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Manufacturing Thermoplastic Composites by Laser Automatic Tape Placement Toolless Technology with Dual Robot System

Filip Kochoski[1], Vladimir Dukovski[2], Samoil Samak[1], Dijana Cvetkoska[1], Biljana Petkoska[3]
[1]Mikrosam DOO, Prilep, N. Macedonia;
[2]Ss. Cyril and Methodius University, Skopje, N. Macedonia;
[3] Institute for Advance Composites and Robotics, Prilep, N. Macedonia

***Abstract*—One of the advanced technologies for the production of polymeric thermoplastic composite structures is the automatic tape placement technology (ATP). The application of this technology is widespread throughout the entire industry for the production of cars, airplanes and the aviation industry in general. However, the application of this technology with two robots, one of which is playing mandrel function, contributes to lower costs and time required without producing expensive and complex mandrels. The merging of these two technologies contributes to a more optimal production of composite structures. This paper describes dual (two) robot composite manufacturing technology with ATP technology, which provides additional freedom in the design of composite structures without the presence of geometrically complex mandrels.**

Keywords*—Composites, automatic placement, tool-less production, robot synchronization

I. INTRUDUCTION

Fiber-reinforced polymer composites are a major advantage over other materials for the production of composite structures, primarily due to their light weight and corrosion resistance. These composites have a high level of energy absorption which can be added additionally in terms of stresses and reinforcements on the composite part. This is why these composites are the primary target of the automotive, aerospace and airplane industries. The most common advanced technologies for composite production are: the Automatic Fiber Placement(AFP) and Automatic Tape Laying (placement) (ATL/ATP) technologies, both of which are similar in process techniques, with ATL using a wide tape unlike AFP where multiple tapes (fibers) are used. While AFP technology lays a large number of individual tapes, ATL lays unidirectional tapes of fiber or fabric. Both processes use continuous fibers, dry or impregnated with a thermoset or thermoplastic polymer matrix. Which of the two technologies will be used depends on the part geometry, the production yield to which the manufacturer aspires as well as the ultimate purpose of the product [1]. In terms of aviation components, ATP technology proves to be the most appropriate application and provides the best performance for this purpose. AFP is a technology that combines other composite manufacturing processes to produce a variety of airplane parts, but this process is not ideal for creating all types of shapes and parts (there is no process ideal for all types of shapes) [2].

ATP is a computer-controlled process that uses tows or strips to lay laminates on non-geodetic forms. The head with which material is laid is in contact with the surface of the mandrel during the laying process. The material is laid on the surface of the mandrel with tension and compression pressure. The multiaxial machine is programmed to follow the exact contour of the mandrel and to maintain contact between the head and the mandrel.

The advantages of the ATP process include reduced production labor, reduced need for in-process inspection, and significant reduction of waste material during processing. The cost advantages of this process vary depending on the specific purpose - some components that are produced are more cost effective than others. Usually large components (such as airplane fuselages) that allow the machine to move at maximum speed are more cost-effective than highly complex parts that require slow machine operation. ATP is a very efficient process that has a small percentage of waste material (3-5%), which can significantly contribute to the consumption effectiveness of this process.

The equipment required for the ATP process is usually quite expensive, which limits the use of the process by large airplane producers, but its cost is expected to become more affordable and more accessible to more manufacturers. A form of ATP technology suitable for the wind turbine industry has also been developed. Wind turbine blades are very big structures whose production can benefit from automation [3].

Major manufacturers of ATP systems are: Automated Dynamics (USA), Accudyne (USA), MAGCincinnati (USA), Coriolis (France), Electroimpact (USA), Foster Miller / ATK (USA), Ingersoll (USA), Mikrosam (N. Macedonia) and MTorres (Spain). Automated Dinamics, Accudyne, Coriolis and Electroimpact mainly use portal structure of the machine equipped with ATP head[4]. Cincinnati, Foster Miller, Ingersoll, Mikrosam and MTorres use either vertical columns or portal structures. Robotic laying systems usually have lower initial capital requirements and can be better adapted for specific purposes. However, when relying on this ATP technology, we should also consider the mandrel that will be used, i.e the geometrically processed physical body that will be the support for ATP technology. Most commonly, these mandrels can be very complex and expensive to produce. In this paper is presented ATP technology without using mandrel as a tool and use of a second robot is used with the purpose of substituting mandrel (tool less production).

The first patent referring of in-situ consolidation process dates from 1986, associated with DuPont [5]. Northrop Corporation, the American aircraft manufacturer, issued a patent on this topic in 1991 [6] applying the automatic layup to a thermoplastic material using a heating source on the substrate and the material being supplied. The Boeing Company in 2002 also protected its work on the heating method and the heating control system in the process of layup of thermoplastic material [7]. For to improve the quality of layup, heating sources must be rapid for heating and elevate temperature layups [8-13]. The work of Felix Raspal and others [14] describes a similar study of complex 3D composites produced by fusion of AFP technology. This paper explains the key benefits of the so-called additive technology, i.e its integration with AFP technology, which, as in this research, implies low costs of mandrels (or molds), compatibility of the material with the mandrel at 250°C polymerization, and complete automation of the production of composites [15-18].

As we said before the automatic lamination and in-situ consolidation process with thermoplastic reinforced material has been studied since the 1980s [19]. Most of the initial references based on this process refer to the development of laminates for the development of large structures [20, 21]. This manufacturing process reduces costs due to a limited amount of scrap or excess material in the tapes, improvements in the positioning of the material, repetitive results, and lower labor costs

The first study where the application of this manufacturing process to the layup of flax fibers with polypropylene polymer was conducted and with PEI matrix [22, 23]. Later [24], results on flax fiber-reinforced polyamide layup were published. The critical aspect of productivity, a need for transfer of this process to an industrial scale, has been considered by different authors addressing different aspects. Among them, the reduction of the prohibitively high prices of materials [25] and of the auxiliary elements has helped to promote it as an alternative to consider in its application to the production of aeronautical parts.

Due to the growing structural requirements of aeronautics, high-performance thermoplastic polymers are commonly studied. Poly-aryl ether-ketone polymers family is the most attractive for the aerospace industry and many studies regarding poly-ether-ketone-ketone and poly-ether-ether-ketone (PEEK) can be found in the literature, [26-29] as well as research related to other high-performance thermoplastic polymers such as polyamide, poly-phenylene-sulfide or polyetherimide. The main advantages of thermoplastic polymers when compared to thermoset have been widely reported in the literature [30, 31] as excellent mechanical properties and behavior against impact, no need of cold storage for long shelf-life, no chemical reaction during the consolidation

Many authors [32-42] today work to improve the in - situ laser assisted LATP process. Some work [25] on intimate contact and heat transfer, some work [33-37] on fixing and removing defects that occur in the whole process and some work [37-42] on technological processes that require the appropriate technological parameters to improve product quality.

The presented paper introduces an automated process for fabrication of thermoplastic composites without the use of molds or tools during robotized LATP process. One of the primary objectives of this phase of the study is to identify the dominant processing parameters and establish their influence on the quality of final composite materials.

II. LAFP PROCESS

One of the main component of complex production equipment is the laying head used in composite material laying technology, shown in Figure 1. There is one key element on it - the press roller. Its function is to apply pressure when laying the strips on the surface, to consolidate them and connect them with the lower layers. With programmed pressure roller control, it is possible to change pressure during one cycle. The choice of pressure to be applied depends on the material, the surface on which it is applied, the type of pretreatment, the characteristics needed to achieve the other parameters of the process such as speed, temperature, laying angle and so on.

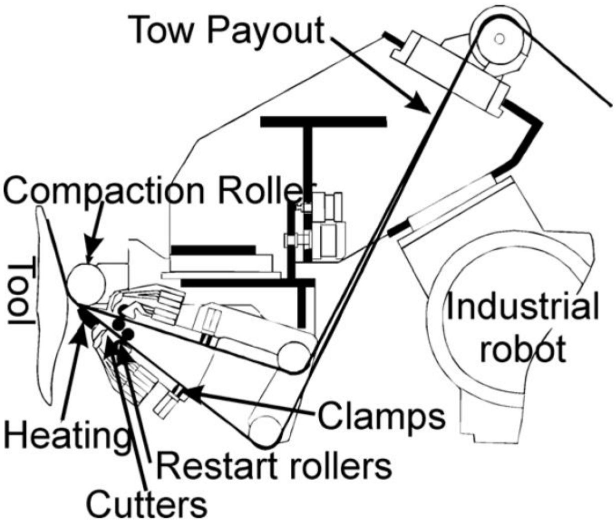

Fig. 1: Schematic of an AFP/ATP head [4]

Heating is another important element. For thermoset prepreg, it is advisable to keep the tapes at a lower temperature right before the process of laying, in order to prevent them from sticking through the transport system (on the rollers for changing direction or on the cutting mechanism). For thermoplastic prepreg, the temperature should be higher at the place of their exit from the head, where they are laid on the surface, where the increased temperature contributes to their consolidation and adhesion to the lower layers.

A. *Dual robot process methodology*

To increase the flexibility potential of ATP technology, the option of introducing two robots, a main and auxiliary one, is offered as a method to produce a specific geometric composite structure of thermoplastics, which will be supported by a rotating auxiliary robot with a roller that will play the role of a mandrel throughout the laying process. ATP was used to create an automated tape placement (ATP) to create an integrated manufacturing cell with dual robots working in tandem: one robot lays up thermoplastic unidirectional (UD) tape, another robot acts as a tool opposite the placement head. The movements of the robots should be precise and coordinated to obtain spatial 3D in-situ consolidation across multiple layers.

The system is integrated with MikroPlace, Mikrosam's simulation, control and automation software, and Mikro Automate, software which enables multiple robots to work as a single cell to produce a composite part. With this integration the material placed in space can be held together by a metal frame on one or both ends, depending on the desired final shape. This application of thermoplastic carbon fiber 3D printing is targeted at industries such as aerospace and marine, where building a new mandrel or tool isn't always feasible, or where complex or specialized applications may require flexibility.

The multi-robot 3D printing system leverages Mikrosam's advances in producing in-situ consolidated thermoplastic parts over the last several years. The LATP systems from Mikrosam include a laser heating source with precise temperature and angle control as well as closed-loop feedback with thermal models.

B. *Design and development of a dual robot placement system*

The two-robot system has a very important and unique property for the production of highly complex and expensive to make geometries: the absence of a mandrel, i.e. the tool on which the desired design of the composite structure is placed and formed. This system provides a high degree of freedom in designing and optimizing of different operations and allows production to be reduced to a minimum on an economic scale in terms of costs. This system consists of two 6-DOF robots placed opposite each other and a metal frame that serves as an auxiliary mandrel. Each laying of the frame is planned based on the CAD model for the part to be produced, shown in Figure 2.

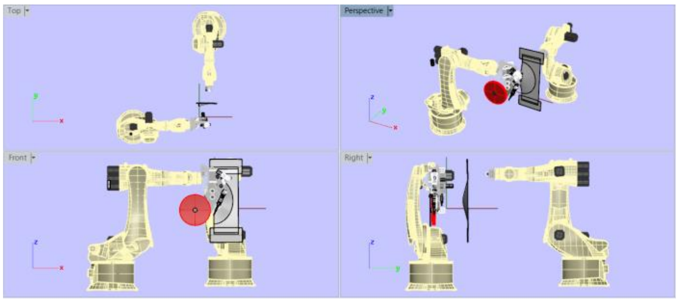

Fig. 2. Robots layup of fiber/tape placement system

Dual robot system consists of several components including two 6 DOF robots. One of the robots (master) is equipped with an AFP head, while the other (slave) robot is equipped with an electric movable roller that serves as a support during the process and a metal frame for the initial gluing of tape. The key in setting up the whole system is the synchronization of the two robots, the master and the slave. The synchronization method takes place through the programming language KRL which is the source language of communication of KUKA robots [1]. However, the two robots do not always have to be synchronized during the whole laying process. They interact only when it is necessary to lay on the support robot playing the role of tool (slave robot).This means that the master robot will lay at beginning and at the end of the set frame, in order to maintain the courses taken, while the slave robot will be always synchronized with the main robot in those places where there is no more support for the main robot, between the top and bottom of the frame.

As shown in Figure 3, the metal frame serves to lay the thermoplastic material only at the beginning and at the end of the frame, which consists of a flat parts. This serves to maintain the stability of the composite piece form which is in the middle of the structure where support from the slave robot is required.

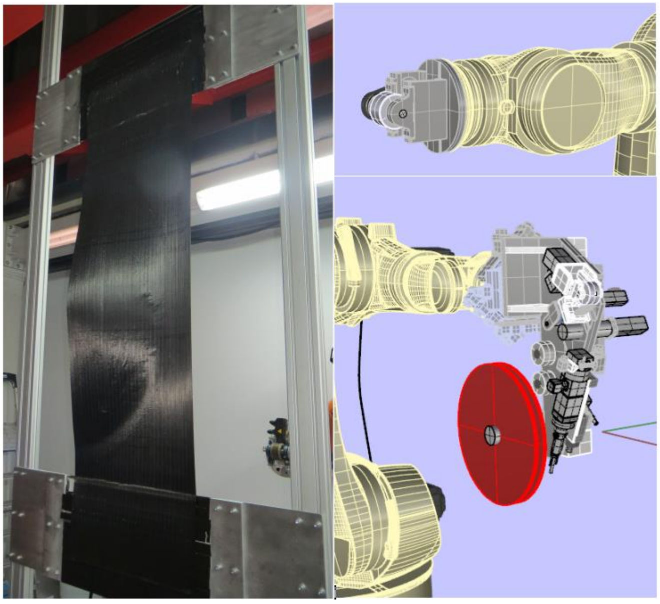

Fig.3. Metal frame with composite - left, mandrel roller (slave robot) - upper right and AFP head (master robot) - lower right

C. *Calibration and synchronization of dual robots.*

The first step in synchronization of two robots, i.e the two controllers, is done through the RoboTeam software [1], which establishes a physical and software connections between two robots. After connecting the two robots, the next step is calibration, which is an important part of further synchronization between the robots. There are several methods for robot calibration. One of the methods proposed by KUKA is calibration with four different positions. For precise calibration of the two robots, it is recommended to make two tools with three spikes that are placed at the end effectors position. The height of the spiked tool should be the same as the height of the robots' rollers, one electric for the slave robot, and the pressure roller for the AFP head of the master robot (Figure 4).

The next step in connecting the two robots in terms of their synchronization, which was done by creating the KRL code with the appropriate commands for synchronization, interpolation and block iteration. The generation of the machine KRL code, the model of the mandrel and the machine path are done through the MikroPlace® software from the Mikrosam company (Figure 5)[1].

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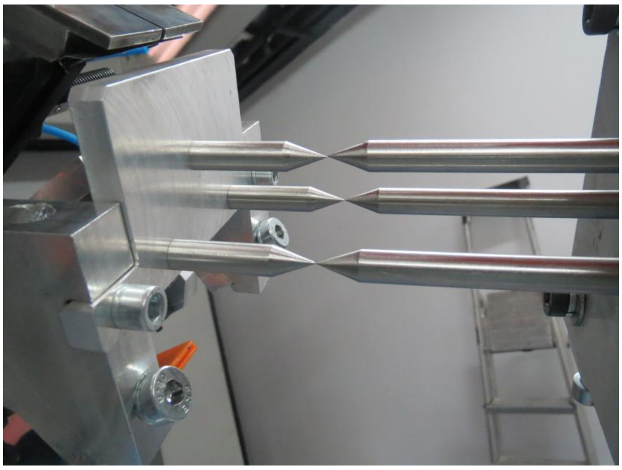
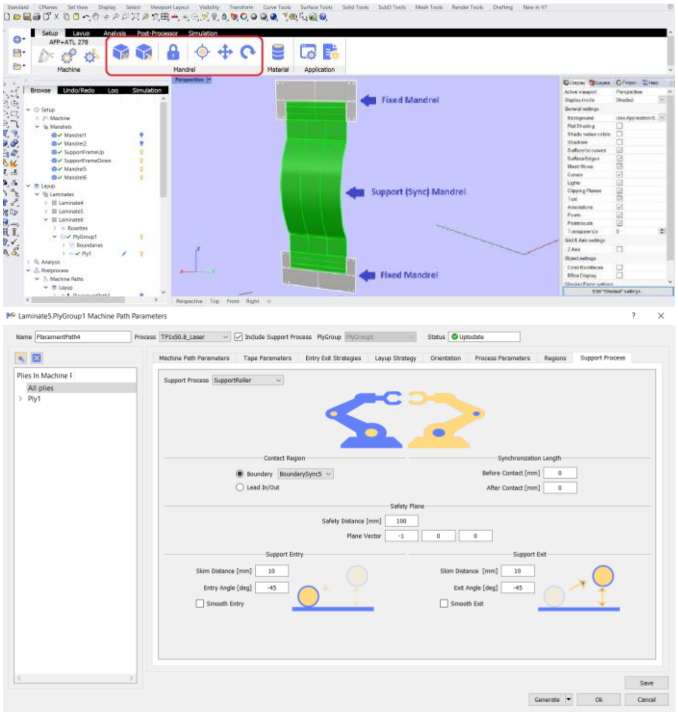


Fig.4. Dual robot calibration with spikes tool



Laminate5.PlyGroup1 Machine Path Parameters

Name PlacementPath4 Process TP1x50.8_Laser ☑ Include Support Process PlyGroup PlyGroup1 Status Uptodate

Support Process SupportRoller

● Boundary BoundarySync5
○ Lead In/Out

Before Contact [mm] 0
After Contact [mm] 0

Safety Distance [mm] 100
Plane Vector -1 0 0

Skim Distance [mm] 10
Entry Angle [deg] -45
☐ Smooth Entry

Skim Distance [mm] 10
Exit Angle [deg] -45
☐ Smooth Exit

Fig.5. MikroPlace$^{®}$ software for synchronized robots

III. EXPERIMENTAL INVESTIGITION

A. *Materials and equipement*

For this purpose, we used two KUKA robots with 6DOF of which one is with the AFP head attached and the second one is playing the role of mandrel. This means that the two robots need to be perfectly synchronized with each other in order to perform tool less production, shown in Figure 6. The materials use for the experiments are

1. Tencate - Catex TC1320 PEKK AS4D 145gsm, 34% RC, 1.00 " and
2. Suprem PEEK AS4D 195 gsm 34% 1 ".

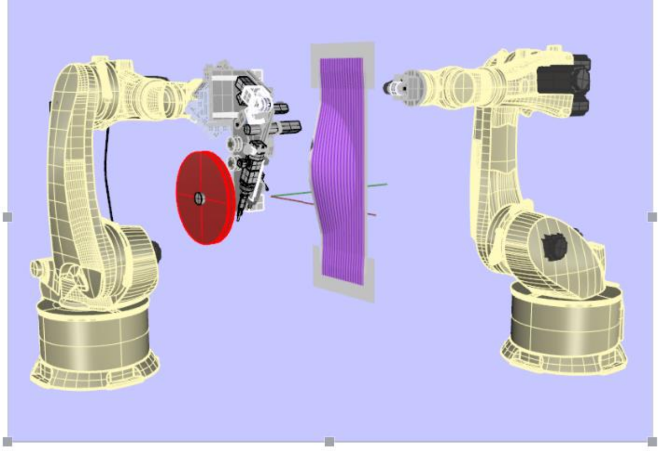


Fig.6. Simulated view of the Dual Robot System

B. *Experimental work with toll less dual robot system*

For the purpose of conducting experiments with the two-robot system, a metal frame with dimensions 660x1700mm is used. The part on which the thermoplastic material is laid to maintain the stability of the composite piece is 450x200mm on both sides, up and down the frame. The remaining open part in the length of 1100mm is used for the production of a composite part with synchronized robots. Two materials were used for the tests, the first of which proved to be suitable in the production of composite parts and a better option in the process of production. The composite piece design is also modeled in MikroPlace®. The tests are performed on three types of composite parts, hemispherical, recessed and completely curved (wavy), presented in Figure 7, of which only the first two composites designs proved successful.

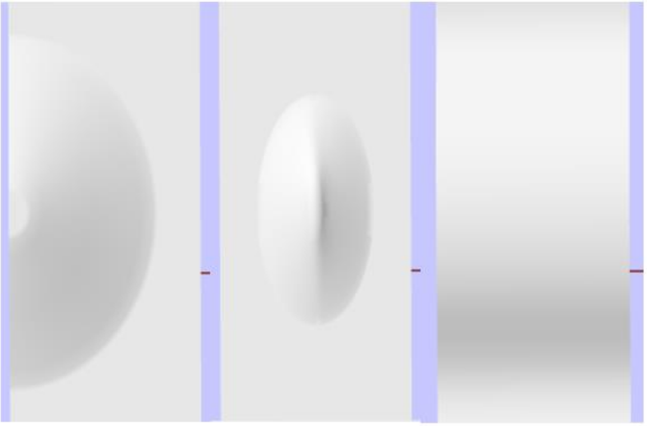


Fig. 7. Composite sample models

Layers are laid at different angles, vertically along the frame, dispersed angles in different range and a network of small angles. The overlap with which the longitudinal placement courses are taken has a 50% overlap.

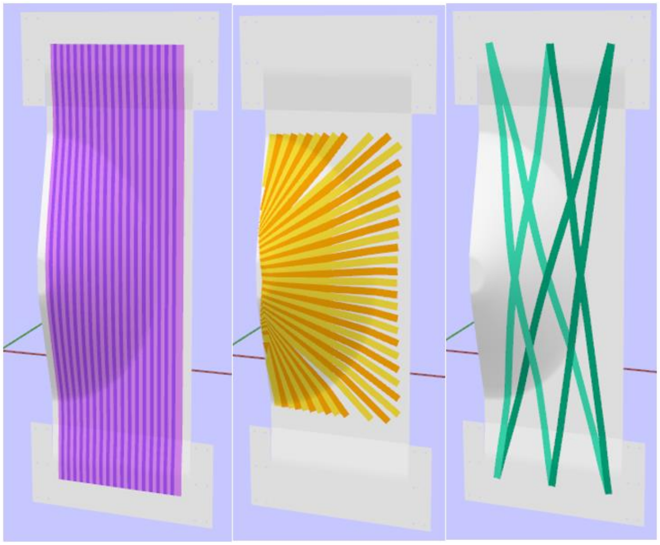


Fig.8. Generated placement plies by MikroPlace®

The tension during the test proved that it is best to take the first few courses with higher tape tension, such as 20N, while the rest of the course with 7-10N, as well as the other layers, and 2bar compression. Programmed speed of 7m/min and were used melting point between 350 and 400°C. For the laying process itself, the tape tension and the melting temperature of the thermoplastic have been shown to be crucial.

IV. RESULTS AND DISSCUSION

From the obtained tests regarding the thermoplastic materials, it was shown that the PEKK thermoplast from Tencate is better in terms of laying, unlike the PEEK thermoplast of Suprem, which is thicker than the first material. The better qualities of the composite may not depend on the type of thermoplast, but on its thickness for which new parameters of tension and temperature may need to be adjusted in the future. In these experiments, Tencate material proved to be a better solution primarily due to the physical characteristics obtained on the composite as a whole, such as the desired geometry, smooth laying after polymerization and the like.

Better results have been observed in the geometric modeling of the composite, primarily due to the transition to the curvature of the courses. Thus, according to the models from Figure 7, the best results in retaining the geometry were observed in the hemispherical model of the composite, then in the concave and worst in the curved model where there is no transition from milder to sharper curvature of the courses.

The analysis of the results showed that the tension of the laying of the tape was crucial, so the best results were achieved by taking the first courses that have no curvature at a tension of approximately 20N, which gives additional strength to the beginning of the production of the composite part during layering and the continuation of the following courses that are taken with a given curvature. For the other courses, it is necessary to reduce the tension to the optimal value between 5 and 7N in order to be able to pass the curvature correctly, otherwise if the curved courses are taken with high tension, it will contribute to a drastic increase of the deviation of the laid composite.

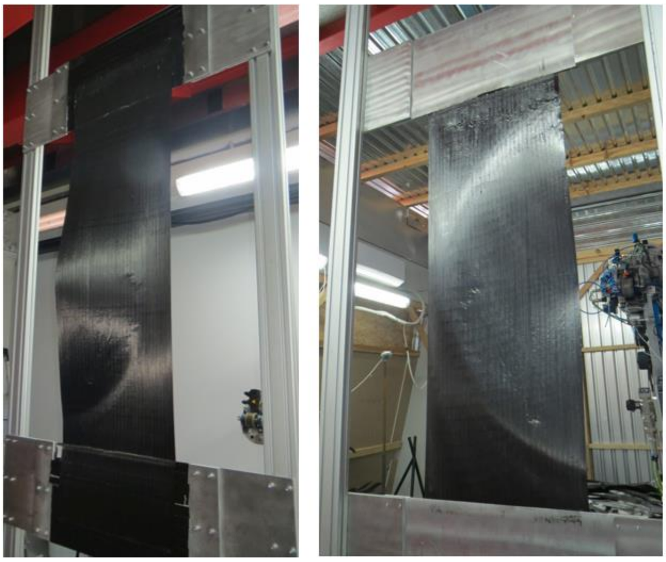


Fig.9. Hemispherical composite manufactured by Dual Robot System with Tencate PEKK material, front side (left) and back side (right)

An important factor in the test is the temperature of the polymerization of the thermoplast, in this case ~ 300°C, but it is crucial to take the first courses under high tension with a lower temperature of approximately ~ 150 °C in order to avoid deformation during high tension after polymerization of the material.

The overlap of the material that is added during the longitudinal laying also proved to be an important factor in maintaining a stable structure of the laying part. During the testing, layers with 30%, 50% and 80% overlap of the strip were taken, where the half-strip overlap proved to be the most stable in maintaining the geometric shape of the composite piece.

Finally, it remains to be discussed about the deviation of the final piece with the designed composite structure, which was expected in these tests due to the laying without a mandrel base. The largest deviation in the deepest part of the curved surfaces reached ~ 10mm, which is a challenge for the future to consider and examine other optimal parameters important in the process in order to reduce this deviation and minimize the error.

V CONCLUSION

According to the research and experiments presented in this paper, we can conclude:

- that the introduction and further research of tool less systems is promising technology,
- one of the key advantages is laying without the presence of a physical mandrel which can be really difficult to produce, and the costs for such a mandrel would be very high,
- replacing a mandrel with an auxiliary robot as support can replace many different mandrel designs that take time to design and process, including the complexity of the geometries we might assume and the costs involved.

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