Proceedings in MANUFACTURING SYSTEMS

Proceedings in Manufacturing Systems, Volume 7, Issue 3, 2012 ISSN 2067-9238

# CONTROL OF A THERMOPLASTIC TAPE WINDING PROCESS WITH OPTICAL IN-LINE METROLOGY

**Robert SCHMITT[1], Andreas WITTE[2,*]**

[1)] Prof. Dr.-Ing., Managing Director, Metrology and Quality Management, WZL of RWTH Aachen University, Aachen, Germany
[2)] Scientific Assistant, Production quality and metrology, Fraunhofer Institute for Production Technology IPT, Aachen, Germany

***Abstract:*** *The energy-efficient production of fiber reinforced plastics allow the usage of lightweight products for various applications in future. Structures made of carbon fibers convince through 70% lower weights in comparison to products made of steel or aluminum and can achieve better mechanical and chemical properties at the same time. Carbon fibers are therefore very attractive for automotive applications and can be used to reduce the weight of vehicles and consequently their fuel consumption.*

*The thermoplastic tape winding process is an energy-efficient technique for the production of fiber reinforced plastics. The main disadvantage of this process in comparison to established thermosetting winding processes is the missing quality assurance. Products for safety critical applications like pressure vessels require high process stabilities which are not obtainable without any quality assurance provisions.*

*The process integration of innovative metrology systems enables the industry to use thermoplastic tape winding for safety critical products. One of the main quality weaknesses of the manufacturing process is the exact positioning of the tapes. To increase the tape positioning accuracy, a metrology based control system has to be implemented. As the manufacturing process is using robots as machine tools the control systems needs to be adapted to robot specific requirements. Within this paper we present a system which has been developed to analyze and evaluate the use of optical metrology to control the robot based tape winding process.*

***Key words:*** *quality assurance, tape winding, optical metrology, robot control, pressure vessel, carbon fiber, energy efficient poduction.*

## 1. INTRODUCTION

There are various applications for carbon fiber composites in the industry. They are for example used in specialized sports equipment where efficient light weight structures are needed, like modern sailing race yachts [1]. But in the last years carbon fiber structures cannot only be found in specialized niche markets where the cost-benefit ratio usually is of minor importance than in mass products. One example is the use of carbon composites for the new Airbus airplane series like the A350 [2].

One of the main aims of using carbon structures is to reduce the weight of products. Especially for airplanes and automobiles the weight reduction directly increases the energy efficiency because the powered mass and therefore the fuel consumption are lower. In airplanes or automobiles the saved weight can be used for higher load capacities so that the economic efficiency increases as well.

Currently, there is a low market demand for mass products made of fiber reinforced plastics (FRP) in comparison to steel products, but the automobile industry is planning to use more and more FRP products for the new model generations of their cars. Therefore, growth rates of more than 10% per year are forecasted for the next years [3].

The development of the last years in the automobile industry is furthermore strongly shifting to the use of alternative fuels as a substitution for fossil ones. In terms of electro mobility one of the most important developments is the use of fuel cells and hydrogen for a reduction of carbon dioxide emission [4]. Though, a huge challenge is the storing of the hydrogen inside the car. As the volatile gas needs to be stored under high pressure, vessels with a big wall thickness have to be used. These pressure vessels, made of steel, have a high weight and increase the overall weight of the car significantly.

Carbon fiber composite (CFRP) pressure vessels can save up to 50% of weight in comparison to steel pressure vessels, which make them interesting for applications in the automotive sector even though they are more expensive than steel products. In automobiles it is furthermore not only interesting to use the carbon pressure tanks for hydrogen and for CNG (compressed natural gas) as well. There are already a significant number of cars with CNG technology in the market [5].

Besides the automotive use of carbon fiber composite pressure vessels, a field of application for these products is breathing air bottles, especially for firefighting

[*] Corresponding author: Fraunhofer Institute for Production Technology IPT, Steinbachstrasse 17, 52074 Aachen, Germany
Tel.: +49 241 8904-488
Fax: +49 241 8904-6488
E-mail addresses: *r.schmitt@wzl.rwth-aachen.de* (R. Schmitt)
*andreas.witte@ipt.fraunhofer.de* (A. Witte),

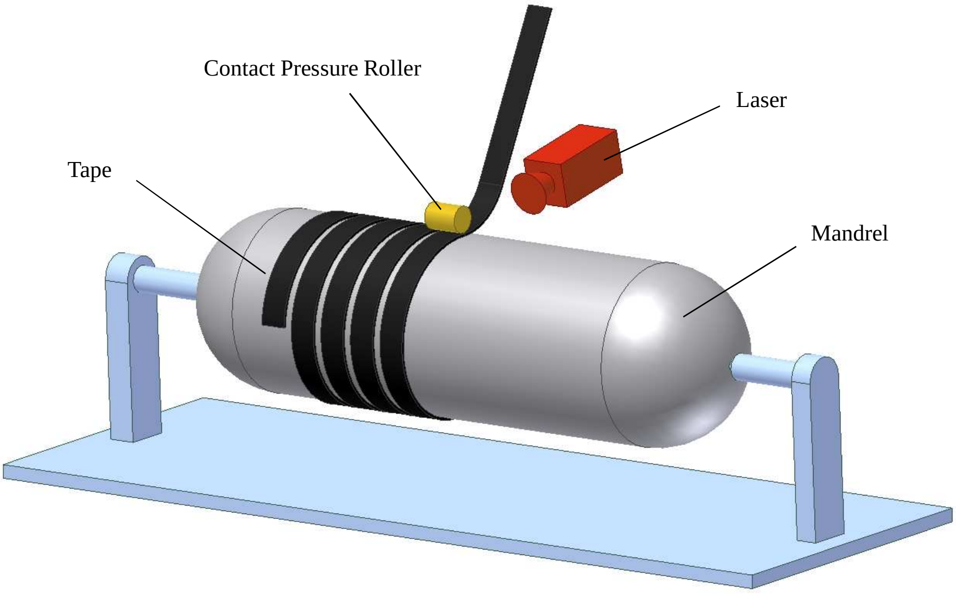


**Fig. 1.** Laser-assisted thermoplastic tape winding of a pressure vessel.

purposes. For the relief forces these breathing air bottles are of vital importance and lowering their weight can improve the force's firefighting performance.

If CFRP products in general and pressure vessels in particular shall be used in mass application, it is necessary to advance the existing production technologies towards these new requirements as well. With regard to quality assurance the new FRP production processes are not as developed as the manufacturing processes for steel products, which are already existing for decades. Especially for security relevant products like pressure vessels, a closed quality control loop is very important to avoid hazards for the people or the environment.

Fraunhofer IPT is developing quality assurance methods for FRP production processes. One of these quality assurance methods for a thermoplastic tape winding process will be described in this article.

## 2. PRODUCTION TECHNOLOGY FOR CARBON FIBER BASED PRESSURE VESSELS

### 2.1. Laser-assisted Thermoplastic Tape Winding

Pressure vessels made of carbon fiber composites are usually manufactured in thermosetting filament winding processes [6] which are established for mass production purposes. There are several different variations of this process depending on their exact application [7,8]. The common functional principal however is, that resin impregnated filaments are winded around a mandrel until the desired wall thickness of the pressure vessel is reached [9].

An efficient manufacturing process for pressure vessels in comparison to the thermosetting filament winding is the laser-assisted thermoplastic tape winding. Both processes are similar in some points but differ in the way of winding the fiber impregnated material around the mandrel. In the thermoplastic winding process pre-impregnated tapes are used which are in solid state of aggregation when they are fed into the process. When the current tape layer is put on the previously laid layer of the mandrel the thermoplast is melted by a laser to allow a subsequent consolidation [10]. A schematic of the machinery and the process for laser-assisted thermoplastic tape winding is shown in Fig. 1.

The mechanical properties of the whole component depend among other things on the laser power and the pressing force which are both controlled by the tape winding system. The laser power can be controlled by a pyrometer and the pressing force of the current tape against the underlying layer by a combination of a force sensor and a contact pressure roller [11–14].

The disadvantage of dissipating energy through continuous reheating furnaces cannot be found in the laser-assisted thermoplastic tape winding process because the laser is able to heat up the material locally. Consequently, the temperature can be controlled for every point and layer in the process individually so that it is possible to adapt process parameters due to changing environmental influence factors.

### 2.2. Process Challenges

For security relevant products like pressure vessels it is important to assure a continuous high level of product quality also in mass production. As already mentioned in chapter 2.1 one of the main influence factors in the laser-assisted thermoplastic tape winding is the exact temperature control of the laser, which was already solved in the past [15].

Moreover, the geometrical position of the tapes is very important for the component quality. Especially the positions of the tapes relative to each other are relevant for the mechanical properties of the pressure vessel. The ideal condition assumes the tapes lying in the path directly close to each other. There are mainly two irregularities from that ideal condition that can influence the further production process and therefore the mechanical properties: gaps between the tape paths and overlaps (illustrated in Fig. 2).

Gaps can cause mechanical instabilities because material is missing in areas where it is expected to be.

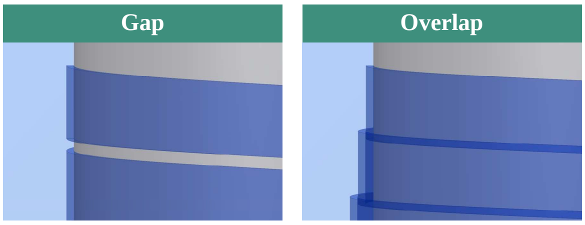


**Fig. 2.** Irregularities in thermoplastic tape winding processes.

However, there are low influences on the further process because the gap, if it is not too wide, will not cause irregularities to the behavior of the contact pressure roller. Otherwise, overlaps of two tape paths cause uneven surface structures and are consequently able to influence the contact pressure roller. In [16] it has been shown that uneven surface structures caused by overlaps prohibit a correct bond of the underlying tape.

If all machines and environmental parameters were ideal and constant there would be no errors during the process. However, there are several reasons for the two mentioned process errors. The path of the robot as well as speed and acceleration of the mandrel are calculated during the process planning and machine programming. Robots under load usually have certain path errors, even though they can be compensated partially [17], so that the position of the tape can vary in the dimension of the absolute accuracy of the robot.

A process parameter with a high influence on possible path errors is the quality of the raw tape. The influences of the tape quality on the laminate in general and different quality properties were analyzed in [18]. If there are any tape material inhomogeneities it will be formed in different ways, even if all the other process parameters, like the pressure of the roller, are constant. Besides that, the width of the tape can vary and therefore directly influence the position of the tape on the carrier. Additionally, the environment parameters like temperature, pressure and air humidity affect the process stability as well.

In summary, there are several influences which are responsible for tape misalignments. These misalignments can decrease the component quality significantly and consequently increase the risk of a severe component failure. To avoid that a process control concept is necessary, which is able to control the robot and therefore the tape position during the manufacturing of the carbon fiber vessel to compensate the influence factors.

## 3. PROCESS CONTROL CONCEPT

### 3.1. Requirements

To control the process, it is necessary for all components and the overall concept to fulfill the requirements regarding for example the control rate, temperature, contamination, resolution and measurement uncertainty. Therefore, the most important points will be described in this sub-section.

The metrology requirements are depending on the speed and accuracy which are defined by the manufacturing process. For an economic and competitive production of pressure vessels made of CFRP a tape speed of more than one meter per second is necessary. In order to quickly respond to tape misalignments, it is furthermore required to be able to measure with a lateral sampling smaller than 50 millimeters. Consequently, with a tape speed of one meter per second, a measurement rate of at least 20 Hz is needed to fulfill that requirement.

The resolution and measurement uncertainty influence the misalignment of the tapes relative to each other. Gap sizes and overlaps of more than a several tenth of a millimeter are not tolerable and have to be avoided to guarantee the structural integrity of the component. To detect gaps and overlaps in that order of magnitude reliably the metrology has to be able to resolve at least one tenth of the detectable gap and overlap width.

The metrology has to be further adapted to the process environment and the material. In the consolidation area high temperatures and contamination with material residues can be found. Additionally, the surface of the FRP material has certain properties which affect the measurement because it has a black surface with varying reflectivity. The measurement device has to provide reliable results even under these process conditions.

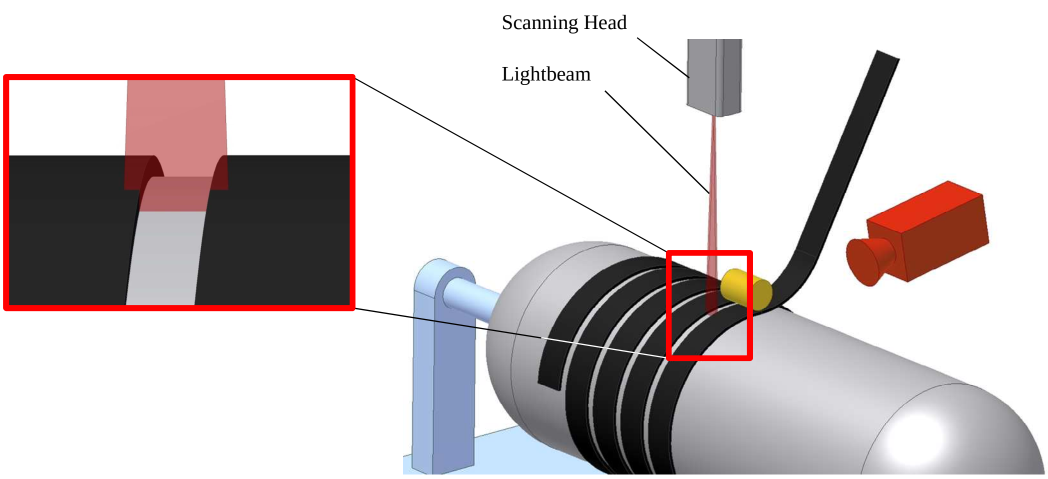


**Fig. 3.** Process control through optical measurement.

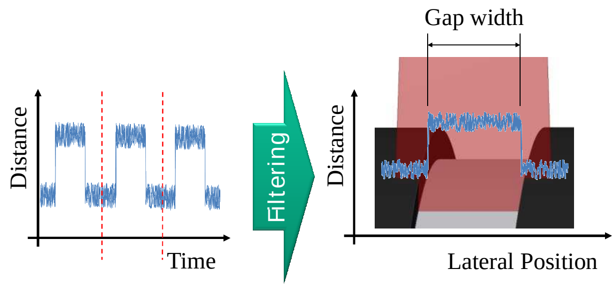


**Fig. 4.** Signal processing.

Other process variables need to be controlled separately to reduce the number of influence factors and requirements on the process control. The consolidation pressure for example is controlled with the contact pressure roller so that it cannot affect the tape form.

### 3.2. Metrology

To meet the requirements of in-process measurements with the needed resolution and control rate, tactile metrology is hardly possible to use. There are different optical measurement methods which have certain advantages and disadvantages. One method which is able to meet all discussed requirements is interferometry, although it is not commonly used in production environments.

White-light interferometry is moreover able to detect absolute distances and is therefore suited for the discussed application. However, for a point based measurement system a line scan is required to measure the gap or overlap width. Therefore a particular line scanner for the mentioned production environment has been developed.

### 3.3. Integration Concept

For an integration of the metrology into the manufacturing machine it is necessary to consider the mechanical configuration of the machine as well as the process conditions like temperature and contaminations. The principle of the metrology inside the machine for an in process control is shown in Fig. 3.

The scanning device is mounted in a certain height over the mandrel. The scanner is performing a line scan rectangular to the moving direction of the tape. The monitored area is close to the consolidation point to assure a fast reaction on changing process parameters.

The smaller the line width, the higher can be the lateral resolution or the higher can be the measurement frequency. Hence, the monitored area should be in the transition zone of the current tape and the previously laid one.

### 3.4. Detection of Gaps and Overlaps

The interferometer provides a continuous signal. The line scanning is an independent process and has to be therefore integrated separately. The acquired signal needs to be filtered to extract the information of gap and overlap width. The qualitative signal and the filtering process are shown in Fig. 4.
In a first step an encoded position signal has to be added to the continuous measurement data to be able to assign the lateral position to a measured distance. With this information the continuous signal can be sampled to the correct line width.

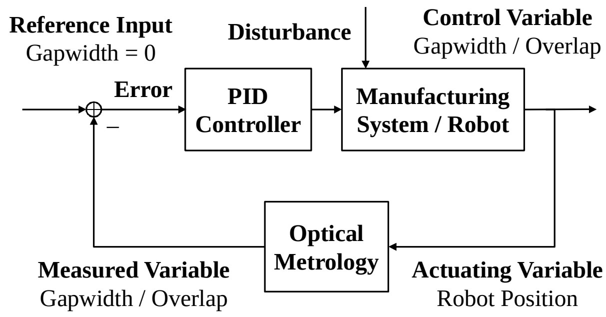


**Fig. 5.** Feedback control system.

In a second step the remaining signal needs to be corrected with a compensation function to assure a correct dimensional measurement. The optical design already causes a non-linearity, which can be mathematically corrected with simulated data. Additionally, misalignments in the assembly of the scanning device cause deviations in the measured data that are impossible to simulate. These deviations have to be compensated with a calibration process.

In the last signal processing step the gap width has to be extracted. The edges of the tape can be found by using the derivative of the signal and analyzing its maximum peaks.

### 3.5. Process Control Strategy

The basic scheme of the process control can be found in Fig. 5. The model is simplified and consists of the main elements which are important for the process control. These elements are the robot, the controller and the optical metrology.

The actuating variable in this control concept is the path offset for the robot which influences directly the real gap width and can be defined as the control variable. This control variable is acquired by the optical metrology and is therewith converted from the dimensional gap width to a measured variable, which is subject to the measurement uncertainty. The reference input for the whole system is the gap width, which should be as small as possible. Through the measured variable and reference input the error can be calculated, which is used as the input for the controller.

## 4. EXPERIMENTAL SETUP

### 4.1. Concept for the Control Development

In the previous sections the necessity of a process control in the manufacturing process for pressure vessels made of carbon fiber reinforced plastics has been described. However, a control development at the manufacturing system is connected with some disadvantages. Influence factors induced by the process like temperature variations or contamination complicate the control development process and can avoid the correct assignment of influence parameters.

For the development process it is therefore necessary to build up an experimental setup where no process influences can interfere with the control. This experimental setup has to represent the robot based manufacturing equipment as close as possible.

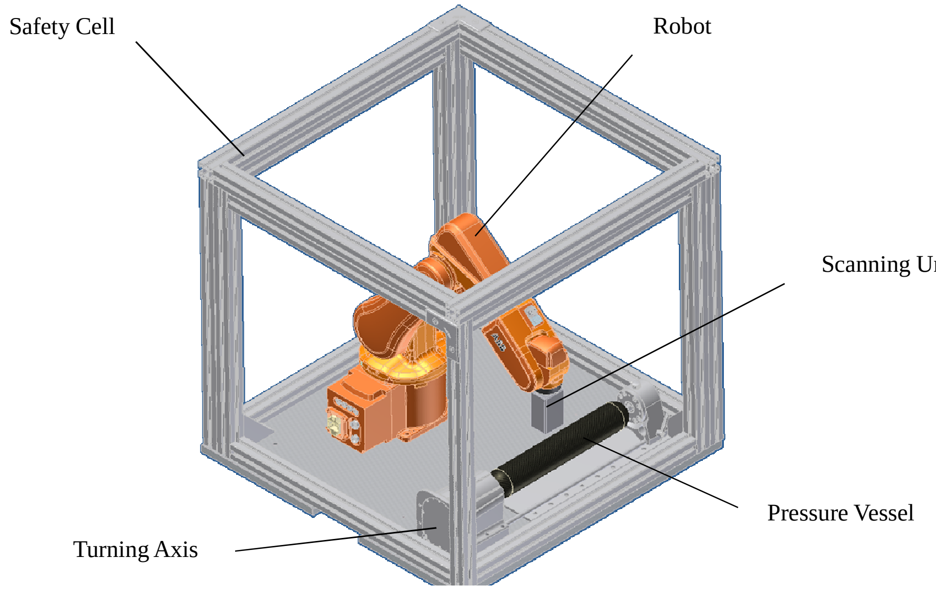


**Fig. 6.** Experimental setup.

### 4.2. Components of the Experimental Setup

The experimental setup for the control development is shown in Fig. 6. A robot is used as a machine tool to represent the manufacturing system because the different behavior of robots in comparison to standard linear axes based machine tools has to be considered in the development process. For the experimental setup an ABB IRB 120 industrial robot in combination with an IRC 5 control unit is used. The technical specification of repeatability, working load, possible accelerations and software control options meet the defined requirements. When using a robot a security concept is needed to protect individuals working close to the machine. The robot cell is surrounded by safety glass to allow a view inside.

An Isel RDH-S rotation axis is used in the experimental setup to have the virtual tape path being emulated as exact as possible. In the manufacturing process of pressure vessels tumble winders are used to reach the caps of the vessel. Here a standard rotation axis is adequate because the position and orientation of the robot tool center point relative to the mandrel does not differ from the manufacturing process.

The measurement system which is used in the experimental setup is a Precitec CHRocodile IT. The system can be either used for coating thickness or distance measurements.

The scanning unit is developed exclusively for the control development and is directly mounted to the robot. The mounting position of the scanning unit does not influence the measurement results. With the scanning unit the vertical measurement range of the entire system is 12 mm with a resolution of 0.84 μm.

## 5. EVALUATION MEASUREMENTS

For measurements with the described system a test specimen has been used. This test specimen (Fig. 7) has a defined spiral gap of 0.5 mm in a distance of 10 mm with a depth of 1 mm. With this test specimen the control can be developed and the measurement device can be characterized as well as calibrated.

In Fig. 8 a scan of a flat metal surface is shown. The curve progression is not linear flat but has a certain characteristic through the non-linear optical design and misalignments in the scanning unit, which were already discussed in section 3.4. Therefore, a correction function is calculated with the data of a flat surface and can be used to correct the measured values.

An example of a correction function is shown in Fig. 9. For the calculation of the correction table the data from the calibration process is filtered so that no measurement errors can cause incorrect calibration data. Measurement errors are interpolated with the nearest clean measured data. Furthermore, the absolute measured height has to be subtracted to be able to not influence the reference values.

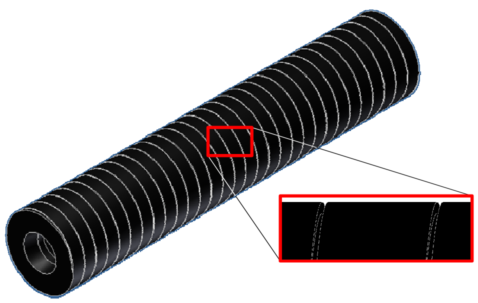

**Fig. 7.** Test specimen.

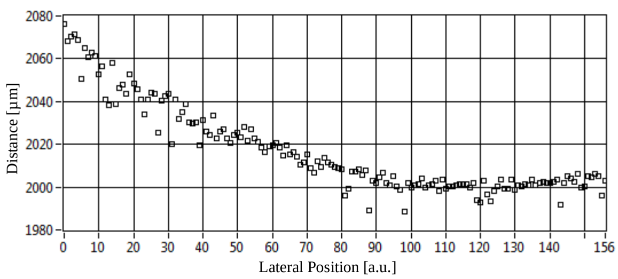


**Fig. 8.** Scan of flat metal surface.

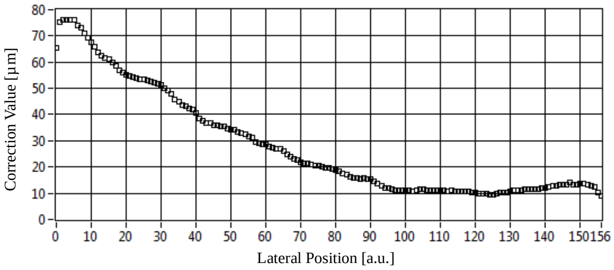


**Fig. 9.** Correction table.

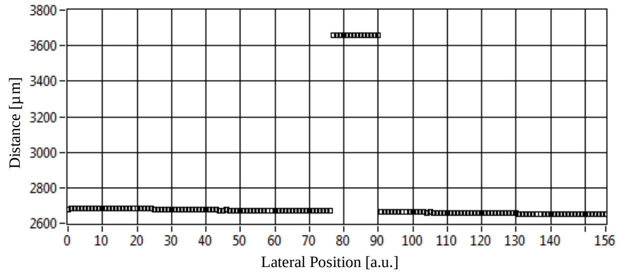


**Fig. 10.** Measurement of test specimen.

A measurement of the test specimen is shown in Fig. 10. The gap is represented by the characteristic peak in the curve progression. This peak can be used to calculate the gap width through the derivative of the measurement data.

## 6. CONCLUSIONS

The market of products made of carbon fiber reinforced plastics is continuously growing. Especially carbon fiber products used for vehicles or airplanes can increase the energy efficiency significantly. Lower weights of cars and airplanes decrease the fuel consumption which allows higher payloads and lower environmental pollution. Very important products in this context are pressure vessels as tanks for hydrogen or CNG fuels.

However, especially products for mass markets, like the automotive sector, need new manufacturing approaches to increase the economic and ecological process efficiency. Newly developed processes like laser-requirements on the efficiency. Though, unavailable in-process metrology prohibits the usage of that process for security relevant products like pressure vessels.

A particular problem in the laser-assisted tape winding process is the correct alignment of the carbon fiber reinforced tapes to each other. Fraunhofer IPT is developing a control system for the tape winding process to avoid misalignments of the mentioned tapes.

First results show that the applied interferometric sensor is generally applicable for the described field of application. The relative tape positions can be detected and used for further process controls.

**ACKNOWLEDGEMENTS:** The authors would like to acknowledge financial support by the BMBF within the research project “FiberScan” (02PJ2024).

## REFERENCES

[1] X. Bai, N. Li, *The Application of Carbon Fiber Composite Material for Sports Equipment*, AMR, vol. 496, 2012, pp. 480–483.

[2] G. Marsh, *Airbus takes on Boeing with reinforced plastic A350 XWB*, Reinforced Plastics, vol. 51, no. 11, 2007, pp. 26–29.

[3] R. Stewart, *Rebounding automotive industry welcome news for FRP*, Reinforced Plastics, vol. 55, no. 1, 2011, pp. 38–44.

[4] D. Stolten, T. Grube, *The Potential Role of Hydrogen and Fuel Cells*, in 18TH World hydrogen energy conference 2010, pp. 57–65, Jülich, 2010, Forschungszentrum Jülich, Jülich.

[5] F. Dudenhöffer, K. Pietron, *CNG as Automotive Fuel for Europe*, Duisburg, 2010.

[6] J. Velosa, J. Nunes, P. Antunes, J. Silva, and A. Marques, *Development of a new generation of filament wound composite pressure cylinders*, Composites Science and Technology, vol. 69, no. 9, 2009, pp. 1348–1353.

[7] S. T. Peters, *Composite filament winding*, ASM International, Materials Park, 2011, pp.2-4.

[8] S. D. Pandita, M. S. Irfan, V. R. Machavaram, N. Shotton-Gale, R. S. Mahendran, C. F. Wait, M. A. Paget, D. Harris, C. Leek, G. F. Fernando, *Clean wet-filament winding - Part 1: design concept and simulations*, Journal of Composite Materials, 2012.

[9] S. Beckwith, *Filament Winding: The String and the Glue*, Salt Lake City, 2004.

[10] E. Beyeler, W. Phillips, S. I. Guceri, *Experimental Investigation of Laser-Assisted Thermoplastic Tape Consolidation*, Journal of Thermoplastic Composite Materials, vol. 1, no. 1, 1988, pp. 107–121.

[11] S. C. Mantell, G. S. Springer, *Manufacturing Process Models for Thermoplastic Composites*, Journal of Composite Materials, vol. 26, no. 16, 1992, pp. 2348–2377.

[12] W.-C. Sun, S. C. Mantell, K. A. Stelson, *Demonstration of Bond Quality Improvement for Closed Loop Control of Thermoplastic Tape-Laying*, Journal of Composite Materials, vol. 35, no. 1, 2001, pp. 57–76.

[13] C. Brecher, M. Dubratz, J. Stimpfl, M. Emonts, *Innovative manufacturing of 3D-lightweight components*, LTJ, vol. 8, no. 5, 2011, pp. 36–40.

[14] M. A. Khan, P. Mitschang, R. Schledjewski, *Parametric study on processing parameters and resulting part quality through thermoplastic tape placement process*, Journal of Composite Materials, 2012, pp.1–15.

[15] P. Kölzer, *Temperaturerfassungssystem und Prozessregelung des laserunterstützten Wickelns und Tapelegens von endlos faserverstärkten thermoplastischen Verbundkunststoffen* (Temperature measurement and process control of laser-assisted tape laying and winding of fiber reinforced composites), Shaker, Aachen, 2008.

[16] J. Colton, D. Leach, *Processing parameters for filament winding thick-section PEEK/carbon fiber composites*, Polym. Compos, vol. 13, no. 6, 1992, pp. 427–434.

[17] P. Zengxi, Z. Hui, *Improving robotic machining accuracy by real-time compensation*, in ICCAS-SICE, 2009, pp. 4289–4294.

[18] A. Maffezzoli, L. Mascia, M. A. Khan, P. Mitschang, R. Schledjewski, *Identification of some optimal parameters to achieve higher laminate quality through tape placement process*, Adv. Polym. Technol, vol. 29, no. 2, 2010, pp. 98–111.