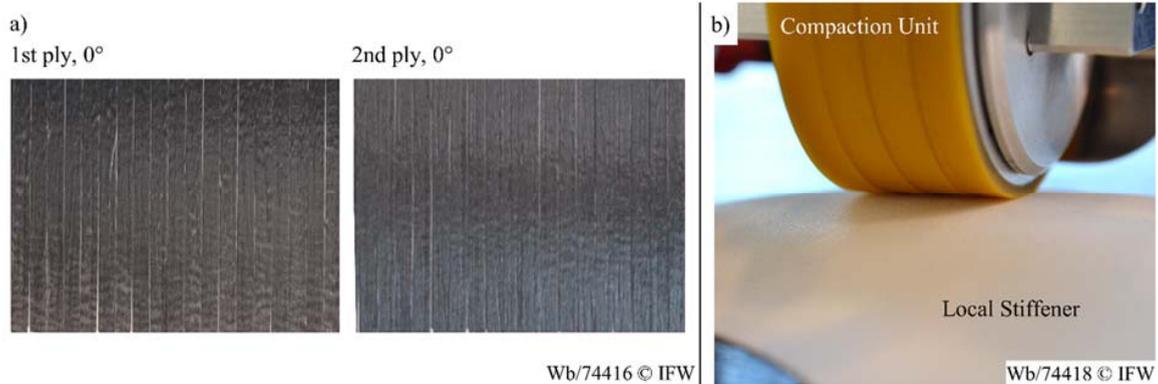


Fig. 11. (a) First and second ply placement in flat manufacturing process; (b) Adjustment of the compaction unit to the shape of the local stiffener.

For manufacturing, it is important to reach a short minimum placing length for tows. Thanks to its design, the AFP head achieves 68 mm. Due to the parallel cutting of tows, this length is constant at any time.

In experiments for validating the flexibility of the compaction unit, the local stiffener was placed on CFRP layers on a metal mold. The local stiffeners are designed with the geometric boundary conditions of the AFP head with respect to the optimal ratio between mass and stability. Within a first test, the rollers are able to follow the surface of the local stiffener during drive over (see Fig. 11b).

## 6. Conclusion and outlook

The AFP head presented in this paper exhibits an approach for a modular AFP production system. Especially in R&D environments, this system opens the opportunity to test new assemblies for AFP heads without comprehensive changes to the rest of the production system. For research purposes it has only four compaction roller segments, but can easily be enhanced to industrial standards due to its scalable design approach. The heads design and especially the design of the compaction unit allows in particular the manufacturing of stiffening structures with curved surfaces. Thus, design-wise the area of application for AFP processes could be broadened to complex curved structures. First experimental investigations in flat placement processes show the potential of the new laying head. The next step will be to investigate its capabilities on laying on complex curved parts, like the local stiffener. In addition to increase the process complexity, laying tests with maximum laying speed up to 3 m/s will be carried out. The goal is to determine the influence of higher laying speeds to laying qualities and process failures.

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