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Development of Equipment and Mathematical Model for Manufacturing of Steered Fibre Laminate

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for doctoral or equivalent academic degree.

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Seadmete ja matemaatilise mudeli arendamine muutuva kiuga laminaadi valmistamiseks

ANTI HAAVAJÕE

TALTECH KIRJASTUS

Contents

List of Publications

The list of author's publications, on the basis of which the thesis has been prepared:

I Haavajõe, A., Mikola, M., Pohlak, M. Design and Manufacturing of Variable Angle Tow Laminate. Engineering Materials and Tribology. 2016.

II Haavajõe, A., Mikola, M., Osali, H., Pohlak, M., Herranen, H. Experimental study of steered fiber composite production. Proceedings of the Estonian Academy of Sciences. 2017, 66, 3, 295–299.

III Haavajõe, A., Mikola, M., Pohlak. Modelling Process Parameters of the PA12-CF60 Carbon Fiber Laminating Tape for Low Cost Laminating devices. International Conference of Numerical Analysis and Applied Mathematics 2019.

List of Author's other publications

I Majak, J., Eerme, M., Haavajõe, A., Ramachandran, K., Dieter, S., Lepik, A. Function Approximation Using Haar Wavelets. International Conference of Numerica Analysis and Applied Mathematics 2019.

II Mikola, M., Haavajõe, A., Arak, M., Majak, J., Pohlak, M., Shvartsman, B. Accuracy issues of the haar wavelet method. Proceedings of the NSCM28: 28th Nordic Seminar on Computational Mechanics 22–23 October, Tallinn, Estonia, 2015.

III Majak, J., Shvartsman, B., Karjust, K., Mikola, M., Haavajõe, A., Pohlak, M. On the accuracy of the Haar wavelet discretization method. Composites Part B: Engineering, 2015, 80, 321−327.

IV Kirs, M., Mikola, M., Haavajõe, A., Õunapuu, E., Shvartsman, B., Majak, J. Haar wavelet method for vibration analysis of nanobeams. Waves, Wavelets and Fractals Advanced Analysis, 2016, 2, 20−28.

V Haavajõe, A., Mikola, M., Herranen, H., Pohlak, M. Manufacturing of steered fiber composite. Proceedings of the 10th International Conference of DAAAM Baltic Industrial Engineering 12–13th May 2015, Tallinn, Estonia

Author’s Contribution to the Publications

Contribution to the papers in this thesis are:

I Background study on the topic, design of experiments, carrying out the tests and manufacturing testing jigs and equipment. Analyzing results.

II Manufacturing of the laminating test device for continuous laminating. Solving problems with heat source. Design of experiments, carrying out the experiments and processing results.

III Conducting the investigation by using different equipment and approach to get more accurate results from the experimental part. Preparing specimens and processing results. Application of new modelling technique.

Introduction

A composite material (or also called a composition material or a composite) can be defined as materials that consist of two or more chemically and physically different phases separated by a distinct interface. The different phases are combined deliberately to achieve a system with more useful structural or functional properties non-attainable by any of the constituent alone (Jawaid et al., 2018).

During the last decades advanced composites have been constantly replacing traditional materials in various fields of life. The demand for composite material is increasing even today due to the demand for new high-strength lightweight materials. Higher demands and expectations on different spheres of life put great pressure on technology, science and research and development. The main reason why advanced composites have become so widespread nowadays is that they fulfil the needs and expectations better, than any conventional materials. The main advantages over other materials are specific strength and stiffness, energy absorption, and their structural capabilities like corrosion resistance, radar transparency, electrical insulation, reduction in tooling and assembly costs. (Jawaid et al., 2018). Also, one way to add extra value to advanced composites is to make them “smart”. In general, smart material can be defined as a material that is capable of reacting to stimuli or the environment in a prescribed manner (Vardan et al., 2006). For example, material that has self-structural health monitoring capabilities can be called smart. Such materials are covered in (Herranen et al., 2018).

Due to the properties of the composites mentioned before, composites more and more occupy the market share at the expense of other materials and will keep doing this in the future for sure.

Using new and advanced materials require new manufacturing methods. Some of the traditional manufacturing methods are:

- Hand and automated tape-layup
- Resin injection
- Compression moulding
- Pultrusion
- Extrusion
- Filament winding

One new direction in composite production is robotized composite manufacturing (Schuster et al., 2017). The current study focuses on a manufacturing method called Automated Tape Laying (ATL). In some cases, also called Automated Fibre Placement. The motivation of investigating this method is based on the following facts (Heinecke et al., 2019):

- The method enables to automate production process
- Improves accuracy and minimizes the possibilities of manufacturing errors
- Decreases the costs of labour
- Minimizes the risk of human error
- Enables to produce Functionally Graded and steered fiber composites

The main downside of the ATL manufacturing is the cost of equipment and the lack of knowledge to implement the technology. The thesis of the study is motivated by the latter outlined advantages of the technology and eliminating the downsides – high cost and availability of the equipment and the lack of knowhow to implement it in production. Hereby the goal of the study can be outlined as follows:

The main goal of the study is to investigate Automated Tape Laying technology and finding key laminating parameters and their impact on the laminate, acquiring the knowhow of manufacturing and using ATL systems and finding mathematical models to predict the properties of the product. The following activities have been performed in order to achieve the posed goal.

Activity 1:

- Carrying out an experiment to find out the importance and border values of the main laminating parameters using PA12-CF60 material and gas torch as the cheapest heat source available.

Activity 2:

- Choosing new heat source and designing a control system for the heat source using Arduino controller and a pyrometer.
- Designing and fabricating a testing device to evaluate the key parameters on a continuous laminating process using PA12-CF60 material.
- Carrying out new sets of experiments.

Activity 3:

- Finding new test setup to minimize the influence of outer factors on the test results.
- Carrying out set of experiments using heat oven, tensile-compression machine and PA12-CF60 material.

Activity 4:

- Development of mathematical model for estimating the inter-laminar shear strength utilizing Haar wavelet method.

The novelties of the current study can be outlined as follows:

- Acquiring knowhow for designing low price ATL equipment.
- Lamination with selected PA12-CF60 material is little investigated.
- Study of process parameters for building low price equipment.
- Mathematical model was developed to evaluate the inter laminar shear strength of the PA12-CF60 using Haar wavelets.

The findings and results of the study have been published in various peer – reviewed journal papers and presented at number of conferences.

Abbreviations

AFP	Automated Fibre Placement
ANN	Artificial Neural Network
ATL	Automated Tape Laying
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CF	Carbon Fibre
CM	Composite Material
DT	Digital Twin
DOE	Design of Experiments
DQM	Differential Quadrature Method
FDM	Finite Difference Method
FRP	Fibre Reinforced Plastic
FTIR	Fourier Transform Infrared Spectroscopy
HWM	Haar Wavelet Method
MMC	Metal Matrix Composite
MV	Machine Vision
PA	Polyamide, known “Nylon” as a trademark
RFP	Robotized Fibre Placement
SME	Small and Medium-size Enterprise
VR	Virtual Reality

1 Theoretical background

1.1 Composites today

During the last decades advanced composites have been constantly replacing traditional materials in various fields of life (McWilliams et al., 2007). The demand for composite material is increasing even today due to the demand for new high-strength lightweight materials. Higher demands and expectations on different spheres of life put great pressure on technology, science and research and development. The main reason why advanced composites have become so widespread nowadays is that they fulfil the needs and expectations better, than any conventional materials (Vasiliev et al., 2018). The main advantages over other materials are specific strength and stiffness, energy absorption, and their structural capabilities like corrosion resistance, radar transparency, electrical insulation, reduction in tooling and assembly costs. Also, one way to add extra value to advanced composites is to make them “smart”. In general, smart material can be defined as a material that is capable of reacting to stimuli or the environment in a prescribed manner (Vardan et al., 2006). Due do the properties of the composites mentioned before, composites more and more occupy the market share at the expense of other materials and will keep doing this in the future for sure. The following chart, Fig.1.1, vividly represents the growth of demand or the change in proportional demand of the composite materials from 2015 and gives an estimate values of the proportional demand until the year 2025.

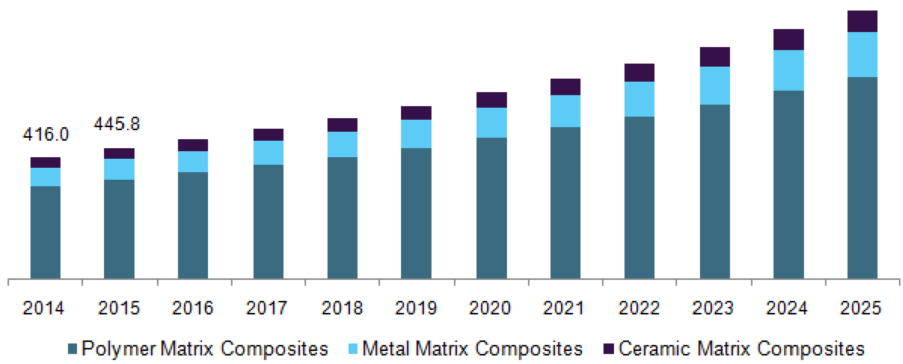

Figure 1.1 *U.S. composite market in automotive industry 2014–2025 (USD Million). [Automotive Composite Market Analysis by Product, by Application, by Region, And Segment Forecasts, 2018–2025. 2017. Report ID: GVR-2-68038-839-8]*

Fig.1.2, and Fig.1.3, demonstrates the global market shares of composite materials and global composite market opportunity, respectively.

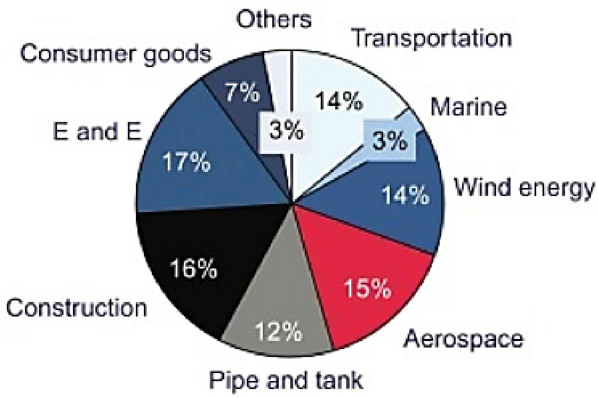

Figure 1.2 *Global composite material shipment by market segment 2017. [JEC Asia Business Review. April 2018. Issue 11]*

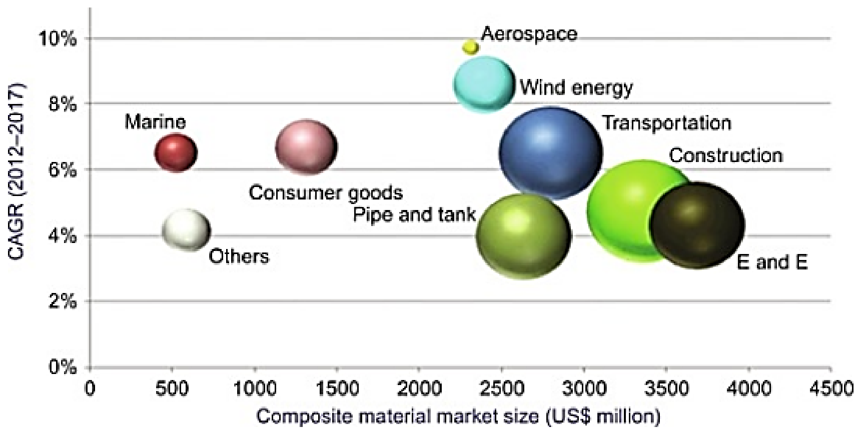

Figure 1.3 *Global composite market opportunity. [Pathan et al., 2014]*

1.2 Manufacturing

Hereby, it would be appropriate to mention, that the term composite material, is a very broad term going from clay and straw bricks used by thousands of years ago to the high-tech exotics like carbon nano-tubes reinforced beryllium MMC (Bharat et al., 2018) and etc. Therefore, it is difficult to name all the advantages and disadvantages of the composites over other materials and it is good to bear in mind that in this thesis the emphasis is put more on technologies and materials used in the present times, therefore some generalizations can be made.

In addition to the excellent features that different composite materials have, like high strength to weight ratio, excellent physical and chemical properties, their structural capabilities like corrosion resistance, radar transparency, electrical insulation (Vasiliev et al., 2018), they also have the possibility to manufacture complex shapes with designed properties or so-called tailored properties (Grimshaw et al., 2001).

Although composite materials have many advantages over conventional materials like metals and plastics, biological materials like wood, paper, leather etc., they also have some major disadvantages. The most common generalized disadvantages of the composites are:

- The difficulty to achieve fine tolerances
- Low mass to energy absorption
- Expensive research
- Sometimes very expensive raw materials (carbon fibre, carbon fibre nano tubes)
- Low damage resistance
- Process dependent material properties
- Manufacturing cost

Probably the major disadvantage is their manufacturing cost (Wille et al., 2012). Manufacturing of the composites usually include human labour, which depending on the region can be very expensive. Also, manufacturing of the composites needs special equipment (autoclave etc.) and skilled workers. It can be hazardous to the health and to the environment. Utilizing composites can be problematic since most of the composites are based on some sort of plastic or polymer that are well known to be hazardous to the nature and environment due to their long period of decomposition. Also, the ability to form micro particles that can get to the food chain and therefore cause serious consequences to the living organisms (Novotna et al., 2019; Oßmann et al., 2018). Further and continuous investigation of the composite can serve different purposes:

- Finding new materials to fulfill the needs of rapidly evolving technology
- Developing existing materials to make them eco-friendlier and to minimize the ecological footprint
- To bring down the manufacturing costs to make it possible to implement composites in more price sensitive fields.

This thesis is focused more on the manufacturing side. Today, some of the most common processes for manufacturing composites are:

- Hand and automated tape-layup
- Resin injection
- Compression moulding
- Pultrusion
- Extrusion
- Filament winding

The aim of the current thesis is to investigate one of the layup technologies – the Automated Tape- Layup (ATL) and the possibility to steer fibre (control it's direction) and laminating parameters during the laminating process. Automated Fibre Placement is one way to manufacture high performance composite parts. Traditionally, the method has been used in aerospace (Bannister et al., 2001), automotive industry and other large-scale industries, which have the necessity and means for adapting such technologies. The wind energy, small ship building, medical equipment and small-scale automotive industry would be the major targets of this technology. If the costs of the equipment were lower, the technology could be easily harnessed in SME-s. Although smaller enterprises have many advantages over large ones like flexibility, economic efficiency, quick response times and ability to adopt new technologies, they are financially not as capable as larger enterprises. Due to the fact that newer technologies are always expensive when they are introduced, it is very difficult for smaller companies to compete with larger ones from the aspect of investment capabilities.

Since SME-s play strategic role in Estonian economy it is vital to find ways to make SME-s more competitive. Switching to automated manufacturing processes is an essential step towards enhancing productivity and reproducibility of composite parts (Marsden et al., 2011; Lukaszewicz et al., 2012). One way to make it happen is subsidizing through various channels like EAS development programs or start-up grants or some other channels depending on the field of activity of the enterprise. Another way is effective collaboration that can be in the form of virtual organization or partner network (Mahmood et al., 2018). The other way is to bring the high end technology closer to entrepreneurs by cooperating with local research and development institutions to cut out dealers from the supply chain and therefore save up some money, but also to develop devices, methods, software exactly to entrepreneurs' needs and therefore be more efficient by bringing the know-how closer to final customer.

The central idea of the current paper was to investigate and analyze the perspective of automated composite laminating in Estonia. At this point, it is not difficult to determine whether automated composite laminating has its place in Estonia. Currently there are some bigger and many smaller composite manufacturing enterprises that may be interested in such technologies.

For example, we have companies like Silberauto and Magnetic MRO that have already claimed that they might be interested in robotized laminating and they would use that technology and know-how if they had it but they are not willing to make the research and development to obtain it. Previously mentioned companies accordingly deal with automotive industry and aviation. Other main fields in Estonia that might be interested in robotized laminating are mainly related to boat and ship building and wind energy or renewable energy in general. Work in these companies is today mainly done by hand lay-up.

The fact that impedes these companies from obtaining such technology is the high price of the laminating head. Only the laminating head itself can cost up to one million euros. Adding the training of the workers and engineers and the infrastructure that goes with the system, we get a final cost that is beyond of the capabilities of an average Estonian company.

Based on that fact, the author behind this paper has taken an obligation to find ways how to bring down the cost of such systems. Of course, in case of success in the research, the fruits of this work will not be only for the companies that already exist and deal with composites, but it can create a fertile land for emergence of new businesses. And in a small country like Estonia, every exporting company is relevant.

When talking about trends in Estonian industry and manufacturing, the only reasonable course is towards high-end manufacturing with great know-how. For that, there are many reasons. First of all, the number of skilled workers is limited and that is directly connected to the small population of Estonia. These problems are not solvable in five, ten or fifteen years. It takes time and probable some major changes in social policy. Secondly, the productivity of one worker or the amount of added value that one Estonian worker creates is claimed to be low when compared to other developed European countries. Thirdly we will never be able to compete with countries like China and India from the aspect of production volume so, therefore high-tech manufacturing is a way to go. Robotized composite manufacturing and robotic systems are just integral part of it. That does not apply only for the composite world or machine industry in general but for every possible field. An industrial robot as an integral part of the ATL system must be also utilized in maximum way possible. One way is to program and monitor the work of the robot using machine vision (Kuts et al., 2018) and/or VR and DT solutions (Kuts et al., 2019).

The main reason why ATL technology is chosen as a topic of this thesis is mainly to introduce this technology to the Estonian manufacturers. Since the price tag of such equipment is very high and unreachable for the SME-s, that are de facto the most common forms of enterprises in Estonia, and also to find ways to cut down the cost of such equipment. The main topics covered in this thesis are the following:

1. Investigating the working principle of the ATL head.
2. Generating ideas and finding ways to cut down the cost of ATL.
3. Determine important parameters when laminating.
4. Finding the importance and relations between different laminating parameters from the point of adhesion quality and visual appearance using PA12-CF60 material.
5. Finding basic theoretical relations to predict the properties of the product
6. Conclusions on the topic

1.3 Overview of the ATL technology

1.3.1 Working principle

Historically, advanced composites have been manufactured by hand lay-up of prepreg to produce composite parts that are then consolidated and cured in an autoclave. This labour consuming process results in high fibre volume fraction, void-free, well-consolidated composite structures with excellent mechanical properties. However, the costs of these structures are high due to the labour costs for hand layup processing. Automated Fibre Placement (AFP) and Automated Tape Layup (ATL), as one of the steered fibre composite manufacturing techniques, have gained attention for their cost-effective, flexible, and automatic process. Application of the AFT and ATL techniques allows to design of composite structures with variable stiffness (Guo et al., 2014; Khani et al., 2015; Sliseris et al., 2013, 2014). Pioneering work in this area has been done in Delft University of Technology by research group headed by Z. Gürdal. Their latest results concerning numerical modelling of AFP/ATL techniques are presented in (Guo et al., 2014; Khani et al., 2015). Design and modelling has also been the main topic of the work group (Kers et al., 2008, 2010; Herranen et al., 2012; Karjust et al., 2010; Majak et al., 2009, 2010, 2015) with a focus on optimal material orientation (Majak et al., 2010a, 2010b) In (Sliseris et al., 2013, 2014, 2015) the simulation models and optimization techniques are developed for design of discrete variable stiffness structures. One of the main technologies for producing advanced composites with variable angle tow is AFP which belongs to the robotized fibre placement method (RFP). A typical configuration of the RFP system with its main modules can be seen in the Fig. 1.4.

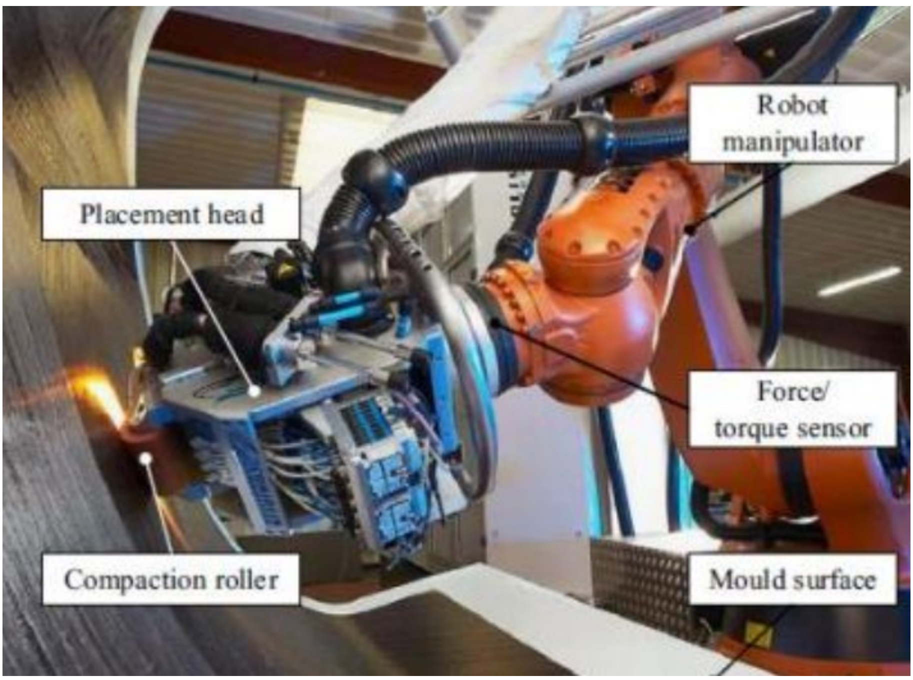

Figure 1.4 *Typical fibre placement system. [Coriolis Composites]*

The main parts of the system are industrial robot with its manipulator and force/torque sensor, a mould and the heart of the system- the laminating head. The basic working principle of the laminating head is shown in the Fig. 1.5.

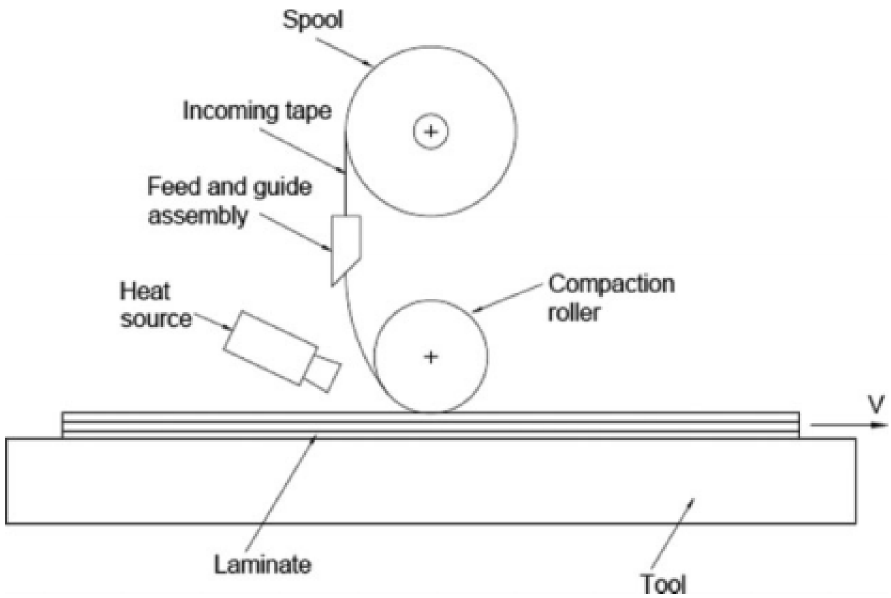

Figure 1.5 *Working principle of the ATL head. [Yassin et al., 2018]*

1.3.2 Process parameters

The main issues today concerning these technologies are improving the heating process controllability and deeper understanding of the influence of heating parameters, compaction process, compaction force, positional/speed errors, also possible variations of the robotic machinery and laminating head under a working condition.

The primary operational parameters are:

- Compaction force (Pitchumani et al., 1994; Lee et al., 1987)
- Temperature in the consolidation area
- Time (Duration. The time how long the consolidation area is kept under constant pressure and temperature)

Secondly the important parameters are:

- The radius of the roller
- The material and the coating of the roller
- Curvature of the mould etc.

The following part of this study focuses on testing the main laminating parameters – the temperature, compaction force and time. The suitability of different heat sources for automated tape laying is also considered.

2 Experimental study

The experimental study of this thesis focuses on testing of the lamination parameters and different heat sources by examining the adhesion quality in the laminating zone and its visual appearance. Since parts made of composite materials using ATL are quite often used in places where they are visible to the eye and therefore have to be aesthetically acceptable. Also, visual defects can refer to the fact that the laminating parameters are not chosen correctly. This usually expresses in voids and dents in the laminate that act as a stress concentrator and therefore weaken the structural integrity of the laminate and the product overall. The key to success when laminating such material is a uniform heat input to maintain appropriate temperature in the laminating zone.

2.1 Material PA12-CF60 analysis

The material used in the experiments is PA12-CF60. It is unidirectional carbon fiber tape with polyamide matrix and 60% of unidirectional carbon fiber. According to the supplier, the melting point of that material is 170 °C. It is specially designed for automated tape laying without the necessity to add any extra resin during the laminating process. Since the plan was to use this material in a laminating head, the material was delivered in a spool with diameter of approximately 300 mm and with the width of 25,4 mm (1 inch). The thickness of the tape was 0,1 mm. Despite the certificate provided by the supplier, the material was double checked by Fourier transform infrared spectroscopy (FTIR) method to get the full picture of the composition of the material. Due to the fact, that at first glance, the two sides of the strip seemed to be different (one side was glossy and other was matte), the decision was made to analyze the sides separately and compare the results afterwards. The analysis and results are discussed in the results and discussion section.

The specific material was chosen mainly because:

- This type of material is little investigated
- It is environmentally friendlier than resin-based tapes
- We had access to the material
- No need to apply resin during lamination
- No need for a supplying device on a laminating head to deliver resin
- It is not hazardous to health and it is safe to work with. It is not flammable.

2.2 Investigating the effect of different laminating parameters on the quality of adhesion using gas torch

As the main goals of the study is to gain knowhow for developing a laminating head for an industrial robot that would be competitive from the aspect of the price and versatility and to find mathematical models that could describe well enough the relations between the laminating parameters and the properties of the final product, an appropriate heat source has to be found, to replace the most commonly used heat source – laser. The necessity to replace the laser is derived from the essential purpose of the investigation. The price of the laser is not acceptable if the purpose is to design an affordable laminating device. As there is little information about the automated tape laying and different heat sources, the investigation has to begin from „a “and „b “.

The first choice of the heat source is the cheapest and simplest propane-butane gas torch. An air-only torch will reach temperatures up to 2000 °C, but it has to be bared in mind that the tape will not be heated directly, but only the surfaces that are to be compressed. During the experimental study, optimal laminating parameters like temperature and compressing force and their relations will be investigated and the suitability of controlling those parameters using a gas torch will be assessed. Hot gas torch has also been used in continuous processes. It was first used by Werdermann (Werdermann et al., 1989).

In the following set of experiments there will be used a simple testing approach because it can be already said at this point, that we will not get any mathematical model as a result of these experiments but rather a discrete answer is a gas torch suitable for such an application or not. For measuring the compaction force, tensile-compression measurement system will be used. The temperature of the consolidation area and the heat distribution will be screened with the thermal camera. Gas torch heater will be used as a heating source. Findings show that in addition to the main parameters – the compaction force and the temperature, there are many minor parameters such as the diameter of the compaction wheel, the pretension of the laminating tape, etc. All of them influence the quality of the final product. Thus, designing a low-price machine for manufacturing of steered fibre products, yet making no trade-offs from the aspect of the controllability of the laminating parameters, proves to be a real challenge.

The following part of this investigation concentrates on testing the two main parameters – the temperature and compaction force on carbon fibre reinforced polyamide material PA12-CF60 tape with 0,1 mm thickness, 25,4 mm width and with melting point of 170 °C. Firstly, to find an optimal laminating temperature to the material, simple tests were carried out. The tests comprised cutting the material into right length and positioning it to the simple fixture made of cardboard to ensure approximately the same overlay surface area during every test attempt. The fixture can be seen in the Fig.2.1, where the red rectangle in the middle indicates the location of the contact area that is going to be heated and compressed. Fixture consists of four main parts and features:

1. The specimen
2. Cardboard frame
3. Paperclip
4. Opening

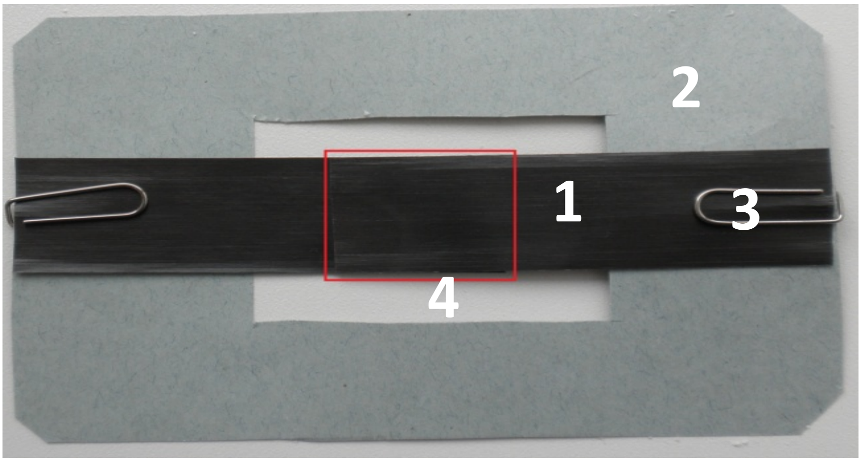

***Figure 2.1** Fixture for holding the two halves of the specimen.*

The estimated contact area is 645 mm^2. The opening in the cardboard is for heating and for pressing, so that during the process all the force is applied to the contact area of the material stripes and the thickness of the cardboard does not influence the result. The two test pieces are fixed with simple paperclips. The test setup can be seen in the Fig. 2.2.

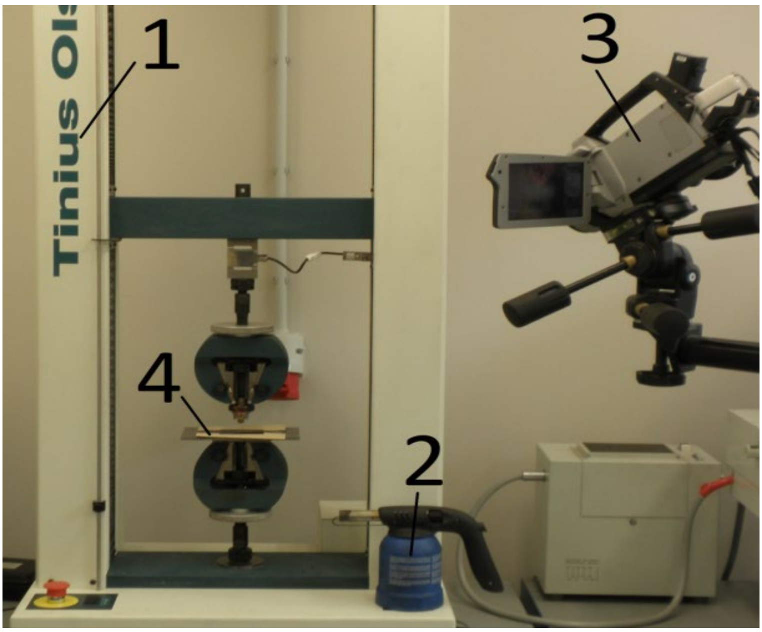

***Figure 2.2** Equipment used for testing. (1 – tensile compression machine, 2 – gas torch, 3 – thermal camera, 4 - jigs)*

For applying compressive force, a testing machine Tinius Olsen H10KT (pos. 1.) and some simple jigs (pos. 4.) were used. As a heating source, a gas torch (pos. 2.) was used. The temperature was observed with a thermal camera Flir ThermaCAM SC640 (pos. 3). In the Fig. 2.3, there is a close-up picture of the testing jigs and testing parts.

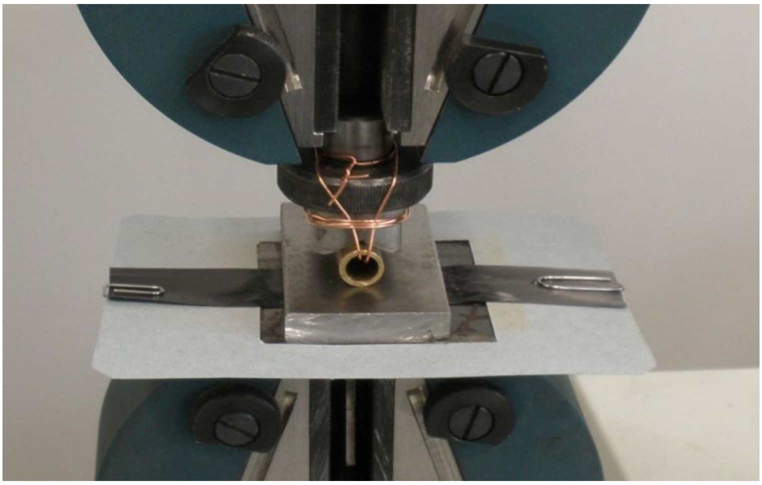

Figure 2.3 *Specimen in the testing jig.*

The first tests were carried out as follows:

1. Firstly, the lower steel plate was heated above the melting point of the material to approximately 200 °C to 220 °C.
2. The test pieces fixed in the cardboard jig were placed on the lower steel plate imitating the mold. Extra heat was added to the testing pieces to ensure the uniformity of the temperature in mold and material. Temperature was observed with thermal camera seen in Fig. 2.4.
3. An upper pressure plate was positioned on the material and constant force 400 N was applied during 30 seconds.
4. The test piece was removed from the machine. The test was repeated several times varying the heating temperature up to 300 °C.
5. Test pieces were torn apart in the tensile machine and investigated from the aspect of adhesion.

The secondary stage of the testing PA12-CF60 material comprised the investigation of the compaction force. The test was carried out as follows:

1. Testing pieces were positioned on the mold, in that case a planar sheet of steel. The same contact surface area (645 mm^2) was used.
2. Material was heated to the optimal temperature (200–220 °C).

3. Using compaction roller, the material was pressed together using three different pressures: 0,62 MPa, 1,09 MPa and 1,55 MPa. The manufactured test pieces were then torn apart with a tensile machine to find out the shear force when the seam breaks.

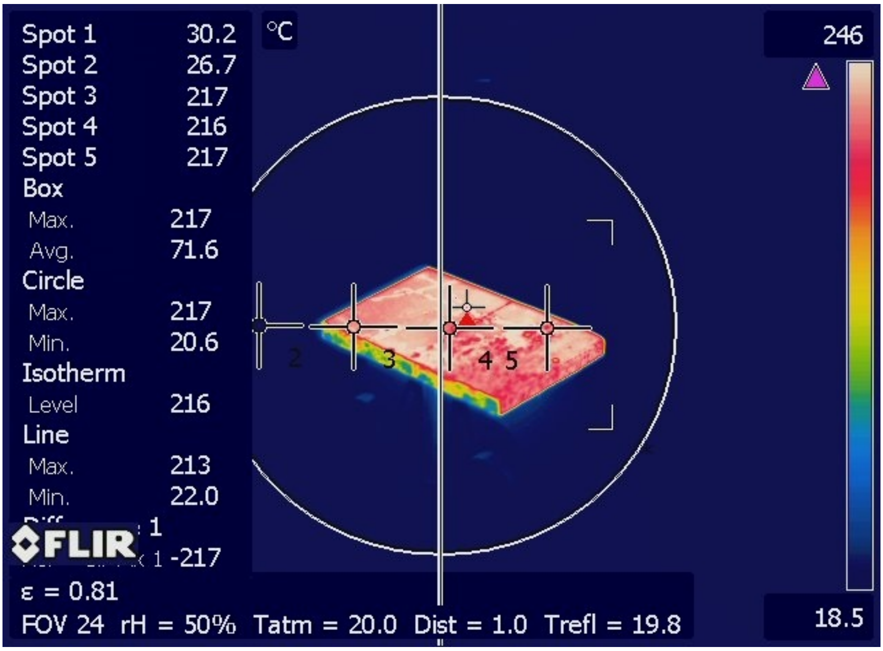

Figure 2. 4 *Image of the readings from the thermal camera.*

2.3 Investigating the parameters in continuous process using IR-heater

The next step from manual laminating is continuous laminating. Continuous laminating should, in theory, give better quality, fewer voids in laminate and uniformity (Astrom et al., 1997; Lee et al., 1992; Khan et al., 2011) and also give minimum waste (Aized et al., 2010; Dell'Ano et al., 2012).

The hypothesis is that during a continuous laminating process, a different combination of laminating parameters values has to be used to get a well adhered laminate. An overall working principle and main units can be seen in the Fig. 2.5. The importance of specific units of the ATL head is described in (Grimshaw et al., 2001; Olsen et al., 1993).

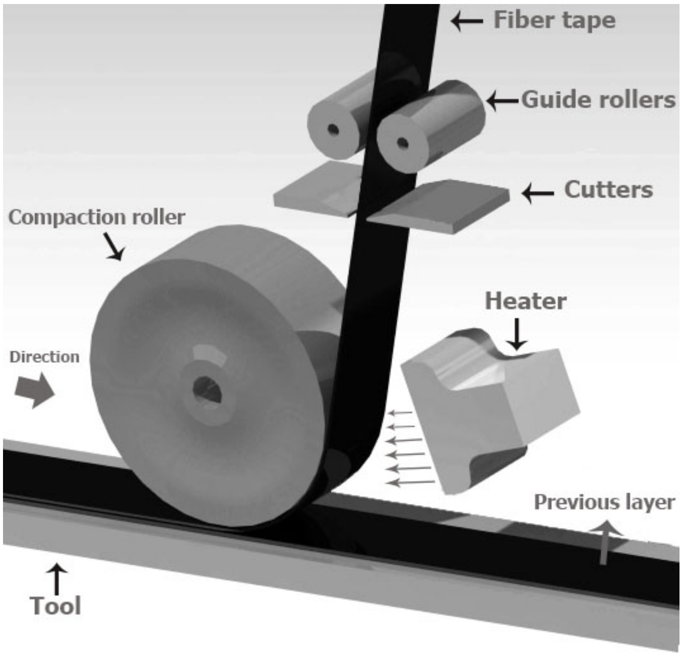

Figure 2.5 *Principle and main units of the ATL system. [Bakhshi et al., 2019]*

To perform continuous laminating test, a simple testing device had to be designed and fabricated. In a sake of simplicity, some of the units like guide rollers, and cutters will be left out. The tests will be carried out as continuous process and parameters will be observed during the laminating process. The tape will be cut into correct length and positioned on an aluminum mold while ensuring that the overlay surface area during every test attempt is the same.

The test piece placed on an aluminum sheet imitating the mold can be seen in the Fig. 2.6, where the red rectangle in the middle indicates the location of the contact area between two tapes. For maintaining the estimated contact area as in the previous static testing (645 mm^2) during the rolling process both parts of the tape were fixed to the aluminum mold. One of the specific characters of the ATL is the predefined fiber orientation (Campbell et al., 2003), with the purpose of optimizing the laminate (Lellep et al., 2000; Aruniit et al., 2012). In this case, the orientation is straight line.

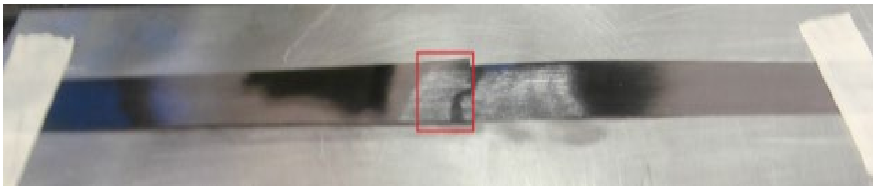

Figure 2.6 *Specimen fixed on an aluminium plate.*

The test setup can be seen in the Fig. 2.7 and some key dimensions in Fig. 2.8.

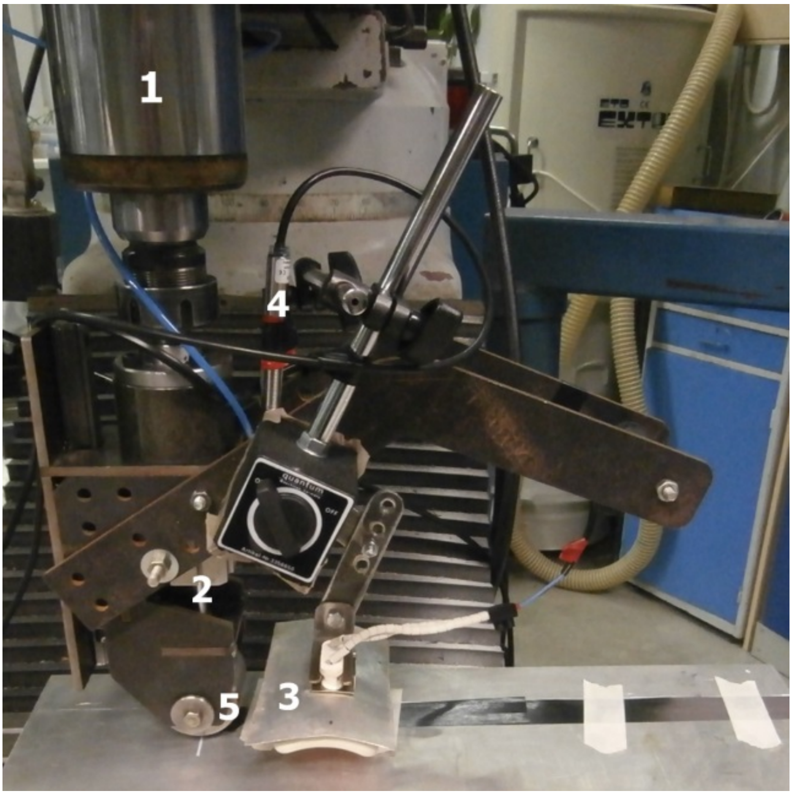

Figure 2.7 *Fabricated testing device and its units. (1 – NC machine, 2 – Pneumatic cylinder, 3 – IR-heater, 4 – Pyrometer, 5 – Compaction roller)*

For controlled laminating movements, instead of the commonly used robot (Olsen et al., 1993), the test device was attached to a NC milling machine. In order to maintain and vary the necessary compaction force a pneumatic cylinder and a pressure regulator were used. A curved ceramic infrared heater Ceramicx HTE 500 with 500 W output power was used as a heating source. The temperature was observed with an Optris CS LT contactless infrared pyrometer on the contact area during the laminating process. An Arduino based controller was used to control the infrared heater and to get readings from the pyrometer. At first the infrared sensor was meant to be used as a feedback to the Arduino but it appeared that the heat inertia of the heater was too high to be controlled via feedback system. A consolidation roller made of steel S355JR was used for transmitting the compaction force from the pneumatic cylinder to the contact area between two tapes.

The main units of the test setup were:

1. NC milling machine.
2. Pneumatic cylinder and a pressure regulator.
3. Curved ceramic infrared heater Ceramicx HTE 500 with 500 W output power.
4. Optris CS LT contactless infrared pyrometer.
5. Consolidation roller.
6. Mould.
7. Mandrel (was not used in current setup).

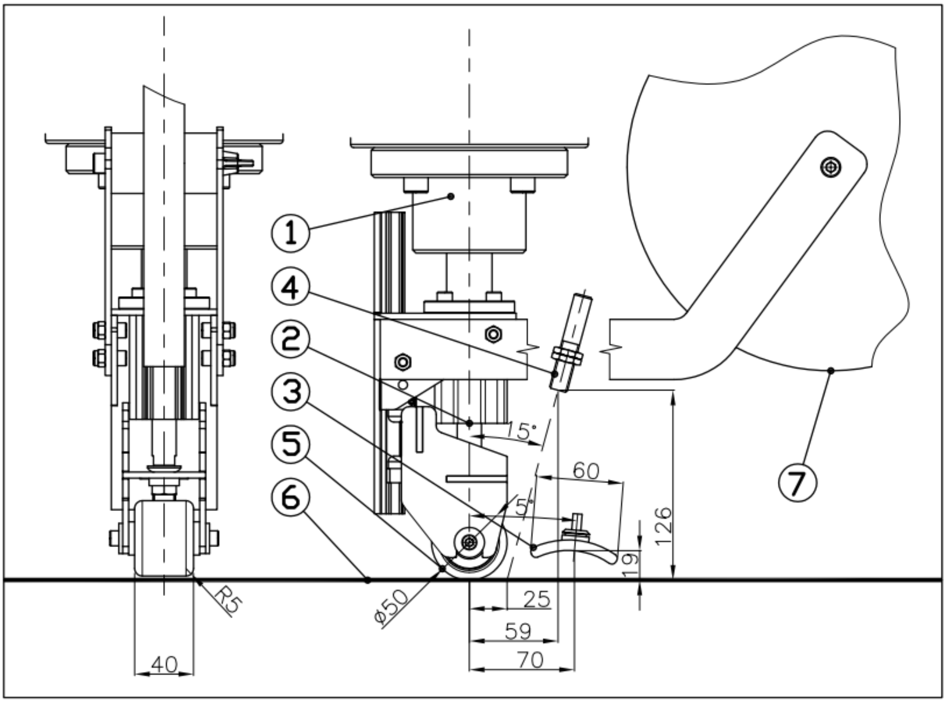

Figure 2.8 *Key dimensions and units of the testing device.*

The tests were carried out as follows:

1. Both parts of the tape were fixed to the aluminum plate imitating the mold.
2. The heater was warmed up to a stabile temperature.
3. While maintaining a constant laminating speed with a NC milling machine, the contact area between two tapes was heated with the IR heater and consolidated with the compaction roller.

4. The consolidated test piece was removed from the aluminum plate.
5. Test pieces were torn apart with the tensile testing machine and investigated from the aspect of adhesion.

As the previous studies (Haavajõe et al., 2015, 2016) have shown the optimal laminating temperature range should be between 200 °C to 230 °C. Therefore, the laminating temperature during the laminating process was kept in that range by adjusting the power of the infrared heater. To simplify testing the range ±15 °C was considered sufficiently precise enough to carry out the experiment and therefore the temperature is taken into account as a constant.

To find out the correlation between the consolidation force, consolidation speed that is covered in (Matveev et al., 2016; Crossley et al., 2011) and the shear strength of the test piece, the full factorial design of experiment has been performed. To minimize the effect of random factors on the test results, every test set was repeated twice. Since a pneumatic cylinder and a manometer were used for measuring the compaction force, the force was converted from the air pressure. The levels were as follows:

1. 1 bar – 80 N
2. 4 bar – 322 N
3. 7 bar – 563 N.

The levels of the laminating speed were as follows:

1. 0,3 m/min;
2. 0,4 m/min;
3. 0,5 m/min.

The choice of levels was greatly influenced by the opportunities of the equipment. The test results are discussed in the results and discussion chapter.

2.4 Adhesion test using thermo-oven and different equipment for measuring the shear strength

Due to the fact that the results from the previous tests were not satisfactory to find any mathematical models to predict the results according to the input values. Some corrective actions must be made. The previous tests have shown that from the three main lamination parameters – the force, time and temperature, it is the last one that is the most difficult to control.

As a solution, a new set of experiments will be made using different methodology and different equipment. It is an assumption that the most critical parameter in the laminating process is the laminating temperature in the laminating zone. To prove this fact, a clever way has to be found how to provide a uniform and well controllable temperature in the laminating zone. To this point the temperature has been controlled with local heat sources like gas torch and IR heater. With such devices it is difficult to predict how much heat is applied to the lamination zone. How uniform is the heat distribution or how much heat radiates to the other parts of the testing device. Therefore, it is difficult to evaluate if this redundant heat that is transferred to the surroundings, has any effect on the testing results.

The new study will still cover three main laminating parameters – consolidation force, temperature and consolidation duration (time, how long the test piece is kept under constant pressure). Assessment of the suitability of the parameters will be given according to the results from the tensile testing. Testing will be carried out in two stages. Firstly, preliminary study to set the limit parameters and find the effective working area. This is needed to minimize the number of repetition tests. Secondly, tests in the estimated effective area.

2.4.1 Preparing test pieces

Test pieces are this time made according to the standard EVS-EN 1465:2009 that is usually used for estimating different adhesives. This standard is used because there is no specific standard for laminating tapes and the current standard is the closest that was possible to find for such application. The scheme of the test piece can be seen in the Fig.2.9. The two carbon fibre tape halves are cleaned with alcohol and fixed with masking tape and cooking paper. This is needed for maintaining the position of the two halves and to avoid sticking the test piece to the consolidation equipment. Alcohol was needed for removing any residue from the shear area. The specimen can be seen in the Fig. 2.10.

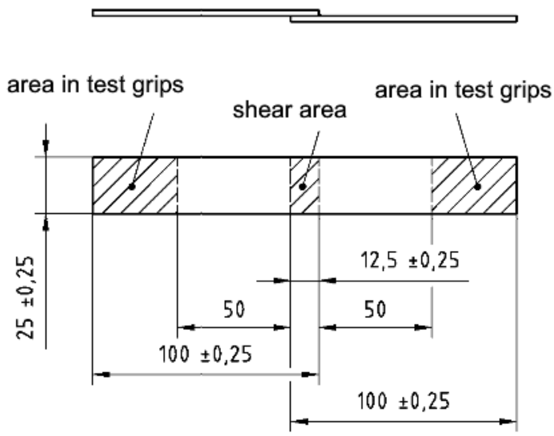

Figure 2.9 *Layout of the specimen according to the EVS-EN 1465:2009.*

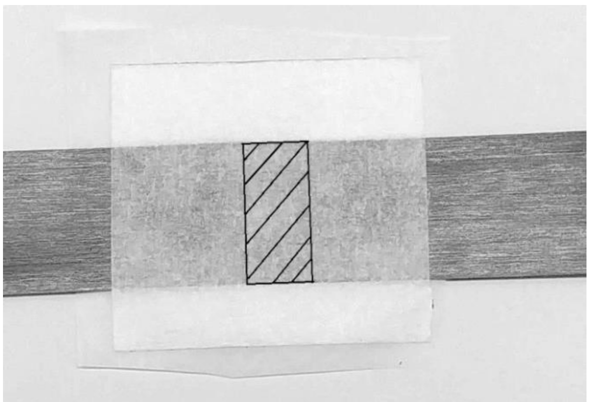

Figure 2.10 *Prepared specimen ready for testing.*

2.4.2 Testing equipment

The main components of the test set-up are numbered in the Fig 2.11. The test pieces were consolidated in a tensile-compression machine Instron, (pos. 1) equipped with force sensor, (pos. 2), for lower forces and better accuracy and automatically controllable thermo-oven (pos. 3). The shear or consolidation area is pressed between two planar surfaces when they have reached the desired temperature. The upper support (pos. 5) is equipped with a thermocouple sensor (pos. 9) to get more accurate readings from the working area. Upper support is also insulated from the gripper (pos. 4) by using glass fibre canvas. The lower support (pos. 6) is made of bronze to ensure it heats up quicker than the upper support. It is also insulated with glass fibre canvas. The lower support itself (pos. 6) rests on a cast iron support (pos.7) that has a spherical joint in it to compensate positioning errors. Underneath the cast iron support, there is a hollow section of a rectangular tube (pos. 8) to decrease the heat inertia.

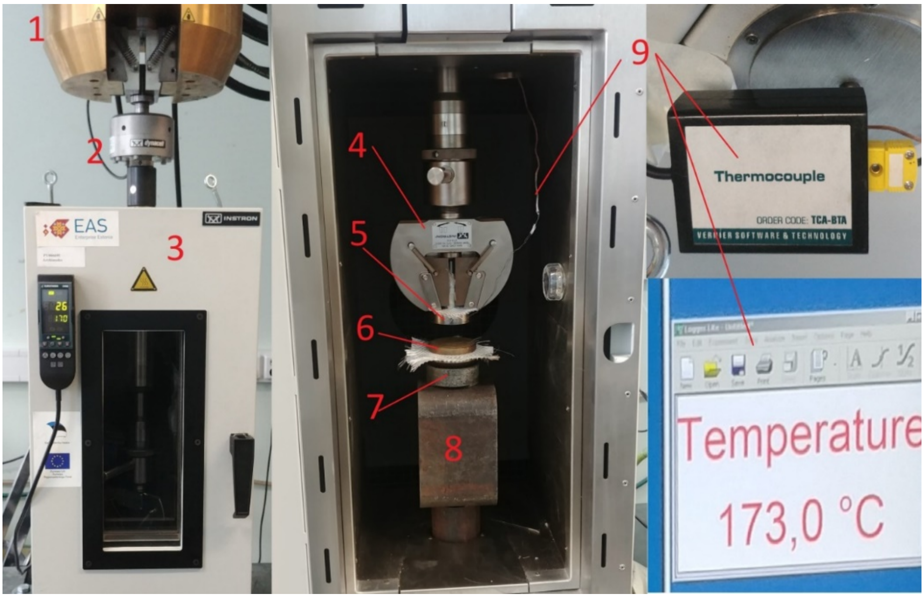

Figure 2.11 *Testing equipment. (1 – Tensile-compression machine, 2 – Force sensor, 3 – Thermo-oven, 4 – Gripper, 5 – Upper support, 6 – Lower support, 7 – Cast iron spherical compensator, 8 – Hollow section tube, 9 - Thermocouple)*

For testing the shear strength, different, more sensitive machine was used. Machine can be seen in the Fig 2.12.

Figure 2.12 *Specimen in the tensile- compression machine.*

2.5 Mathematical model

Current section is focused on development of the mathematical model describing relation between the laminating parameters and the shear strength (Haavajõe et al., 2019; Majak et al., 2019). The particular model developed is based on experimental data obtained above. A large number of metamodeling methods and tools are available in literature including linear and nonlinear regression, splines, kriging and artificial intelligence tools. The artificial neural network (ANN) can be considered as challenging tool in engineering design. The optimization workgroup in Tallinn University of Technology has developed ANN based solutions for a number of engineering design problems like design of new composite materials, technology root planning for large composite parts, etc. (Kers et al., 2008; Aruniit et al., 2011, 2012; Karjust et al., 2010).

During last ten years, the Haar wavelet method (HWM) has been developed for solving various structural analysis problems covering solid structures (Lepik &Hein 2014; Majak et al., 2015, 2019; Xie et al., 2014a, 2014b, 2014c; Hein et al., 2011a, 2011b; Feklistova et al., 2016a, 2016b; Jaanuska et al., 2017, 2019). In monograph Lepik & Hein, 2014, the thoroughgoing overview on development and application of the HWM is given. In Majak et al., 2009 and Xie et al., 2014a, 2014b the HWM is adopted for free vibration analysis of composite laminated plate and shell structures. The functionally graded structures are examined by applying HWM in Xie et al., 2014c, Fan et al., 2018, Majak et al., 2015 and Hein et al., 2011a). Delamination in composite structures is studied in (Hein, 2011b and Feklistova et al., 2012). Interesting approach is utilized in (Feklistova et al., 2012, 2016; Jaanuska et al., 2017, 2019), where the HWM is combined with machine learning tools for detection of imperfections (cracks, delamination). New higher order Haar wavelet method (HOHWM) has been introduced in (Majak, 2018).

In order to provide compatibility of the solution, the functions involved in governing differential equations can be expanded into Haar wavelet series (Xie et al., 2014a; Wang et al., 2014; Islam et al., 2014). In latter studies the function is expanded directly into Haar wavelets. It has been shown in (Babolian et al., 2009) that in the latter case the rate of convergence with respect to mesh/resolution is equal to one. Obviously, such an approach is robust and may lead to inaccurate results.

2.5.1 Haar functions

The Haar functions represent the quadratic waves and are defined as (Lepik & Hein., 2014)

$$h_i(x) = \begin{cases} 1 & for \quad x \in [\xi_1(i), \xi_2(i)) \\ -1 & for \quad x \in [\xi_2(i), \xi_3(i)) \\ 0 & elsewhere \end{cases}. \tag{2.1}$$

In (1) $i = m + k + 1$, $m = 2^j$ is a maximum number of square waves deployed in interval $[A, B]$ and the parameter k indicates the location of the particular square wave

$$\xi_1(i) = A + 2k\mu\Delta x,\ \xi_2(i) = A + (2k+1)\mu\Delta x,\ \xi_3(i) = A + 2(k+1)\mu\Delta x,\ \mu = M/m,$$

$$\Delta x = (B - A)/(2M),\ M = 2^J\ . \tag{2.2}$$

2.5.2 Generalized approach for function approximation

Motivated on higher order Haar wavelet method developed in (Majak et al., 2018) the generalized approach for function approximation using Haar wavelets is introduced (see paper 3). According to proposed approach the n-th order derivative of the function is expanded into Haar wavelet series (formula (2.3)). This approach provides increase of the convergence rate and reduction of absolute error in comparison with approach used in (Xie et al., 2014a; Wang et al., 2014; Islam et al., 2014) for $n > 0$. The mathematical modeling problem considered above is obviously 2D problem. However, the method is introduced and validated for 1D problem first and then extended to 2D problem. In the case of 1D function the wavelet expansion proposed read

$$f^{(n)}(x) = \sum_{i=1}^{2M} a_i h_i(x), \quad n = 0,1,2,... \tag{2.3}$$

In (2.3) a_i stand for unknown coefficients. In the following the particular cases, where n=0, n=1 and n=2, are examined.

Case n=0:

The function is expanded directly into Haar wavelet. The approach reduces to one used in (Xie et al., 2014a; Wang et al., 2014; Islam et al., 2014). The unknown coefficients can be determined by satisfying the equation

$$f(x) = \sum_{i=1}^{2M} a_i h_i(x), \tag{2.4}$$

at 2M collocation points. In the case of uniform mesh, the collocation points are chosen as

$$x_l = \frac{2l-1}{4M}, \; l = 1, \dots, 2M. \tag{2.5}$$

Case n=1:

The first order derivative of the function is expanded into Haar wavelets. The function $f(x)$ can be computed as first integral of the equation (2.3).

$$f(x) = \sum_{i=1}^{2M} a_i p_{1,i}(x) + c_1, \tag{2.6}$$

Based on properties of the Haar wavelets, it is reasonable to determine the integration constant c_1 by satisfying the differential equation at point x=0.

Case n=2:

The second order derivative of the function is expanded into Haar wavelets. The function $f(x)$ can be computed as second integral of the equation (2.3).

$$f(x) = \sum_{i=1}^{2M} a_i p_{2,i}(x) + c_1 x + c_2. \tag{2.7}$$

In the case of engineering structures, the integration constants can be determined at "boundary points" i.e. fulfilling (2.6) at points x=0 and x=1 (commonly simplest approach).

According to general principle of the collocation methods, first the relation (2.4), (2.5) or (2.6) is satisfied in given $2M$ points (called collocation points). Next, the obtaine $2M$ linear algebraic equations are solved with respect to coefficients a_i. Finally, when the values of the coefficients a_i are known, the function $f(x)$ can be computed in any point in design domain.

The numerical results obtained for 1D sample problems in the case of n=0, n=1 and n=2 are compared in paper 3 (see Tables 1–3). It can be observed from Table 1 that in the case of n=0 the rate of convergence tends to one for both sample test functions considered $f_1(x) = e^x$ and$f_2(x) = \sin(x)$. In the case of n=1 (see Table 2), the rate of convergence increases to two. The absolute error obtained for n=0 with 1024 collocation points, is reached with 16 collocation points only if n=1. Taking n=2 (see Table 3), the rate of convergence increases to four and the absolute error decreases substantially (several orders of magnitude).

Next let us consider 2D problem.

The Haar wavelet expansion based 2D mathematical model is introduced for n=0 as

$$f(x,y) = \sum_{i=1}^{2M} \sum_{j=1}^{2M} a_{il} h_i(x) h_l(y), \tag{2.8}$$

and for n=1 as (in the case of 2D problems, the total order of the derivative is 2n)

$$\frac{\partial^2 f(x,y)}{\partial x \partial y} = \sum_{i=1}^{2M} \sum_{j=1}^{2M} a_{il} h_i(x) h_l(y), \tag{2.9}$$

where a_{il} stand for matrix of unknown coefficients.

In the case of n=1, the function $f(x,y)$ is determined by integration the relation (2.9) by x and y as

$$f(x,y) = \sum_{i=1}^{2M} \sum_{j=1}^{2M} a_{il} p_{1i}(x) p_{1l}(y) + \varphi(x) + \psi(y). \tag{2.10}$$

The numerical validation of the model is covered in the chapter 3, using $f(x,y) = e^{x+y}$ as a sample test function. The proposed model was applied for analysis of the ALT process.

2.6 Heat flux density and heat input

In practice, in production technologies that use heating as one part of the production process often term heat input is used instead of the temperature. This is due to the fact that the term temperature can be used to describe heating processes only if the other parameters that affect the heating process are known, but this rarely happens in practice. In the current investigation using the term temperature is justified because the investigated material is the same throughout the whole investigation. Also, in the experiments, the influence of outer factors has been tried to keep minimal and similar. For the future, to help choosing the right heat source for the material, the aspect of heat input will be slightly covered in this chapter.

Some parallels can be drawn with arcwelding metals. In welding, the heat input is calculated trough voltage and amperage, also considering the coefficient of process efficiency that is an empiric factor (Han et al., 2012). In other words, the heat input can be described as the amount of energy that has to be inserted to the material to keep the material at the same temperature at the same traveling speed. The heat input in welding can be calculated as follows:

$$heat\ input = k\frac{UI}{v}\ , \tag{2.11}$$

where U stands for voltage (V), I stands for amperage (A), v stands for traveling speed (mm/s), and k is the unitless coefficient of process efficiency.

Roughly, heat input in a process like ATL, can be described by the same logic, yet there are many factors that make calculating analytically the desired heat input and choosing the heat source more difficult. The main heating related factors can be outlined as follows (Kollmannsberger et. al 2018):

- The initial temperature of the tooling (device and mould)
- Thermal insulation at the bottom of the mould
- Free convection at outer areas of the laminate, tool, and incoming tape in contact to ambient air
- The thermal conductance at the contact surfaces between the different components (i.e. tool, layers of the laminate, compaction roller)

Still, the most common way for finding the right laminating parameters is experimental study. The heat input of the laser, as the most used and most accurately controllable heat source in ATL devices has been successfully described in Kollmannsberger et al., 2018. Kollmannsberger used a near infrared diode laser (wavelength 1030–1060 nm) and thermocouple embedded CF tape specimens to evaluate the heat input. As a result of the investigation it was possible to determine the average heat input during the layup. A following models were developed, that describe the average heat flux density during ontime step d_t in a 2-D element with a length dx_1 in a x_1 direction:

$$\dot{q}_d = \frac{\dot{Q}}{dx_1 dt}\int_0^{dt}\int_x^{x+dx_1}\frac{\left(1-\rho_r(\theta_1(X,t),n)\right)\cos(\theta_1(X,t))}{A(X,t)}\,dXdt, \tag{2.12}$$

where $\dot{Q}$ is the laser power, θ_1 the angle of incidence, and *A the* size of the laser spot at point *x*. ρ_r represents the percentage of the reflected radiation. *A* is dependent on the distance between the laser lens and point *x*. The heat flux density is also dependent on the angle of incidence with factor $cos(\theta_1(x,t))$. Since the process is continuous, the laser spot size *A* at point *x* and the angle θ_1 are dependent on time.

And the model that describes the average heat flux density originating from the reflected irradiation:

$$\dot{q}_r = \frac{\dot{Q}}{dx_1 dt} \int_0^{dt} \int_x^{x+dx_1} \frac{\rho(\theta_1(X,t),n)\left(1-\rho_r(\theta_2(X,t),n)\right)\cos(\theta_2(X,t))}{A(X,t)} dXdt, \tag{2.13}$$

where θ_2 is the angle of incidence of the laser after the first reflection with respect to the absorbing element. An explanatory scheme can be seen in the Fig. 2.13.

As a result, the heat flux density in the irradiated zone is **the sum of $\dot{q}_d$ and $\dot{q}_r$.** The practical value of these equations is that knowing the necessary heat flux density, the power of the heat source laser can be found.

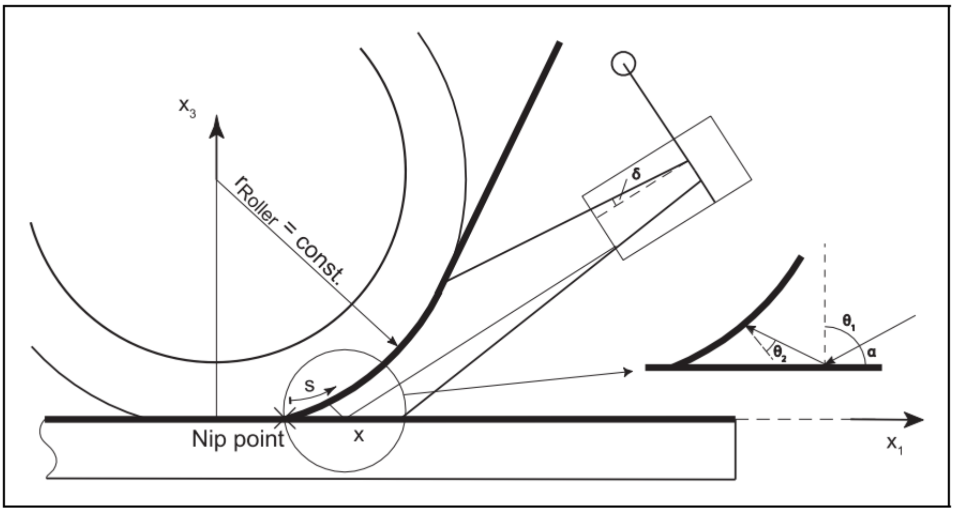

Figure 2.13. *Key parameters regarding the laser-heating process (Kollmannsberger et al., 2018)*

At this point, laser seems to be the only heat source that can be chosen according to the pregiven parameters like heat flux density or heat input.

3 Results and discussion

In this chapter, the analysis and results of the previously performed experimental part will be more thoroughly discussed. The chapter will cover the PA12-CF60 analysis to evaluate its suitability for the testing. The two sides of the tape were evaluated to confirm that the same matrix material (PA12) is used on both sides and no coating is applied to the tape that would make laying the tape side dependent. The applicability of the different heat sources used in the experimental part and their advantages and disadvantages will be also discussed.

3.1 PA12-CF60 tape

3.1.1 Side 1 analysis

The results from the analysis of the Side 1 can be seen in the Fig. 3.1. The upper, blue graph line represents the data gained from the specimen. The lower, red graph line represents the reference values from the material library. Places, where the specimen and reference graph lines overlap or fall into one, a known material is recognized from the library.

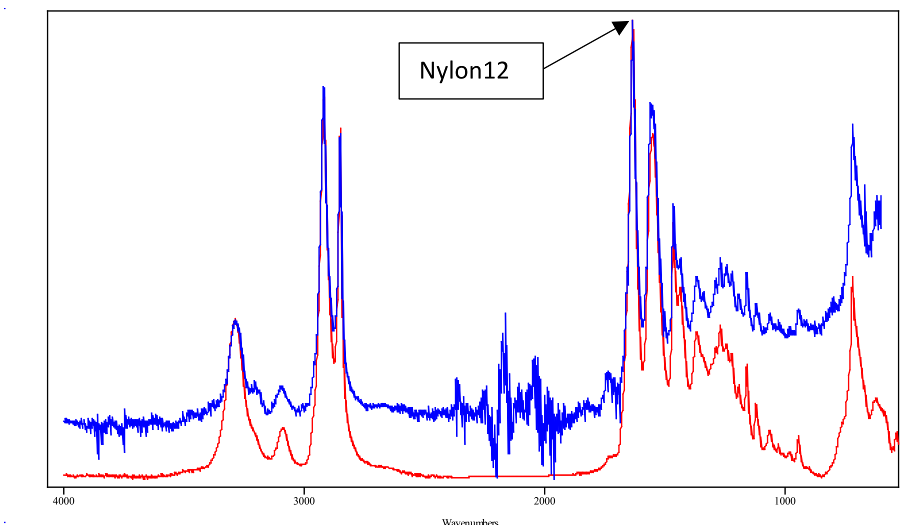

Figure 3.1 *Side 1 correlation coefficient. Search region - full spectrum.*

Numerical values can be seen in the Table 3.1. The correlation coefficient (row "Score") represents the certainty that the analyzed material is the one specified in the library.

Table 3.1 *FDM Library Spectrum: Nylon 12.*

Score	Name	Entry	Library
0.9716	Nylon 12, 25038-74-8	0184	FDM ATR Polymers
0.9147	TPX HTN-01027A Nylon 33% glass filled, natural, pellets	1006	FDM ATR Polymers
0.9127	Wear and Moisture-Resistant Nylon	1057	FDM ATR Polymers
0.9098	Advanced Composites, Nylon, pellets, glass filled	0946	FDM ATR Polymers
0.9095	ABS + Nylon alloy	0934	FDM ATR Polymers
0.9060	Nylon 6/10; Poly (hexamethylene nonane diamide), Tg=40, 9011-52-3	0187	FDM ATR Polymers
0.9042	Nylatron G5-51 Nylon 6,6, 32% glass filled	0964	FDM ATR Polymers
0.9041	Nylon AS-1945 HS, glass filled, natural, regrind	0967	FDM ATR Polymers
0.9007	Self-Lubricating MDS-Filled Nylon Rod	1049	FDM ATR Polymers
0.8995	Wear-Resistant Black Nylon Rod	1058	FDM ATR Polymers

3.1.2 Side 2 analysis

The results from the analysis of the Side 2 can be seen in the Fig.3.2. Numerical values can be seen in the Table 3.2. The upper, green graph line represents the data gained from the specimen. The lower, red graph line represents the reference values from the material library.

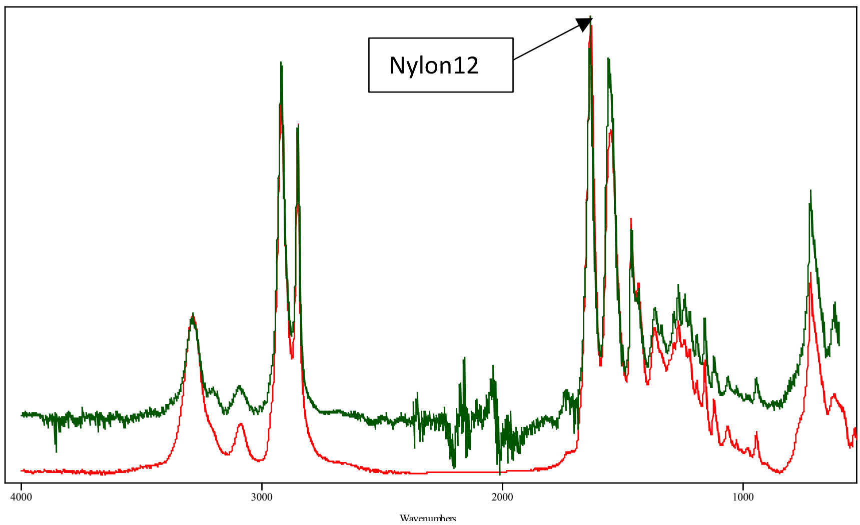

Figure 3.2 *Side 1 correlation coefficient. Search region - full spectrum.*

Table 3.2 *FDM Library Spectrum: Nylon 12.*

Score	**Name**	**Entry**	**Library**
0.9684	Nylon 12, 25038-74-8	0184	FDM ATR Polymers
0.9511	Nylon 11, 25035-04-5	0183	FDM ATR Polymers
0.9309	Nylon 6, Enbarr 2020 B-N, natural, pellets	0965	FDM ATR Polymers
0.9307	Nylon 6/10; Poly(hexamethylene nonanediamide)	0187	FDM ATR Polymers
0.9194	Nylon 6/12, 25191-04-2	0188	FDM ATR Polymers
0.9171	Wear and Moisture-Resistant Nylon	1057	FDM ATR Polymers
0.9035	Nylon 6/9, 28757-63-3	0190	FDM ATR Polymers
0.8831	Polyamide resin, viscosity 70p (210C), 68989-76-4	0457	FDM ATR Polymers

3.1.3 Comparison of the Side 1 and the Side 2

The x-axis, or horizontal axis—represents the infrared spectrum, which plots the intensity of infrared spectra. The given analysis is done in a mid-IR range. The y-axis, or vertical axis—represents the amount of infrared light absorbed or transmitted by the material being analyzed. The score represents the coefficient of comparison of the known materials from the material's library. The top scores are from comparing the specimen to Nylon 12. The next scores are Nylon 11 and Nylon 6. The analysis makes it possible to claim that the matrix material of this tape is Nylon or polyamide 12.

The comparison graph of the two sides in the Fig.3.3 claims that, with small deviations, the two sides can be considered as identical. The difference in appearance can be a result of the different thicknesses of the PA layer or due to some differences in manufacturing methods. In the following, the matrix material will be treated as a pure Nylon 12 (polyamide 12).

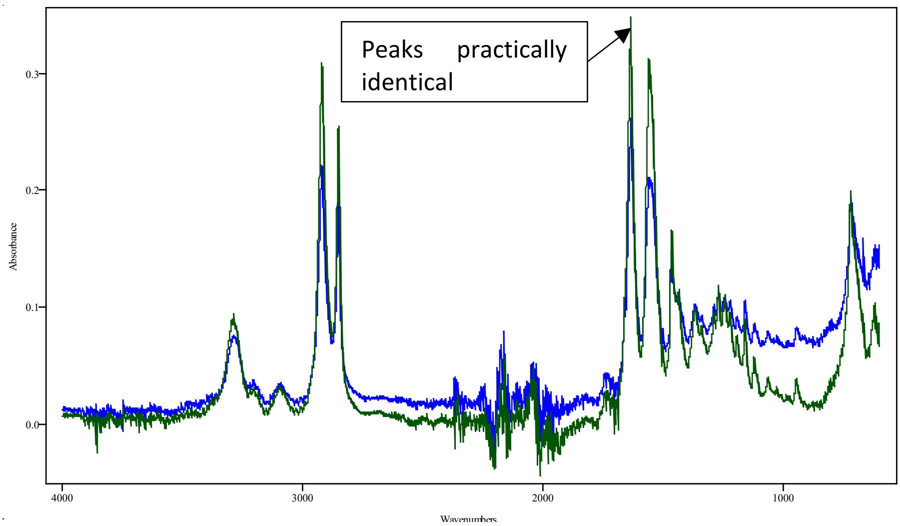

Figure 3.3 *The comparison of Side 1 and Side 2.*

3.2 Investigating the effect of different laminating parameters on the inter laminar shear strength using different heating methods

3.2.1 Investigating laminating parameters using gas torch

Findings from the first temperature tests with the gas torch show that:

1. The optimal temperature using such method to get the perfect seam is between 200 °C to 220 °C.
2. Using lower temperature can cause improper adhesion.
3. Using higher temperature is not recommended because high temperature can cause the matrix material (PA) to flow out of the seam or to evaporate leaving gaps or cracks in the seam zone (Fig. 3.4, on the left).
4. Even heat distribution is crucial to get high-quality seam. Uneven heating causes improper adhesion (Fig. 3.4, on the right).
5. Excessive heating can cause flashing of the carbon fiber.
6. Considering point 4 and point 5, gas torch as a heat source is bad solution for the current material used.

Figure 3.4. *Defects in the laminate. Evaporation of the matrix material on the left and improper adhesion on the right.*

The next stage of the testing PA12-CF60 material comprised the investigation of the compaction force. The results can be seen in the Table 3.3.

Table 3.3 *An estimation of the correlation between shear strength and compaction pressure.*

No	Compaction Pressure	Shear Strength
	MPa	**MPa**
1.	0,62	121
2.		179
3.		218
4.		282
5.		285
6.	1,09	401
7.		437
8.		442
9.		493
10.		512
11.	1,55	450
12.		546
13.		559
14.		618
15.		673

It can be seen that there is a positive correlation between the compaction force and the tensile strength of the seamed testing body. Increasing the compaction force has positive effect on tensile strength. Due to the methods used in the experimental study these results are not suitable for finding any mathematical relations (models) between the compaction pressure and shear force, but rather gives some picture of the border values.

3.2.1.1 Conclusion

The purpose of this experiment was to make a preliminary study concerning AFP process in order to design later affordable AFP equipment. For that we have chosen a material and tested it to find the relations between the main operational parameters and a way to control them.

As a result of the experimental part, it appeared that gas torch is not suitable for heating the material PA12-CF60 because of the uneven heat distribution. Proper heating of the material is one of the key factors when high quality is the goal.

Secondly, maintaining the constant consolidation force during the lamination process is crucial because it greatly affects the mechanical properties of the final product. To make further tests with the material, alternatives have to be found to replace the gas torch and improve the heat controllability. The next experiments should be focused on using a more controllable heating source.

3.2.2 Investigating laminating parameters using IR heater in continuous process.

The levels were chosen as follows:

1. 1 bar – 80 N
2. 4 bar – 322 N
3. 7 bar – 563 N.

The levels of the laminating speed were chosen as follows:

1. 0,3 m/min;
2. 0,4 m/min;
3. 0,5 m/min.

The choice of levels was greatly influenced by the limits of the equipment. Test results can be seen in the Table 3.3.

***Table 3.3** Results from the rolling test.*

Test No	Compaction force, N ± 20 N	Laminating speed, m/min	Shear force, N ± 0.5%
1	80	0,3	2103
2	80	0,3	5730
3	80	0,4	1726
4	80	0,4	737
5	80	0,5	4915
6	80	0,5	2313
7	322	0,3	2848
8	322	0,3	3336
9	322	0,4	6360
10	322	0,4	6945
11	322	0,5	905
12	322	0,5	533
13	563	0,3	4340
14	563	0,3	4240
15	563	0,4	2712
16	563	0,4	6315
17	563	0,5	1061
18	563	0,5	3352

Results show that the strongest seam was achieved with 322 N compaction force and with 0,4 m/min laminating speed. The shear strength with these parameter values was 6945 N. However, as it can be seen in the Table 3.3, the results are scattered.

The reason of scattered results is probably because of an insufficient control of the process parameters but also numerous outer factors that may have an influence on process, for example improper alignment of the roller and the mold and improper control of the material temperature and moisture (Campbell et al., 2010) which resulted in improper adhesion (Baker et al., 2004; Roberts et al., 1997; Crossley et al., 2009).

Although the temperature during laminating is constantly monitored with the sensor, it may be possible that the sensor does not reach to the actual consolidation zone and therefore there may be some derivations from the real values.

Also, principally there are possible variations in the surface area of the seam and misalignment of the test strips.

One separate issue is focusing the heat input. In the current study an electrical ceramic infrared heat source was used. It is well controllable by the means of controlling the power of the element. Also, the power of 500 W seems to be enough at low laminating speeds. The disadvantage of that type of heat source is that it is difficult to focus the heat beam. It also generates a lot of excessive heat that cannot be used in the process and therefore has a rather bad influence on the process parameters by heating up the surroundings. Based on factors listed above the next steps that must be taken into consideration concerning the development of the new laminating head are the following:

1. The force control/ position compensation can be left as it is – it is accurate enough.
2. Heat sensor has to be positioned in a way that it would measure the values as close as possible to the consolidation area. It must be guaranteed, that the excessive heat from the heat source does not influence the operation of the sensor.
3. Key factor in this process – the heating element – must be improved. A fast reacting infrared heater, or even better, a laser beam should be used if found with an appropriate price.

3.2.2.1 Conclusion

A new laminating testing device has been developed which is step closer to the attempt to control the fiber direction in a laminate. Tough, the first experiments carried out will be non-steered. Varying the fiber direction is closely covered in [26–28]. The experimental study has been performed in order to determine the relationships between the main laminating parameters – laminating temperature, consolidation force and consolidation speed during the continuous process (in situ laminating). Despite to the fact that a proper correlation between the parameters was not found due to the scattering of the results, the results of experiments show that the values of the parameters used on this specific device are not totally off the scale. The fact that the maximum force achieved was 6945 N which is almost the tensile strength of the tape itself, proves the fact. Grouve et al. 2010 and Rao et al. 2016, have found that increasing the feed rate but especially the temperature increases the bond in the laminate.

According to Endres et al., 1990 and Calhoun et al., 1990 using infrared heater should give satisfactory results. In this case, it can be concluded that high heat inertia of the heater does not provide satisfactory temperature control for laminating PA12-CF60 tape at higher speeds that are needed to make the device usable in industry. A quick response, quick acting heaters can be used only to maintain reasonable process speeds.

3.2.3 Investigating laminating parameters using thermo-oven

3.2.3.1 Preliminary tests

Preliminary tests were carried out to screen the optimal limit parameters of the PA12-CF60. Known parameters for this material are melting point 170 °C and Vicat softening point 125 °C. Before composing the preliminary test plan, some preparative tests were made around the melting point to get to know where to start. Three parameters – temperature, force and duration were tested. It appeared that irrespective of the force, below the melting point 170 °C, no adhesion appeared. At the melting point but with force below 10 N, also no adhesion appeared. The force was increased step by step up to 2000 N. It appeared that forces above 300 N are not practically applicable because higher forces cause mechanical damage and distortions to the test piece. This is not acceptable from the esthetical point of view and distortions also act as a stress concentrator. All the preparative tests were made using one second laminating time. Due to the viscoelastic properties of the material, laminating duration will be also investigated.

As a result of the preparative tests, a test plan was made. Test pieces were laminated and then tested in the tensile - compression machine. The chosen parameters of the test plan and the results can be seen in the Table 3.4. Three parameters with three levels had to be tested. Therefore, to get the full factorial test plan, 3^3 or 27 tests total had to be carried out.

Table 3.4 *DOE and results.*

No	Temperature	Force	Duration	Peak shear force
	°C	N	Second	kN
1	170	50	0,5	4,8
2	170	175	0,5	5,27
3	170	300	0,5	5,21
4	170	50	1	5,05
5	170	175	1	5,43
6	170	300	1	5,01
7	170	50	2	5,03
8	170	175	2	5,86
9	170	300	2	5,23
10	185	50	0,5	6,16
11	185	175	0,5	5,42
12	185	300	0,5	5,72
13	185	50	1	6,19
14	185	175	1	5,61
15	185	300	1	6,07
16	185	50	2	6,18
17	185	175	2	6,01
18	185	300	2	6,19
19	200	50	0,5	6,04
20	200	175	0,5	6,1
21	200	300	0,5	5,64
22	200	50	1	5,31
23	200	175	1	5,17
24	200	300	1	6
25	200	50	2	5,46
26	200	175	2	5,96
27	200	300	2	5,06

As a result of the preliminary tests, some conclusions can be made:

- Laminating duration 0,5; 1,0; 2,0 seconds does not play significant role in the quality of adhesion. The variation is less than 100 N.
- Max duration 2 s. Anything above this is too slow to apply in practice.
- Force above 300 N is not applicable in practice.
- The optimal heating temperature could be 185 °C to 190 °C. Anything above 200 °C can result in distortions of the test pieces and evaporation of the PA matrix.

3.2.3.2 Final tests

As a result of the preliminary tests, conclusive test plan was made. To minimize the number of experiments that have to be made, duration was left out and attention was put on temperature and laminating force. The following experiments were designed with DOF program using the range of parameters from the previous experiments and also using uncertainty parameters of the testing devices used. The designed table of the experiments and results of the tensile testing can be seen in the Table 3.5 and in Fig. 3.6.

Table 3.5 *DOE and the results of the final testing.*

No	Temperature	Force	Peak shear force
	°C	N	kN
1	192,5	125,0	6,11
2	170,0	300,0	5,54
3	170,0	300,0	5,21
4	200,0	300,0	5,89
5	185,0	175,0	5,9
6	170,0	208,7	6,04
7	185,0	175,0	6,29
8	200,0	191,3	6,49
9	185,0	175,0	5,18
10	185,3	300,0	5,95
11	200,0	176,3	6,28
12	189,1	50,0	5,65
13	185,0	175,0	5,1
14	170,0	50,0	5,41
15	179,5	67,7	5,16
16	170,0	208,7	5,5
17	200,0	50,0	5,93
18	191,9	232,5	5,8
19	178,7	241,5	5,96
20	189,1	50,0	5,85
21	173,6	132,5	5,22
22	170,0	50,0	4,82
23	185,0	175,0	5,21
24	187,0	300,0	5,31
25	200,0	50,0	5,64
26	200,0	300,0	5,25

3.2.3.3 Possible sources of inaccuracy

The purpose of the preliminary and final study was to find an optimal area of parameters that should be used in laminating the PA12-CF60 material. When comparing the preliminary and final results, there can be found some differences in results when using the same parameter values. The accuracy of used devices definitely plays its own part in the variance of the results. Probable the biggest contributors to the inaccuracy are the human factor and the deformations of the test pieces that sometimes happened at higher laminating temperatures and longer laminating time. This led to uneven breakage when conducting the tensile tests. On a graph, it appeared as a multiple black triangle (multiple sudden changes in the load). The deformation of the specimen can be seen in the Fig. 3.7. Specimen no. 11 has a bent symmetry axis when compared to specimens 12, 13, and 14. Deformed shape leads to uneven breakage, seen in the Fig. 3.8. Another non quality specimen can be seen in the Fig. 3.9. The shape of the specimen is a result of a too large compressive force used when laminating. It gives a very good bond and adhesion, but is not acceptable from an aesthetic point of view.

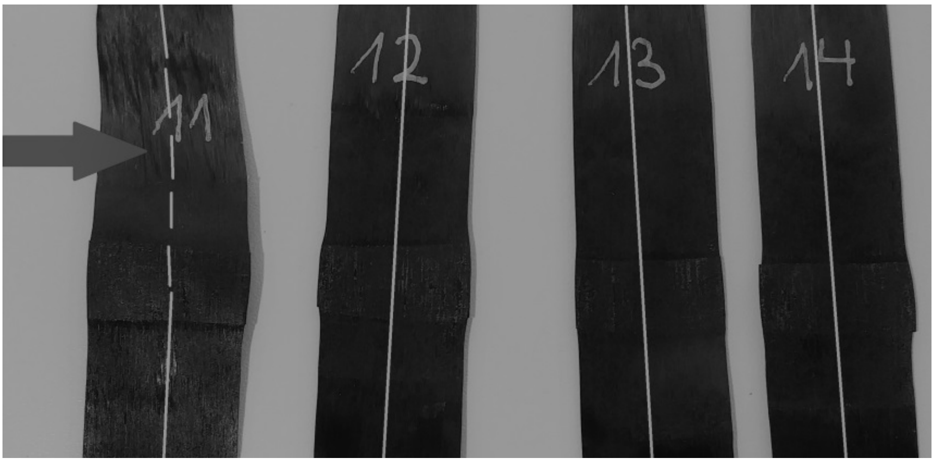

Figure 3.7 *Deformed specimen no.11.*

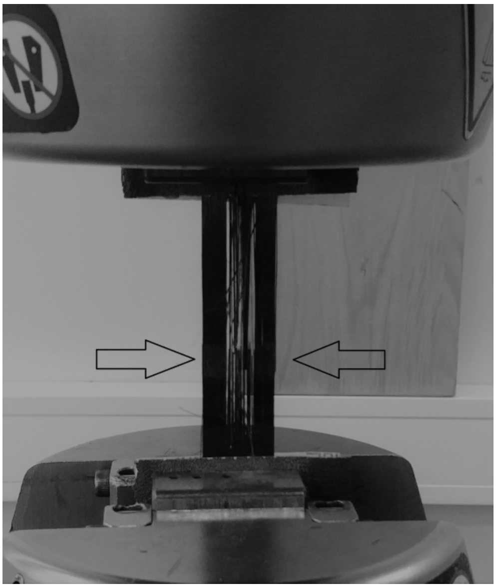

Figure 3.8 *Uneven breakage.*

Figure 3.9 *Result of an excessive compaction force.*

3.2.3.4 Conclusions

As a result of preliminary and final testing, several conclusions can be made:

- There is dependency between tensile strength, laminating temperature and force.
- Laminating duration had minor effect on the quality of adhesion in the laminating area. Duration time more than 2 s. was considered in this study inapplicable in practice because it would result in too slow working rate and low productivity. Duration less than 0,5 s. was not possible to achieve with given equipment.
- Increase in force results in slight increase in tensile strength (approx. 100 N).
- Increased temperature has slightly greater effect on tensile strength than force and also improves the adhesion (approx. 540 N).

- Can be said that between the chosen limit values, the adhesion quality is quite consistent. The quality of adhesion needs more investigation from the point of porosity and defects in the adhesion area by assessing the cross section of the contact area under microscope.
- Results refer to the fact, that the most important of the given parameters is controlling the temperature (or heat input in continuous process), which is also confirmed by the fact that laser is preferred heat source for this application and almost always used in high end devices.

3.3 Numerical validation of the mathematical model

Considering $f(x,y) = e^{x+y}$ as a sample test function numerical results are given in Table 3.6 (n=0) and Table 3.7 (n=1), respectively. Similarly, to 1D problems, in the case of n=0 (Table 3.6), the rate of convergence tends to one and the absolute error is significant.

***Table 3.6** Case $n = 0$, function is expanded into Haar wavelets.*

N	Function value at point x=0.5, y=0.5	Absolute error	Converg. rate
4	3.490342957	7.72E-01	
8	3.080216849	3.62E-01	1.0929844
16	2.893595944	1.75E-01	1.0457885
32	2.804569356	8.63E-02	1.0227182
64	2.761088539	4.28E-02	1.0113151

In the case of n=1 (Table 3.7), the order of convergence increases to two and absolute error reduces substantially. The absolute error obtained with 64 collocation points for n=0, is obtained outperformed with 4 collocation points for n=1.

***Table 3.7** Case $n = 1$, the first derivative of the function is expanded into Haar wavelets.*

N	Function value at point x=0.5, y=0.5	Absolute error	Converg. rate
4	2.711774109	6.51E-03	
8	2.716642197	1.64E-03	1.9888
16	2.71787112	4.11E-04	1.9972
32	2.718179101	1.03E-04	1.9993
64	2.718256144	2.57E-05	1.9998

The Haar wavelet-based methods for function approximation is introduced and validated on numerical samples. Next step is its application for response modeling in ATL process. Considering, the limited dataset currently available, the Haar wavelet expansion based 2D mathematical model (2.8) is employed. The model used can be considered as rather robust utilized for limited dataset. For using model (2.10) the additional tests are needed in order to determine the values of the functions $\varphi(x)$ and $\psi(y)$ at boundary. Based on existing experimental data available, the non-uniform mesh is utilized in (2.8). **To the best of the author's knowledge, it is first use of Haar wavelet expansion for function approximation implemented on non-uniform mesh.**

4 Conclusions

According to the main goal set for the thesis research, an Automated Tape Laying manufacturing method of composite laminates was investigated. The main laminating parameters, and their influence on laminate, were evaluated. During the research process a knowhow was obtained that can be used in the future studies. A mathematical model was found to predict the shear strength of the laminate. The main key points obtained from the research can be outlined as follows:

- Key to success is an accurate controlling of the laminating parameters. This can be achieved by complicated realtime monitoring and feedback systems.
- The most important parameter is the laminating temperature and the heat control in the compaction area.
- Low budget heat sources like hot gas torch and IR heater are not suitable for laminating PA12-CF60 due to their long response time, excessive heat and problems with focusing the heat to the compaction area.
- Controlling heating process appears the biggest challenge in the case of all three technologies employed.
- More accurate heating process controlling can be achieved by utilizing laser heating. However, at current time the laser heating technology is substantially more expensive.
- At this point, the best model for predicting the shear strength is given by the Haar wavelet expansion based 2D mathematical model.

Scientific novelty

From the aspect of novelty, the main scientific achievements of the current thesis can be outlined as follows:

- Acquiring knowhow for development of new lamination equipment with affordable costs.
- Study of process parameters for equipment developed.
- Lamination with selected material is little investigated.
- First use of Haar wavelet expansion for function approximation implemented on non-uniform mesh.

Future work

The future work of the project can cover points like:

- Improvement of the heating source
- Finding possible alternatives to the laser
- Finding funding for buying a laser or professional laminating head
- Validating the Haar wavelet-based model using different methods like FEM, DQM or FDM
- Investigating different ATL laminating materials.

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Abstract
Development of Equipment and Mathematical Model for Manufacturing Steered Fibre Laminate

The current thesis that is focused on designing a variable angle tow laminate and its manufacturing methods, is a brief summary of the papers that have been written regarding this investigation. At the beginning of the investigation, an aim was sought to study the possibilities of manufacturing variable angle tow laminates and its theoretical foundations and the possibilities of creating models to predict the properties of the laminate; to get an overview what has already been done, and what can be done in this field. It has been a known fact that ATL has been around for a while already, but still it is a relatively new phenomena in the composite world ant therefore pretty suitable for a doctoral thesis. One of the reasons why it is difficult to find information about these methods is that most of the institutions that deal whit the investigation and research and development, are private companies. Probable the best known are Mtorres, Electroimpact, Coriolis, BA Composites and Fives Group (Denkena et al., 2016). To maintain their position on a market, they most probable are not willing to share their findings. One of the main goal of this thesis was to find out the basics of this technology, acquire know-how and through this process increase the competitiveness of the Estonian composite manufacturing enterprises. The major disadvantage of the ATL is its high set-up price that make less attractive to the small and medium sized enterprises. Therefore, the main goal of the research group was to find ways to make ATL more available by decreasing the price tag.

During the investigation process, the focal point of the thesis shifted more to discovering the ways to laminate the CFR polyamide tape PA12-CF60 and finding its key laminating parameters. One of the reasons why ATL laminating devices are so highly priced is because of the heat source that is used to heat the tape and compaction area. The results prom the experimental study and also findings from the literature claim that the most important factor of ATL device is the heating source that determines the effectiveness of the process, the quality and the cost of the final product (Yassin et al., 2018). So, as a result, at this point, the most reliable and most used heat source in the ATL technology is a laser (Di Scalea et al.,2000; Khan et al., 2010; Funck et al., 1995; Asse'ko et al., 2015). There are different lasers that are used. For example CO_2 laser (Beyeler et al., 1998), Nd:YAG and diode lasers. The last two are the most common, since the CO_2 laser does not suit all the materials including the PA12-CF60 material. All these lasers have on common feature. It is their high price. So firstly, as a result, the current thesis does not deal with the tests using laser because it would be controversial with the essential task of the study, secondly research group did not have possibility to use suitable laser nor the financial capabilities to buy one during the investigation period. According to the literature, the most important laminating parameters were chosen. They were consolidation force, temperature in the consolidation area and time (laminating speed).

To study the effects of these parameters on a laminate, the cheapest and most available heat source was chosen to carry out the experiments. The choice was a propane –butane gas torch, which means that the material was heated with an open flame. There are many examples from the literature where the laminating with a gas torch has given successful results (Dai et al., 2002a, 2002b; Colton et al., 1992). Unfortunately, laminating the material given in this thesis, was not particularly successful which expressed in great

variance in the results. As a result, a new, more controllable heat source had to be chosen. According to the literature, the next logical choice was an IR heater. The IR heater was accurately controlled via the feedback loop using an Arduino controller. Despite the efforts of the work group, the main issue with the IR heater and gas torch – the residual heat that heats surroundings and affect the testing results, was not eliminated. This again had a bad influence on the results and made it difficult or impossible to make any conclusions regarding the relations between the laminating parameters.

At this point it was obvious, that controlling the heat input accurately in the compaction area, is inevitable. As a result, a totally new approach had to be figured out to isolate the specimen and testing device from the outer factors.

The solution was laminating the test pieces in a thermo-oven. This made it possible to control and keep the temperature constant in the laminating area during the whole laminating period. The results were acceptable and some conclusions regarding the parameters could be done. It could be said that irrespective of the compaction force, under the melting point, there was no adhesion. There is a maximum temperature that must not be exceeded due to the evaporation of the matrix material and deformations in a specimen. The consolidation time did not play a crucial role in the quality of adhesion. Increasing the consolidation force had a positive effect on the strength of the seam but excessive force could cause deformations in a testpiece or final product that is not acceptable from the aesthetic point of view. Sometimes the consolidation force is limited by the mold material like foam etc. (Denkena et al., 2016).

Since it has been a long journey investigating this subject, other research groups have recently had some success in using a gas torch heater and further investigated using the IR heater. Using gas torch in parallel with nitrogen gas as an inert gas has shown great results. This combination should avoid the oxidization of the laminating material at higher temperatures. In the field of using IR heaters, there has not been any major success because their major disadvantage- the great heat inertia, has not been resolved. Great heat inertia is not acceptable from the point of productivity. In addition, new research groups have started to investigate alternative ways to heat the material like microwaves, ultrasonic and induction heating (Stokes-Griffin et al., 2012; Rizzolo et al.,2016; Benataret al., 1987; Levy et al., 2011).

Despite of the efforts done, at this point, as a result of the current thesis, it can be said that if the high quality of the product, accurate controllability and productivity are the key words, then today, there is no substitute to the laser.

Lühikokkuvõte
Seadmete ja matemaatilise mudeli arendamine muutuva kiuga laminaadi valmistamiseks

Käesolev doktoritöö, mis uurib muutuva kiu suunaga laminaadi projekteerimist ja valmistamistehnoloogiaid, on lühikokkuvõte temaatikast kirjutatud artiklitest. Uurimisteekonna alguses sai püstitatud eesmärk uurida muutuva kiu suunaga laminaadi projekteerimise võimalusi ja muutuva kiuga laminaadi projekteerimise teoreetilisi aluseid ja mudelite loomise võimalusi, saada selgust, mis on selles valdkonnas maailmas ära tehtud, ja mis on veel võimalik teha. On olnud teada fakt, et automatiseeritud kiulaotus on olnud olemas juba mõnda aega, kuid siiski on tegemist piisavalt uue nähtusega komposiitide maailmas, mille tõttu on informatsiooni ja algteadmisi selle kohta võrdlemisi raske leida ja on seetõttu sobilik ka doktoritöö temaatikaks. Sellel, miks informatsiooni on raske leida, on ka teine põhjus. Kuna enamus selles valdkonnas teadust ja arendustegevust tegevad asutused on eraettevõtted nagu näiteks Mtorres, Electroimpact, Coriolis, BA Composites ja Fives Group (Denkena et al., 2016), siis soovist oma turupositsiooni hoida, kogutud teadmisi ja oskusteavet väga heldelt ei jagata. Üheks töö põhiülesandeks oligi omandada teadmised ja oskusteave sellest tehnoloogiast, et hiljem need teadmised ja kogemused praktikasse rakendada ja seeläbi tõsta Eestis komposiitmaterjalidega tegutsevate ettevõtete taset ja konkurentsivõimet. Automatiseeritud kiulaotuse kõige suuremaks miinuseks on tema kõrge sisseseadmise hind, mis teeb ta raskesti kättesaadavaks just väiksematele ja keskmise suurusega ettevõttetele. Uurimisgrupi eesmärk oli uurida võimalusi sääraste seadmete kättesaadavamaks muutmisel ja seda just läbi hinna.

Töö keskseks tegevuseks kujunes süsinikkiuga armeeritud polüamiid lindi PA12-CF60 lamineerimisvõimaluste uurimine ja selle lamineerimiseks oluliste parameetrite välja selgitamine ja nendevaheliste seoste leidmine. Üks põhjus, miks tööstuslikult kasutatavad kõrgetasemelised seadmed on väga kallid, peitub nendes kasutatavas kuumutusallikas. On kirjandusest ja ka antud töö praktilisest osast välja tulnud asjaolu, et automatiseeritud kiulaotustehnoloogias mängib võtmerolli just soojusallikas, mis määrab ära tehnoloogia efektiivsuse, toote kvaliteedi ja tootmise maksumuse (Yassin et al., 2018). Seetõttu on ka üldlevinud soojusallikaks kujunenud laser (Di Scalea et al.,2000; Khan et al., 2010; Funck et al., 1995; Asse'ko et al., 2015). Kasutatavaid laserite tüüpe on mitmeid nagu näiteks CO_2 laser (Beyeler et al., 1998), Nd:YAG ja diood tüüpi laserid. Neis kaks viimast on enimlevinud, kuna CO_2 laser ei sobi kõikide lamineeritavate materjalidega sh. PA12-CF60 materjaliga. Kõiki neid lasereid ühendab aga üks kindel tunnus- nad on kõik väga kallid. Seetõttu käesolev doktoritöö ei käsitle katsetusi laseriga, kuna esiteks, see läheks vastuollu ülesanne esialgse püstitusega- luua taskukohasem seade ja teiseks puudus füüsiline ja finantsiline juurdepääs sobilikele laseritele uurimisperioodi vältel.

Kirjandusest lähtuvalt pandi uurimise algfaasis paika kõige olulisemad parameetrid lamineerimisel. Nendeks on konsolideerimisjõud, temperatuur konsolideerimisalas ja aeg (lamineerimise kiirus).

Et uurida nende parameetrite mõju laminaadile viidi läbi katsetused kõige lihtsama ja odavama soojusallikaga, mida oli võimalik hankida. Selleks oli propaani-butaani põleti, ehk siis soojusallikana kasutati lahtist leeki. Kirjandusest on leida näiteid kuidas gaasipõletiga on õnnestunud viia läbi edukat lamineerimist (Dai et al., 2002a, 2002b; Colton et al., 1992). Paraku antud uurimusest kasutatava materjali puhul ei osutunud lamineerimine gaasipõletiga kuigi edukaks, mis väljendus katsetulemuste väga suures kõikumises. Seetõttu tuli valida mõni teine, paremini kontrollitav soojusallikas. Järgmiseks soojusallikaks sai valitud infrapuna soojusallikas, mida oli võimalik tagasiside abil läbi Arduino kontrolleri täpselt kontrollida. Paraku ei õnnestunud uue soojusallika kasutuselevõtuga vältida ka gaasipõletiga esinenud probleemi milleks oli nimelt üleliigne soojus, mis kiirgus katseseadet ümbritsevasse keskkonda ja kuumutas ka seadet ennast sealt, kust ei olnud vaja. See aga omakorda mõjutas katsetulemuste hajuvust, mis ka sel korral oli üpriski suur. Kuna oli selgeks saanud, et temperatuuri kontrollimine lamineerimisalas on protsessi võtmeteguriks, siis tuli võtta täiesti uus lähenemine asjale, ja leida meetod kuidas katsekeha ja katseseade isoleerida välistest mõjutavatest teguritest. Lahenduseks oli katsekehade lamineerimine termokapis, mis võimaldas kogu lamineerimisaja vältel hoida katsekeha konstantse etteantud temperatuuri juures. Sääraselt teostatud katsed andsid märgatavalt paremad tulemused ja sai juba teha mõningaid järeldusi lamineerimisparameetrite kohta. Sai teha järelduse, et alla sulamistemperatuuri, olenemata konsolideerimisjõust ja ajast nakkumist ei toimu. Lisaks leidub temperatuur, mida ületada ei ole mõtet, kuna maatriksmaterjal hakkab aurustuma ja katsekeha (toode) hakkab deformeeruma. Samuti sai teha järelduse, et konsolideerimisaeg ei oma olulist rolli hea liite tekkimisel. Konsolideerimisjõu suurenedes suurenes ka nakkuvus või liite kvaliteet mõnevõrra, kuid konsolideerimisjõu ülemäära suurendamine viib samuti katsekeha või toote deformeerimiseni mis tihti ei ole esteetilisest seisukohast aktsepteeritav. Lisaks paneb konsolideerimisjõule piirid ette ka kasutatav vormimaterjal, näiteks tihti kasutatav vahtplast (Denkena et al., 2016). Kuna antud temaatika uurimine on kestnud pikalt, on teiste uurimisgruppide poolt sügavamalt edasi uuritud gaasipõletite ja IR soojusallikate rakendamise võimalusi antud tehnoloogias. Perspektiivikaks võib kujuneda gaasipõleti kasutamine koos lämmastiku, kui inertgaasiga, mis peaks vältima lamineeritava materjali oksüdeerumist kõrgetel temperatuuridel. IR soojusallikate valdkonnas ei ole tehtud suuremaid edusamme, kuna nende peamine miinus – suur inerts, vähendab tootlikkust ja pikendab tsükliaega ja ei ole tänasepäeva seisuga väga perspektiivikas. Lisaks on tekkinud uurimisgruppe kes proovivad kätt mikrolainetega, ultraheliga ja induktsioonkuumutusega (Stokes-Griffin et al., 2012; Rizzolo et al.,2016; Benataret al., 1987; Levy et al., 2011). Siiski saab teha käesolevas töös tehtud eksperimentide põhjal järelduse, et kui eesmärgiks on toote kõrge kvaliteet, protsessi hea kontrollitavus ja tootlikkus, siis tänase päeva seisuga laserile head alternatiivi pakkuda ei ole.

Appendix

Publication I

Haavajõe, A., Mikola, M., Pohlak, M. Design and Manufacturing of Variable Angle Tow Laminate. Engineering Materials and Tribology. 2016.

Design and manufacturing of variable angle tow laminate

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Abstract. Variable angle tow (VAT) laminates have shown enhanced stiffness/strength performance compared to conventional straight fiber laminates. Employment of VAT allows utilizing variable stiffness design of composite structure, thus it widens the design possibilities. As a result, composite structure with improved mechanical characteristics can be manufactured. The main aims of the current study are to give an overview on methods and algorithms used for analysis and design of VAT laminates, and to develop technology and equipment for manufacturing laminate with improved structural performance. In order to improve the accuracy of the compaction process, a set of experiments were carried out using a simple testing device. For measuring the compaction force, a pneumatic cylinder, pressure regulator and digital manometer were used. The temperature of the consolidation area and the heat distribution were screened with the thermal camera. Infrared heater was used as a heating source. Material used in the experiment was carbon fiber reinforced polyamide.

Findings show that in addition to the main parameters – the compaction force and temperature, there are many minor factors, such as the compaction wheel diameter, material and surface roughness of the compaction roller, the material and surface roughness of the mold and the pretension in the laminating tape and also the laminating speed, all influence the quality of the final product.

Key words: Advanced Fiber Placement Technology, Automated Fiber Placement, Automated Tape Laying, Fiber Reinforced Composites, Laminates

1. Introduction

Advanced composites have been manufactured by hand lay-up of prepreg to produce composite parts that are then consolidated and cured in an autoclave. This labor-consuming process results in high fiber volume fraction, void-free, well-consolidated composite structures with excellent mechanical properties. However, the costs of these structures are high due to the labor costs for hand layup processing. Automated Fiber Placement (AFP) and Automated Tape Layup (ATL), as one of the steered fiber composite manufacturing techniques, have gained attention for their cost-effective, flexible, and automatic process. Application of the AFT and ATL techniques allows to design of composite structures with variable stiffness [1-5]. Pioneering work in this area has been done in Delft University of Technology by research group lead by Z. Gürdal. Their latest results concerning numerical modeling of AFP/ATL techniques are presented in [1-2]. In [3-5] the simulation models and optimization techniques are developed for design of discrete variable stiffness structures. Design and modeling of composite materials and structures has been main topic of the current work group [6-11]. Special attention was paid to optimal material orientation, related tightly with the topic of the current study [12-13]. The main issues today concerning these technologies are improving the heating process controllability and deeper understanding of the influence of heating parameters and compaction process, including compaction force, positional/speed errors, also possible variations of the robotic machinery and laminating head under the working conditions. In the current study, a set of experiments were carried out using a simple testing approach. For measuring of the compaction force, tensile-compression measurement system was used. The temperature of the consolidation area and the heat distribution were screened with the thermal camera. Gas torch heater was used as a heating source. Material used in the experiment was unidirectional carbon fiber reinforced polyamide tape. Findings show that in addition to the main parameters – the compaction force and the temperature, there are many minor parameters such as the diameter of the compaction wheel, the pretension of the laminating tape, etc, all influence the quality of the final product. Thus, designing a low price machine for manufacturing of steered fiber products, yet making no trade-offs from the aspect of the controllability of the laminating parameters, proves to be a real challenge and needs further investigation.

One of the main technologies for producing advanced composites with variable angle tow is AFP which belongs to the robotized fiber placement method (RFP). A typical configuration of the RFP system with its main modules can be seen in the Fig. 1.

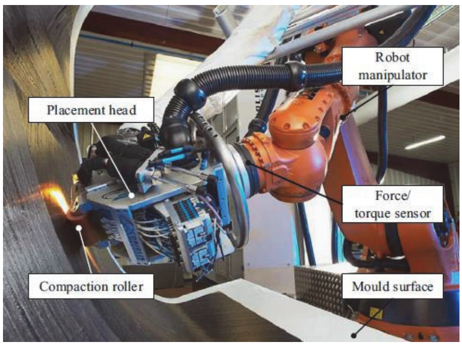


Fig. 1. A typical AFP system [14].

The main parts of the system are industrial robot with its manipulator and force/torque sensor, a mould and the heart of the system- the laminating head. The basic working principle is shown in the Fig. 2.

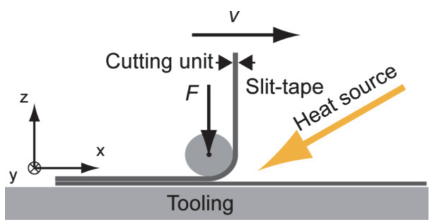


Fig. 2.Working principle of the AFP.

The main parts of the laminating head are the compaction roller that presses the material tape against the mold or previous ply; a heat source, that heats the material tape above the melting point to make it sticky and a cutting mechanism that cuts the tape when necessary. The main operational parameters that have to be reinvestigated when using new materials are:

- Compaction force

- Temperature
- Time (speed)

Compaction force. The major factor that determines the quality of the final product is the compaction force. The experiments carried out by Pitchumani [15] showed that the quality and performance of the final product is directly influenced by the presence of the voids. So, the consolidation process plays an important role in the manufacture of high quality composite parts. Moreover, good consolidation is important for eliminating residual stresses and warpage in the product [16]. In response to the demand for high quality of composite structures, the compaction force for a consolidation process needs to be reinvestigated for possible variations of the force that lead to the variations of the consolidation process. The roller itself is usually made of aluminum but can also be made of different metals with different coatings such as teflon and polyurethane depending on the size and curvature of the mold being laminated. In industrial laminating heads, cooling is used to prevent the composite tape from sticking to the roller.

Heating. As a heat source, laser, infrared heater or gas torch can be used. Laser heating was first introduced by Beyeler and Güçeri [17]. They used CO_2 laser for melting the incoming tape and substrate for thermoplastic filament winding. Laser heating has many advantages over the other methods, like fast response time, excellent energy efficiency and uniform heat distribution and good integration with the overall controlling system. However, the size and weight of a laser requires a large fiber placement head in order to carry it. This restriction limits the application of laser to large machines only not to mention the fact that it is expensive, which is contrary to the main goal of the work group behind this paper. Infrared heating was investigated by Endres [18] and Calhoun [19] from the aspect of applicability for filament winding of thermoplastic composite tapes for its energy-efficient characteristics and good response behavior. Although infrared heating is not as good as laser heating, it is, overall, a good technique and available with reasonable price on the market. Therefore, today it is the most widespread solution for heating the towpreg. However, it is inferior to the laser from the aspect of nip-point heating which needs very high intensity heating on a small area. Hot gas heating for on-line consolidation of thermoplastic composites was first used by Werdermann [20]. In spite of the disadvantages of very low energy efficiency and slow response time, a hot gas heating is the most widely used method in low tech laminating applications for its cost-effectiveness and design flexibility.

The following part of this paper concentrates on testing the two main parameters – the temperature and compaction force on carbon fiber reinforced polyamide material PA12-CF60 tape with 0,1 mm thickness, 25,4 mm width and with melting point of 180° C.

2. Experimental study

To find the optimal compaction pressure and heating temperature to the material PA12-CF60, a simple static pressure test was carried out. The tests comprised cutting the material into right length and positioning it to the simple fixture made of cardboard to ensure approximately the same overlay surface area during every test attempt. The device can be seen in the Fig. 3., where the red rectangle in the middle indicates the location of the contact area that is going to be heated and compressed.

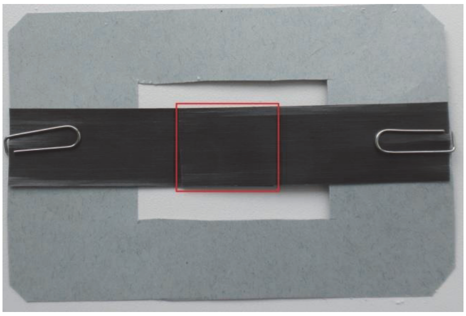


Fig. 3. The test piece.

The estimated contact area is 645 mm^2. The opening in the cardboard is for heating and for pressing, so that during the process all the force is applied to the contact area of the material tape and the thickness of the cardboard does not influence the result. The two test pieces are fixed with simple paperclips. The test setup can be seen in the Fig. 4.

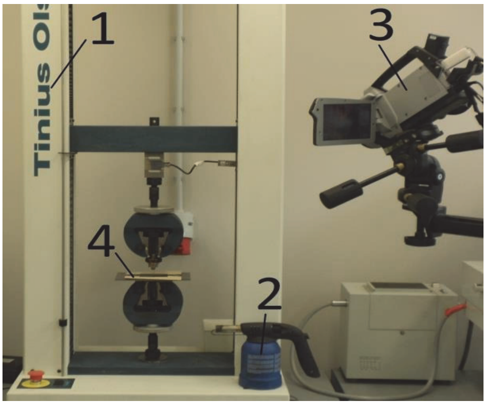


Fig. 4. Test setup.

For applying compressive force, a material testing machine Tinius Olsen H10KT (No. 1) and some simple jigs were used. As a heating source, a gas torch (No. 2) was used. The temperature was observed with a thermal camera Flir ThermaCAM SC640 (No. 3). In the Fig. 5, there is a close-up picture of the testing jigs and testing parts.

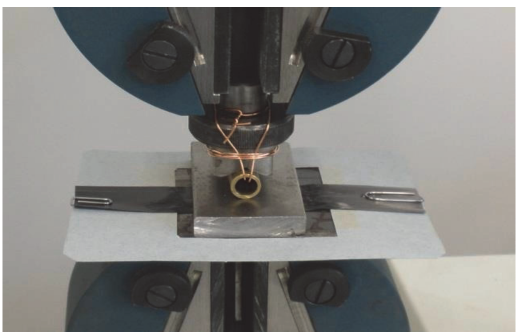


Fig. 5. Jigs.

The tests were carried out as follows: 1. Firstly, the lower steel plate was heated above the melting point of the bonding material to approximately 200 - 220° C. 2. The test pieces fixed in the cardboard jig were placed on the lower steel plate imitating the mold. Extra heat was added to the testing pieces to ensure the uniformity of the temperature in mold and material. Temperature was observed with thermal camera seen in Fig. 6. 3. An upper pressure plate was positioned on the material and constant force 400 N was applied during 30 seconds. 4. The test piece was removed from the machine.

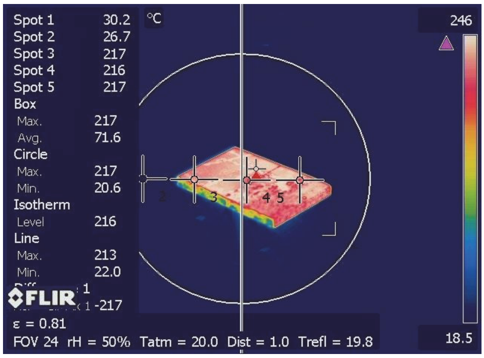
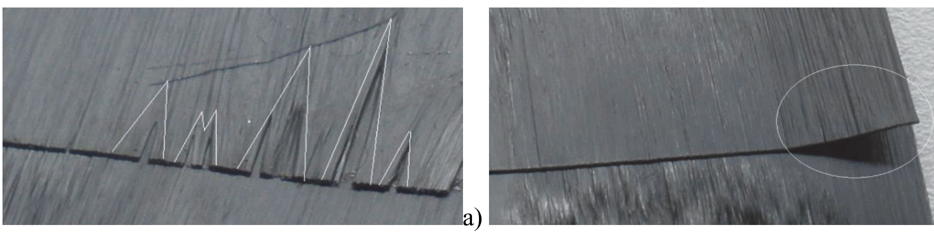


Fig. 6. Thermal image of the mould.

The test was repeated several times varying the heating temperature up to 300° C. Test pieces were torn apart in the tensile machine and investigated from the aspect of adhesion.

3. Results and discussion

Findings from the temperature tests show that: 1. The optimal temperature to get the perfect seam is between 200 – 220° C. 2. Using lower temperature can cause improper adhesion. 3. Using higher temperature is not recommended because high temperature can cause the matrix material (PA) to flow out of the seam or to evaporate leaving gaps or cracks in the seam zone (Fig. 7 a)). 4. Even heat distribution is crucial to get high-quality seam. Uneven heating causes improper adhesion (Fig. 7 b)). 5. Excessive heating can cause flashing of the carbon fiber. 6. Considering point 4 and point 5, gas torch as a heat source is an inappropriate solution for the current material used.



a) b)

Fig. 7. Heating defects.

The investigation of the compaction force was carried out as follows: 1. Testing pieces were positioned on the mold, in that case a planar sheet of steel. The same contact surface area (645 mm^2) was used. 2. Material was heated to the optimal temperature (200 – 220° C). 3. Using compaction roller, the material was pressed together using three different pressures: 0,62 MPa, 1,09 MPa and 1,55 MPa. The manufactured test pieces were then torn apart with a tensile machine to find out the force when the seam breaks. The results are shown in the Fig. 8.

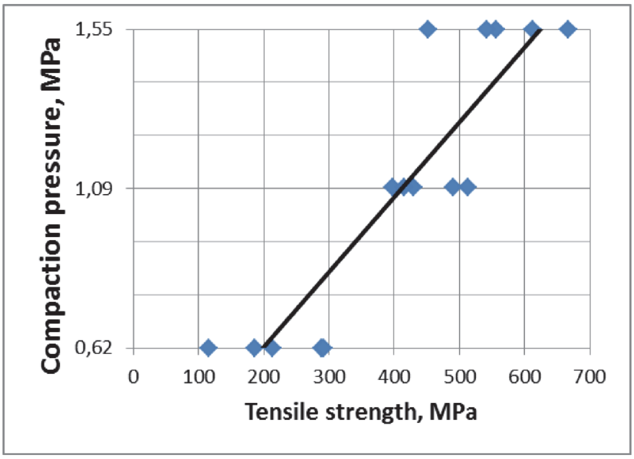


Fig. 8. Tensile strenght of the bodies.

It can be seen that there is a positive correlation between the compaction force and the strength of the bond, increasing the compaction force has positive effect on the strength.

Manufacturing speed. To find out the influence of the manufacturing speed on the quality of the bond, another testing device was designed. The compaction pressure found in the previous chapter can be taken as a reference point to start from. For regulating pressure and also for compensating the movements of the compaction roller due to the geometry of the mold, a pneumatic cylinder is used. Varying the air pressure, different compaction forces can be applied when necessary. As a result, the device enables to find relations between the laminating speed, consolidation force and heat input. The hypothesis is that to accommodate with the increased laminating speed, an increase in consolidation force and heat input is necessary. The device can be seen in the Fig 9, attached to a CNC machine for controlled movements. The main parts of the device are: 1) Body, 2) Pneumatic cylinder, 3) Linear guide, 4) Consolidation roller, 5) Spool for composite tape. A more detailed study with this system is planned in the future.

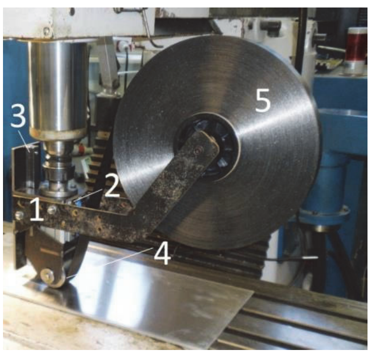


Fig. 9. Testing device in CNC machine.

4. Conclusion

Automated Fiber Placement is one way to manufacture high performance composite parts. Traditionally, the method has been used in aerospace, automotive industry and other large scale industries that have the necessity and means for adapting such technologies. If the costs of the equipment were lower, the technology could be easily harnessed in smaller industries. For example, the wind energy, small ship building, medical equipment and small scale automotive industry would be the major targets of this research.

The purpose of this paper was to make a preliminary study concerning AFP process in order to design later affordable AFP equipment. For that the authors have chosen a material and tested it to find the relationships between the main operational parameters and a way to control them. As a result of the experimental part, it appeared that the simplest heating device – a gas torch is not suitable for heating the material PA12-CF60 because of the uneven heat distribution and difficulties to control the heat input. The proper heating of the material is one of the key factors when high quality is the goal. This is one of the reasons why laser heating has found its place in ATF technology. Secondly, maintaining the constant consolidation force during the lamination process is crucial because it greatly affects the mechanical properties of the final product.

It is planned to perform a follow up study with a developed testing equipment to analyze different heating approaches and the most suitable process parameters combinations.

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Publication II

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INDUSTRIAL ENGINEERING

Experimental study of steered fibre composite production

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Abstract. The main goal of the study was to design the laminating head for an industrial robot that would be competitive from the aspect of the price and versatility and therefore suitable for the SMEs. A set of experiments were carried out to analyse key parameters during the laminating process of PA12-CF60 material.

Key words: advanced fibre placement technology, automated fibre placement, automated tape laying, fibre reinforced laminates.

1. INTRODUCTION

Because of very good mechanical properties of composite materials (specific strength and stiffness, energy absorption) and their structural capabilities like corrosion resistance, radar transparency, electrical insulation, reduction in tooling and assembly costs, there is a high interest in these materials in different areas such as transportation, construction, aerospace, automobile, and marine industries, and renewable energies [1]. Considering the difficulty of maintaining uniformity and the low strength, high shrinkage, porosity, and voids in the laminates manufactured by hand layup process [2] and the necessity to achieve the high required quality, accuracy, safety, and cost efficiency and at the same time manufacture complex shapes for manufacturing composite parts, there is a need for advanced tooling machines [3].

Today, by applying the Automated Tape Laying (ATL) technology and Automated Fibre Placement (AFP) techniques, it is possible to manufacture different composite parts of mechanical components with high accuracy, flexibility, and minimum waste [4]. The ATL technology is an automated layup process for large-scale manufacturing of composite components by constantly laying the heated composite fibre tape on a mould by a compaction roller according to the predefined orientation [5]. This technology is used to manufacture large composite components with flat and not very complex geometries. Compared with the hand layup technique, the ATL technology enables repeatability in production, higher accuracy in placing the fibres in the desired position, and reduction in waste and costs [6]. The ATL process consists of a cutting system to cut the tape in the desired measure and location, guide rollers to move the tape through the cutting system, a heating system to melt the matrix material and increase the tack level for adhesion, and a compaction roller to press the tape on the mould [7] (Fig. 1).

In general, both thermoplastics and thermosets are used in the ATL process [8]. Before full-scale production, the final product should go through some mechanical tests, such as tack test, tensile test of the seam, porosity test, etc., to check the achieved mechanical properties. Tack is the tendency of the prepreg to adhere to the previous layer or the mould surface, and the test is to

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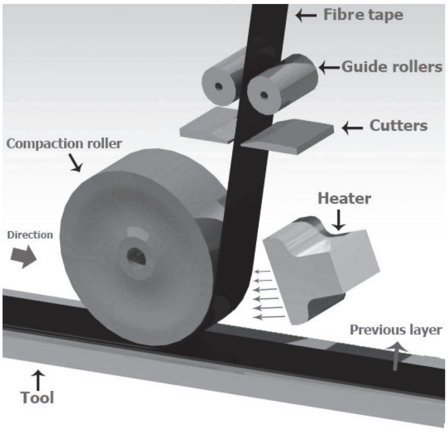

Fig. 1. Scheme of the ATL system.

determine the strength of the adhesion [9]. Depending on the manufacturer, there are different methods for testing the tack level of the layers. The level of tack can be evaluated by the peel-off test but also by a simple tensile test measuring the strength of the seam [10]. Crossley et al. [11] point out the most important factors influencing the tack level characteristics: the temperature, feed rate of the fibre, release agents, and environmental factors, e.g. the moisture. Campbell [12] states that a prepreg containing higher moisture is tackier than the one containing lower moisture. Increasing temperature raises the tack level of the fibres. Thus, the sufficient heating temperature should be achieved before the laying process is started [11].

Grouve et al. [13] used a mandrel peel set-up to test the strength of the laminates manufactured by laser-assisted tape placement. Their work indicates that by increasing temperature and feed rate the bond strength of the laminates increases. Rao et al. [14] employed a floating roller peel test to determine the tack level of the first ply and the mould surface, and found that the temperature has the highest impact on determining the peeling force, while the feeding rate has a low impact.

2. PROCESS PARAMETERS

Based on the literature [15,16], the main operational parameters of the ATL technology considered herein are the following:

- compaction force
- heating temperature
- laminating speed.

Some other important parameters are

- the radius of the roller
- the material and the coating of the roller
- the curvature of the mould, etc.

The following part of this paper concentrates on testing the two main parameters: the laminating speed and the compaction force. A specially designed testing device was used.

3. TESTING

3.1. Test setup

During the experimental study two main operation parameters – compaction force and laminating speed – were investigated on a carbon fibre reinforced polyamide material PA12-CF60 tape with a thickness of 0.1 mm and width of 25.4 mm. The melting point of this material is 180 °C. The tests were carried out as a continuous process and parameters were observed during the laminating. The tape was cut into the correct length and positioned on an aluminium mould while ensuring that the overlay surface area during every test attempt was approximately the same. The test piece can be seen in Fig. 2.

For maintaining the estimated contact area of 645 mm^2 during the rolling process both parts of the tape were fixed to the aluminium mould. The test setup can be seen in Fig. 3. For controlled laminating movements the test device was attached to a CNC milling machine. In order to maintain and vary the necessary compaction force a pneumatic cylinder and a pressure regulator were used. A curved ceramic infrared heater Ceramicx HTE 500 with 500 W output power was used as a heating source. The temperature was observed with an Optris CS LT contactless infrared pyrometer on the contact area during the laminating process. An Arduino based controller was used to control the infrared heater and to get readings from the pyrometer. At first the infrared sensor was meant to be used as a feedback to the Arduino, but it appeared that the heat inertia of the heater was too high to be controlled via a feedback system.

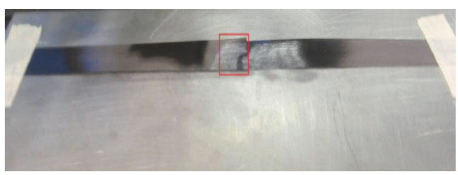

Fig. 2. Test piece. The red rectangle indicates the location of the contact area between two tapes.

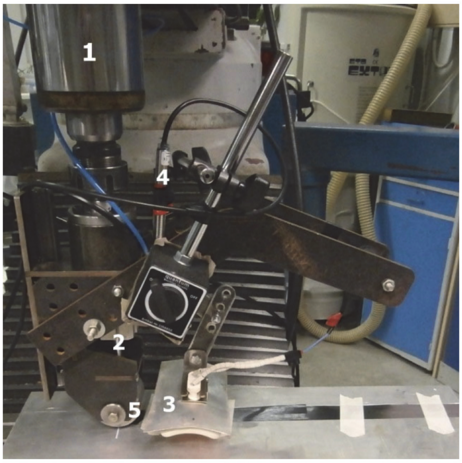

Fig. 3. Test setup. 1 – CNN milling machine, 2 – pneumatic cylinder, 3 – infrared heater, 4 – pyrometer, 5 – consolidation roller.

A consolidation roller made of steel S355JR was used for transmitting the compaction force from the pneumatic cylinder to the contact area between two tapes.

The tests were carried out as follows: (1) Both parts of the tape were fixed to the aluminium plate imitating the mould. (2) The heater was warmed up to a stable temperature. (3) While maintaining a constant laminating speed with a CNC milling machine, the contact area between two tapes was heated with the infrared heater and consolidated with the compaction roller. (4) The consolidated test piece was removed from the aluminium plate. (5) Test pieces were torn apart with the tensile testing machine and investigated from the aspect of adhesion.

3.2. Tests

As our previous studies ([17,18]) showed, the optimal laminating temperature range should be between 200 and 230 °C. Therefore the laminating temperature during the laminating process was kept in that range by adjusting the power of the infrared heater. To simplify testing the range ±15 °C was considered sufficiently precise to carry out the experiment. Therefore the temperature was taken into account as a constant.

To find the correlation between the consolidation force, consolidation speed, and tensile strength of the test piece, the full factorial design of the experiment was performed. To minimize the effect of random factors on the test results, every test set was repeated twice. Since a pneumatic cylinder and a manometer were used for measuring the compaction force, the force was converted from the air pressure. The levels were as follows: (1) 1 bar – 80 N; (2) 4 bar – 322 N; (3) 7 bar – 563 N.

The levels of the laminating speed were as follows: 0.3 m/min, 0.4 m/min, and 0.5 m/min. Test results are presented in Table 1.

The results show that the strongest seam was achieved with 322 N compaction force and 0.4 m/min laminating speed. The tensile force with these parameter values was 6945 N. However, as it can be seen in Table 1, the results are scattered.

The reason of scattered results is probably an insufficient control of the process parameters, but also numerous outside factors, for example improper alignment of the roller and the mould and improper control of the material temperature, may have had an influence on the process. Although the temperature during laminating was constantly monitored with the sensor, it is possible that the sensor did not reach the actual consolidation zone, which may have caused some deviations from the real values. Also, in principle variations in the surface area of the seam and misalignment of the test strips are possible.

A separate issue is using a proper heat source. In the current study an electrical ceramic infrared heat source was used. It is well controllable by means of controlling the power of the element. Also the power of 500 W seems to be enough at low laminating speeds. The disadvantage of that type of heat source is that it is difficult to focus the heat beam and it generates a lot of excessive heat that cannot be used in the process and therefore has a rather adverse influence on the process parameters by heating up the surroundings.

Table 1. Results of the tensile test

Test	Compaction force, N ± 20 N	Laminating speed, m/min	Tensile force, N ± 0.5%
1	80	0.3	2103
2	80	0.3	5730
3	80	0.4	1726
4	80	0.4	737
5	80	0.5	4915
6	80	0.5	2313
7	322	0.3	2848
8	322	0.3	3336
9	322	0.4	6360
10	322	0.4	6945
11	322	0.5	905
12	322	0.5	5333
13	563	0.3	4340
14	563	0.3	4240
15	563	0.4	2712
16	563	0.4	6315
17	563	0.5	1061
18	563	0.5	3352

Based on factors listed above, the next steps that should be taken into consideration in the development of the new laminating head are the following:

(1) The force control/position compensation can be left as it is – it is accurate enough;
(2) The heat sensor has to be positioned so that it would measure the values as close as possible to the consolidation area. It has to be guaranteed that the excessive heat from the heat source does not influence the operation of the sensor;
(3) The key factor in this process – the heating element – must be improved. A fast reacting infrared heater, or even better, a laser beam should be used.

4. CONCLUSION

A laminating head for an industrial robot with a competitive price and versatility has been developed. An experimental study was performed in order to determine the relationships between the main laminating parameters – laminating temperature, consolidation force, and consolidation speed – during the continuous process (in situ laminating). Despite the fact that a proper correlation between the parameters was not found due to the scattering of the results, the results of the experiments show that the values of the parameters used on this specific device are not totally off the scale. The maximum force achieved, 6945 N, which is close to the tensile strength of the tape itself with 7404 N ± 62 N, proves the fact.

It can be concluded that a ceramic infrared heater with high heat inertia does not provide satisfactory temperature control for laminating PA12-CF60 tape at higher speeds that are needed to make the device usable in industry.

5. FUTURE STUDY

The current study is of completely experimental character. However, the theoretical and numerical analysis of the steered composite has been planned. The numerical methods developed by the workgroup for analysis of composite laminates and FGM structures [19,20] are planned to be extended for analysis of steered fibre composites. Also, the results covering optimization algorithms and methods for composite structures [21–23] can be employed for fibre angle determination in designing steered fibre laminates. The experimental and numerical evaluation of the strength and stiffness properties of steered fibre materials and structures are activities that should follow the design and manufacturing process. Here special attention should be paid to robustness of the design and sensitivity analysis.

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Muutuva kiusuunaga komposiitlaminaadi valmistamine

Anti Haavajõe, Madis Mikola, Hadi Osali, Meelis Pohlak ja Henrik Herranen

Käesoleva artikli peamiseks eesmärgiks on lamineerimisseadeldise arendamises astuda samm lähemale tööstusrobotile, mis oleks piisavalt universaalne ja hinna poolest kättesaadav väikestele ning keskmise suurusega komposiitmaterjalidega tegelevatele ettevõtetele. Artiklis kirjeldatud katsete eesmärgiks oli välja selgitada lamineerimisprotsessi peamiste parameetrite vaheline seos materjali PA12-CF60 lamineerimisel.

Publication III

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Modelling Process Parameters of the PA12-CF60 Carbon Fiber Laminating Tape for Low Cost Laminating Devices

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Abstract. Current study is focused on automated fibre placement technology with the purpose of finding possibilities to offer suitable laminating equipment for small and medium sized companies. The temperature, consolidation pressure and consolidation duration are considered as laminating parameters (design variables). The experimental study has been performed and mathematical model developed in order to establish relation between the shear strength and laminating parameters.

INTRODUCTION

During the last decades advanced composites have been constantly replacing traditional materials in various applications. The main advantages over other materials are specific strength and stiffness, energy absorption, and their structural capabilities like corrosion resistance, radar transparency, electrical insulation, reduction in tooling and assembly costs [1,2]. Automated Fiber Placement (AFP) and Automated Tape Layup (ATL), as one of the steered fiber composite manufacturing techniques, have gained attention for their cost-effective, flexible, and automatic process [2]. The main issues today concerning these technologies are improving the heating process controllability and deeper understanding the influence of heating parameters, compaction process, compaction force, positional/speed errors, also possible variations of the robotic machinery and laminating head under a working condition [3-4].

Current paper is focused on study of the influence of laminating parameters on the shear strength. Assessment of the suitability of the parameters will be given according to the results from the shear testing. In previous studies by the workgroup the artificial neural network (ANN) as challenging tool in engineering design has been utilized for response modelling [5-8]. Recently, the Haar wavelet method (HWM) has been developed and applied for solving wide class of structural analysis problems covering composite and nano-strcuctures [9-15], but also differential, integro-differential and integral equations in general [16-22]. In order to keep the solution compatible and simple the functions involved in differential equations have been often expanded into Haar wavelets (mostly 1D functions). Herein, the same approach is applied for response modelling in ATL process.

EXPERIMENTAL STUDY

The test pieces are made according to the standard EN 1465:2009 used commonly for estimating different adhesives. The scheme of the test piece is given in the Figures 1-2. The two carbon fiber tape halves are cleaned with alcohol and fixed with masking tape and cooking paper. This is needed for maintaining the position of the two halves and to avoid sticking the test piece to the consolidation equipment.

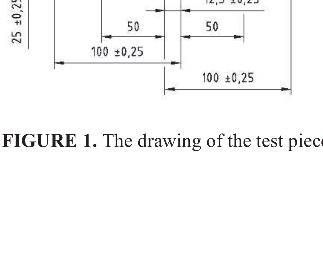


FIGURE 1. The drawing of the test piece

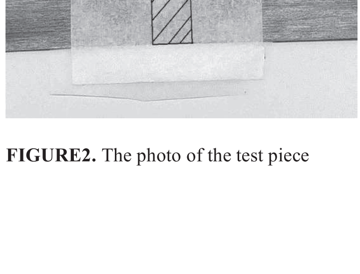
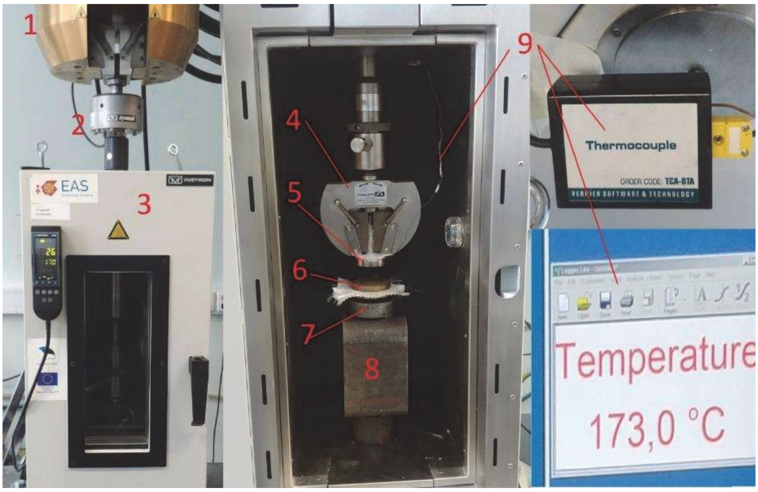


FIGURE2. The photo of the test piece

The main components of the test set-up are shown in the Fig 3. The test pieces were consolidated in a tensile-compression testing machine Instron 1, equipped with force sensor 2, for lower forces and better accuracy and automatically controllable oven 3. The shear or consolidation area is pressed between two planar surfaces when they have reached the desired temperature. The upper support 5 is equipped with a thermocouple sensor 9 to get more accurate readings from the working area. Upper support is also insulated from the gripper 4 by using glass fiber canvas. The lower support 6 is made of bronze to ensure it heats up quicker than the upper support. It is also insulated with glass fiber canvas. The lower support 6 rests on a cast iron support 7 that has a spherical joint in it to compensate the positioning errors. Underneath the cast iron support, there is a hollow section of a rectangular tube to decrease the heat inertia. For testing the shear strength, the Instron 8516 has been employed.



a) b) c)

FIGURE 2. Test set-up

The tests were carried out to screen the optimal lamination limit parameters for the PA12-CF60. Known parameters for this material are melting point 170 C^{o} and Vicat softening point 125 C^{o}. Before composing the test plan, some preparative tests were made around the melting point to get to know where to start. The temperature, force and duration were considered as processing parameters. It appears, that irrespective of the force, below the melting point 170 C^{o}, no adhesion was detected. At the melting point but with force below 10 N, also no adhesion occurs. The force was increased step by step up to 2000 N. It appears that the forces above 300 N are not practically applicable because higher forces cause mechanical damage and distortions to the test piece. All the preparative tests were made using one second laminating time. Due to the viscoelastic properties of the material, laminating duration will be also investigated. The full factorial design of experiment has been employed considering three levels for each of variable as given in Table 1.

TABLE 1. The design variables and levels

Temp, C^{o}	Force, N	Duration, s
170	50	0,5
185	175	1
200	300	2

Based on results of the tests performed the duration was left out and attention was focused on studying the influence of the temperature and laminating force. All test data obtained from initial tests were considered. Additional test points were included based on design of experiments plan and using the range of parameters from the previous experiments. The results of experiments are given in Table 2.

TABLE 2. The measured values of the temperature, laminating force and shear peak load.

	Temp, C°	Force, N	Shear peak load, kN
1	170	50	5.06
2	170	208.7	5.77
3	170	300	5.3
4	173.6	132.5	5.22
5	178.7	241.5	5.96
6	179.5	67.7	5.16
7	185	175	5.56
8	185	300	5.9
9	187	300	5.31
10	189.1	50	5.75
11	191.9	232.5	5.8
12	192.5	125	6.11
13	200	50	5.72
14	200	171.7	6.25
15	200	191.3	6.49
16	200	300	5.57

Each test has been repeated 4-6 times and the average values has been used.

MATHEMATICAL MODEL

Considered limited dataset currently available, the simplified Haar wavelet functions expansion based mathematical model is developed. For convenience, first the design variables are normalized to fit in interval [0,1]. The Haar wavelet expansion based 2D mathematical model is introduced as

$$f(x,y) = \sum_{i=1}^{2M} \sum_{j=1}^{2M} a_{il} h_i(x) h_l(y), \tag{1}$$

where the function $f(x,y)$ stand for the shear peak load, x and y for the temperature and laminating force, respectively. The a_{ij} are unknown coefficients, h_i are Haar functions defined as (similarly h_l)

$$h_i(x) = \begin{cases} 1 & for \quad x \in [\xi_1(i), \xi_2(i)) \\ -1 & for \quad x \in [\xi_2(i), \xi_3(i)) \\ 0 & elsewhere \end{cases}, \tag{2}$$

where $i = m + k + 1$, $m = 2^j$ is the maximum number of square waves deployed in interval $[A, B]$ and the parameter k indicates the location of the particular square wave,

$$\xi_1(i) = A + 2k\mu\Delta x,\ \xi_2(i) = A + (2k+1)\mu\Delta x,\ \xi_3(i) = A + 2(k+1)\mu\Delta x,\ \mu = M/m,\ \Delta x = (B-A)/(2M),\ M = 2^J. \tag{3}$$

In (3) j=0,1,...,J and k= 0,1,...,m−1 stand for dilatation and translations parameters, respectively.

In order to determine the coefficients a_{il} the equation (1) will be satisfied at the collocation points determined by the values of design variables given in Table 2 (normalized values of the temperature and laminating force). The first 16 datapoints given in table 2 are used for composing model and last two points for its validation. Thus, the coefficients a_{il} were determined by solving 16x16 linear system. Finally, the values of the shear peak load can be computed at any point in design space using formula (1). It should be mentioned that the model proposed is robust, foreseen for preliminary analysis - it is built utilizing piecewise constant functions and limited dataset. In the future study similar approach can be applied for acoustic analysis of structures [23-26], structural analysis and design optimization of composites [27-30] and production process modelling [31-32]. The model proposed can be considered as rather robust utilized for limited dataset. The order of convergence of the Haar function and therefore also the proposed model is equal to one.

CONCLUSIONS

The mathematical model developed based on experimental study allows to create the relationship between the shear strength and laminating parameters. The laminating duration had minor effect on the quality of adhesion in the laminating area. Duration time more than 2 sec. was considered in this study inapplicable in practice because it would result in too slow working rate and low productivity. Duration less than 0.5 sec. was not possible to achieve with given equipment. The shear strength appears most sensitive with respect to the temperature. The consistent adhesion quality has been observed in the given range of design variables considered.

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