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Pre-consolidation of hybrid textiles for the production of web based thermoplastic composites

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TFG REALIZADO EN PROGRAMA DE INTERCAMBIO

TÍTULO: Pre-consolidation of hybrid textiles for the production of web based thermoplastic composites.

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FECHA: 15 septiembre 2017

CENTRO: Institut für Textiltechnik Augsburg gGmbH

TUTOR: Prof. Dr. Stefan Schlichter

RESUMEN:

El objetivo de este TFG es desarrollar un nuevo proceso de pre-consolidación del material no tejido que se usará posteriormente para crear una pieza de fibra de carbono reciclada. El proceso de pre-consolidación nuevo permite una forma más efectiva de calentar, presionar y enfriar. Para ello se ha diseñado un prototipo con una máquina de aire caliente y una prensa de rodillos.

PALABRAS CLAVE QUE DEFINEN EL TFG:

Material no tejido, fibra de carbono, preforma, pre-consolidación, reciclaje.

The work was submitted to the

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Univ.-Prof. Dr.-Ing. Stefan Schlichter

Pre-consolidation of hybrid textiles for the production of web based thermoplastic composites.
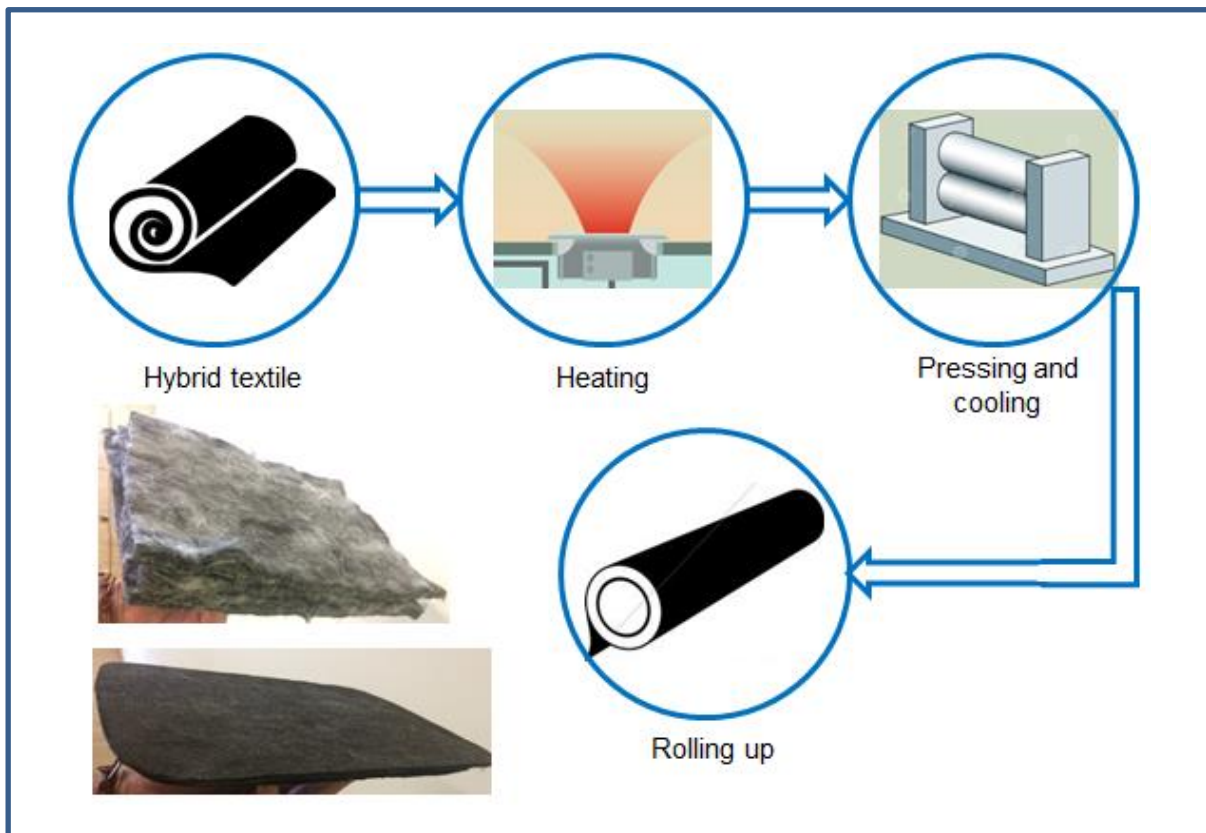
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Augsburg, September 2017

Hybrid textile

Heating

Pressing and cooling

Rolling up

Pre-consolidation of hybrid textiles for the production of web based thermoplastic composites.

Miguel Garcia Pelayo

Abstract

Recycling carbon fiber is an up to date theme around the world. The institute of textile technology of Augsburg has developed a process to use carbon fibers and plastic fibers to create a nonwoven material which is then pre-consolidated into a preform and finally used to build a part. The aim of this thesis is, to develop a new pre-consolidation process of the hybrid textile that permit a more effective way of heating, pressing and cooling.

Preliminary trials have been done in order to obtain some technical data. Then the design process has been elaborated starting with a definition of the functional structure, which is divided in sub-functions. Six Concepts have been created, compared and evaluated.

The Concept selected is composed of a hot air machine that allows a fast and homogenous heating, a rolling press, a conveyer belt to ensure an accurate transport of the preform and a roll which permit to store and transport the preform easily.

Keywords: nonwoven, web, reinforced carbon fiber, preform, pre-consolidation.

Table of Contents

List of Figures

List of Tables

Abbreviations

CF   Carbon Fiber

TFP   Tailored Fiber Placement

rCF   recycled Carbon Fiber

RCF   Reinforced Carbon Fiber

ITA   Institute of Textile Technology Augsburg

m.m.W.C.   millimeters of Water Column

1 Introduction and Objectives

The research of new materials is a constant of our time in all fields of engineering. One of the most important themes that the engineers investigate is the lightweight materials such as the carbon fiber which used has increased a high percentage in the last ten years. Its properties, such as high flexibility, high strength, low weight, high temperature tolerance and low thermal expansion, make them very popular in the aerospace, civil engineering, military applications, motor sports or other sports. Even in jewellery when it is necessary a lightweight material with high resistance.

On the other hand carbon fiber has a really high price and the impact on the environment caused by its production is more important than the impact of materials like steel and aluminium. The recycling ways of these metals are well established, while carbon fiber recycling methods have only been commercially viable for a very short time. In 2016, 18 000 tonnes of carbon fiber were produced worldwide during its manufacturing, from which only about 1 600 tonnes could be recycled. This is an enormous waste and a missed opportunity. The price of the recycled carbon fiber is almost half of virgin fibers and shows similar mechanical properties.

Some carbon fiber recycling methods are the chemical techniques, such as the digestion of resin with nitric acid; the thermal techniques, as well as pyrolysis in a controlled environment and the techniques using compression technology in which we will focus.

The Institute of Textile Technology Augsburg (ITA), investigate the processing of an automated manufacturing of rCF with a thermoplastic matrix to produce test specimens quickly and with consistent quality.

First step is the creation of RCF nonwovens with a thermoplastic matrix in an automated process. Secondly a pre-consolidation process is needed to create a preform and finally the preform is transported with a robot to an injection moulding press (Engel insert 1050H 200) to produce a fiber composite work-part. A schematic vision of the process is shown in Fig. 1.1.
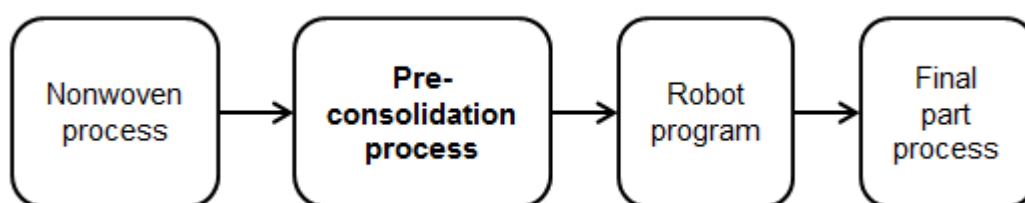
Fig. 1.1:   Schematic vision of the overall process. The main theme of this thesis is highlighted in bold

In this work the main theme is the pre-consolidation process. This process can be divided into two main sub-processes that are heating, and cooling and pressing. Moreo-

ver another sub-process for storing the preform is studied to be added at the end of this process.

The fields of research have been to improve the time of doing the preform and to automated it. For this purpose, another way of heating more efficiently, a continuous way of cooling and pressing or the addition of one more step at the end of the nonwoven machine to obtain a material similar to the preform that can be used on the injection moulding press have been tried to find.

2 State of the art

The fiber-reinforced composite (FRC) is a composite material that is made of three components, the discontinuous or continuous fibers, the matrix and the fine interphase region. The type of material and the process are selected according to the properties that must have the component. This work is focused only in recycling composites with carbon fibers.

2.1 Carbon fiber

In the particular case of the carbon fiber reinforced composite, it is combined a carbon fiber tissue, which provides flexibility and resistance, with a thermo-stable resin (matrix), which solidifies using a hardener agent and acts by bonding the fibers, protecting them and transferring the load throughout the material. The layers have a high orientation which brings the high strength and stiffness of the carbon fibers. Moreover the curing agent helps to transform the resin into a hard plastic. The mechanical properties of the new material are obtained from the combination of these three components.

2.1.1 Manufacturing process

Carbon fiber is a material made up of 5-10 microns diameter fibers, mainly composed of carbon atom, 90%, less than 7% nitrogen, less than 1% oxygen and less than 0.3% hydrogen.

Carbon fiber is made from another polymer, called polyacrylonitrile, through a complicated heating process. When the polyacrylonitrile is heated, the heat causes that the repetitive cyano units form rings. As we increase the heat, the carbon atoms get rid of their hydrogen and the rings become aromatic. This polymer constitutes a series of fused pyridine rings.

Then the temperature is increased to about 400-600ºC. In this way, the adjacent chains are joined. This heating releases hydrogen and gives a polymer of fused rings in the form of a ribbon. By further increasing of the temperature from 600 to 1 300ºC, new ribbons will join to form wider ribbons. This releases nitrogen. The polymer which is obtained has nitrogen atoms at ends, whereby, these ribbons can be joined to form even wider ribbons. As this happens, more nitrogen is released. Once the process is finished, the ribbons are extremely wide and most of the nitrogen is released, leaving a structure that is almost pure carbon in its graphite form. [Ehr11]

Pan Process

Pan — Stretch — Thermoset — Carbonize — Graphitize

Pitch Process

Pertroleum Pitch — Melt Spin — Thermoset — Carbonize — Graphitize

Spool — Epoxy Sizing — Surface Treatment
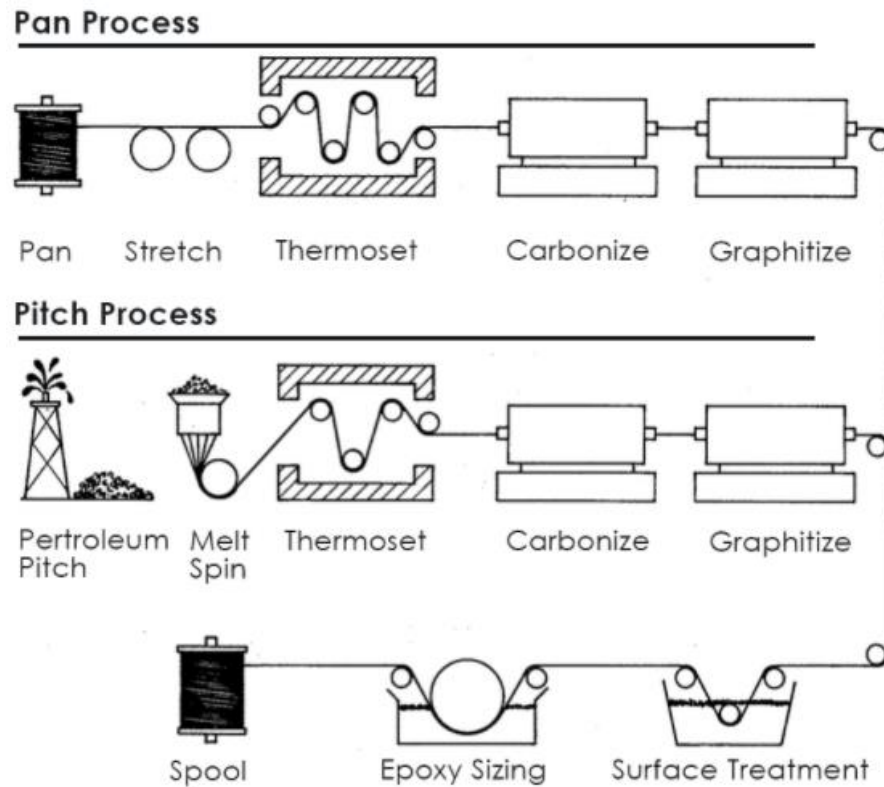
Fig. 2.1:   Schematic of PAN and pitch based carbon fiber manufacturing process. [Ash13]

2.1.2 Features

The structure of the carbon fiber consists of sheets of carbon atoms arranged following a regular hexagonal pattern. The layers have a high orientation which brings the high strength and stiffness of the carbon fibers.

$e_c = 35.7$ GPa

A

$e_l = 1050$ GPa

B — I

the grain

A

Transverse direction C

Strong covalent bonds   Weak van der Waals bonds
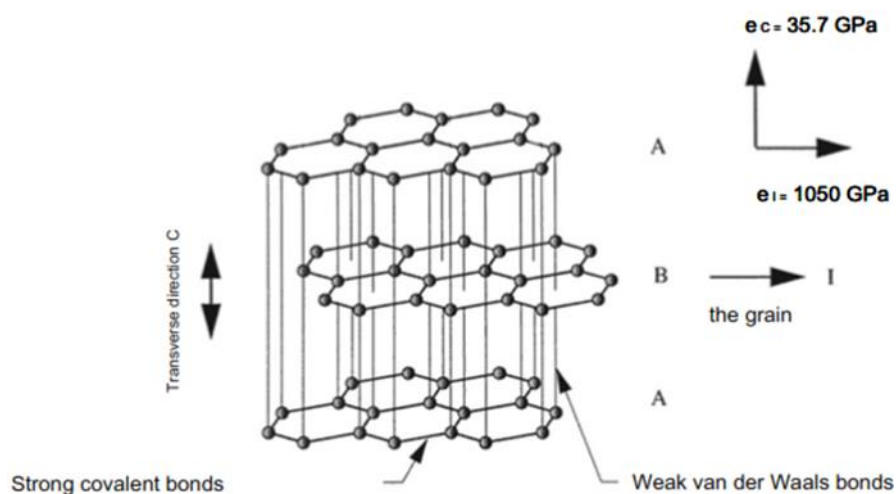
Fig. 2.2:   Structure of the carbon crystals. [Ehr06]

The main properties are the high flexibility, high strength, low weight, high temperature tolerance and low thermal expansion that permit it to take many forms and to have high

energy absorption. Moreover it is resistant to corrosion, moisture and to the formation of metal-carbides. Its appearance is considered elegant and its fabric texture projects luxury in its bright black colour.

The types of carbon fiber which exist nowadays can be classified according to its elasticity modulus:

Tab. 2.1: Mechanic properties of fiber types. [Ege17]

Mechanic properties of the C-Fiber	Elasticity modulus
Ultra High Modulus (UHM)	500 Gpa
High Modulus (HM)	300 Gpa Tensile strength/modulus minor than 1%
High Strength (HT)	3 Gpa Tensile strength/modulus between 0.015-20
Intermediate Modulus (IM)	300 Gpa Tensile strength/modulus around 0.01
Low Modulus	Low modulus and tensile strength

According to the different implementation where it is used, some properties are more important than others, for example:

Tab. 2.2: Relevant properties for different implementations. [www13a]

Properties	Implementation
Mechanical strength, resilience and density	Transports and sports goods
Dimensional stability	Aerospace technology
Vibration damping, strength and resilience	Audio device, robotic arms, textile equipment…
Fatigue strength and self-lubrication	Chemistry and nuclear industry
Chemist and thermic strength	Electric devices
Biological compatibility	Medicine (prostheses, surgical equipment)

2.1.3 Recycling process

One of the main disadvantages of the carbon fiber is that due to the thermoset resins, it is a material hard to recycle. In the future with the use of thermoplastic resins this point will be easier and more viable.

Another problem is the one faced by all new materials, the lack of knowledge about the mechanical properties and lack of large-scale demonstrators which could prove the economic, technical and environmental justification for using these materials. Some justification could be, from an economic point, the use of recycled carbon fiber on its own or in conjunction with virgin carbon fibers in the industry can reduce the cost of light weighting and then increase the use of carbon fiber in much more applications. From an environmental point, is more a question of social responsibility and even in some countries a legislative requirement.

Different methods of recycling carbon fiber have been developed. They can be classi-fied in three main types of composite recycling: mechanical, thermal and chemical methods.

Mechanical recycling

These processes are usually one, or more, size reduction methods applied to compo-site scrap. The large scrap pieces are size reduced by slow speed crushing, typically using a crushing mill or a large granulator. A secondary size reduction step takes place using a hammer or high-speed mills. After this, the fine particles are sorted by cyclones or sieves into fiber-rich and polymer-rich fractions. The sizes of the recycle carbon fiber are between 10 mm and 50 µm. Mechanical carbon fiber recycling has not yet been realized on an industrial scale. [Mel16]

Chemical recycling

It is the object of extensive research and can has potential for industrial application. These processes employ chemical compounds, catalysts or solvents that are used to break the chemical bonds in the polymer matrix and make the fibers free of plastic. The fibers are clean and of good quality, some studies showed tensile strength of 97% compared to virgin fibers. However, the process took 30 minutes because the reaction time is not quick and the surface of the fibers is often contaminated. If these fibers are worked into plastics, such impurity impairs adhesion of the fibers to the plastic. In addi-tion, the solvents used are often ecologically damaging. Most research into chemical recycling methods is aimed at supercritical fluids. [Mel16]

Thermal recycling

It includes pyrolysis and fluidised bed processes. These methods have a greater likeli-hood to achieve closed loop recycling, which entails recovering individual fibers, but also harnessing the reaction energy in some useful way.

Pyrolysis is currently the only process available for recycling carbon fiber reinforced plastics (CFRP) on an industrial scale. It recycles material in an atmosphere free of

oxygen, often nitrogen. Without oxygen, combustible material breaks down into lower molecular weight components and leaves char on the surface of the composite. There is a pyrolysis stage of resin degradation in air, but by removing oxygen, the degradation can only reach a certain stage. The hydrocarbon products can be used as fuels to add heat to the process, since the reaction is exothermic. However since pyrolysis processes by themselves leave char on the surface of the composite, individual fibers cannot be liberated by a single process step, therefore an oxidation step is required to remove the char and recover the fibers.

The fluidised bed recycling consists of a bed of silica sand with average particle diameter minor than 1 mm. The sand is fluidised by a stream of hot air passing through a distributor plate, at a superficial speed in excess of 0.4 m/s at a temperature typically above 500ºC. The resin burns off the composite and the char degrades, when sufficient char has degraded, individual fibers break off and are elutriated/filtrated along with the gases released from the resin. Following elutriation/filtration, the fibers are separated from the gas stream by a cyclone separator and deposited into a collection bin. The gas stream enters a secondary high temperature combustion process in order to oxidize them. [Mel16]

Up to date, the most successful demonstration of recycling has been BMW's use of reclaimed carbon fiber materials in its i3 and 7-series models, in which manufacturing waste from dry fiber processes has been converted into new product forms and used in closed-loop recycling solutions. This was greatly possible by the integrated supply chain that BMW and SGL Group established. If such integrated supply chains do not become the norm in future, then it is essential that all elements of a supply chain work closely together not only to develop methods of recycling carbon fiber but also to get recycled carbon fiber products back into the supply chain.
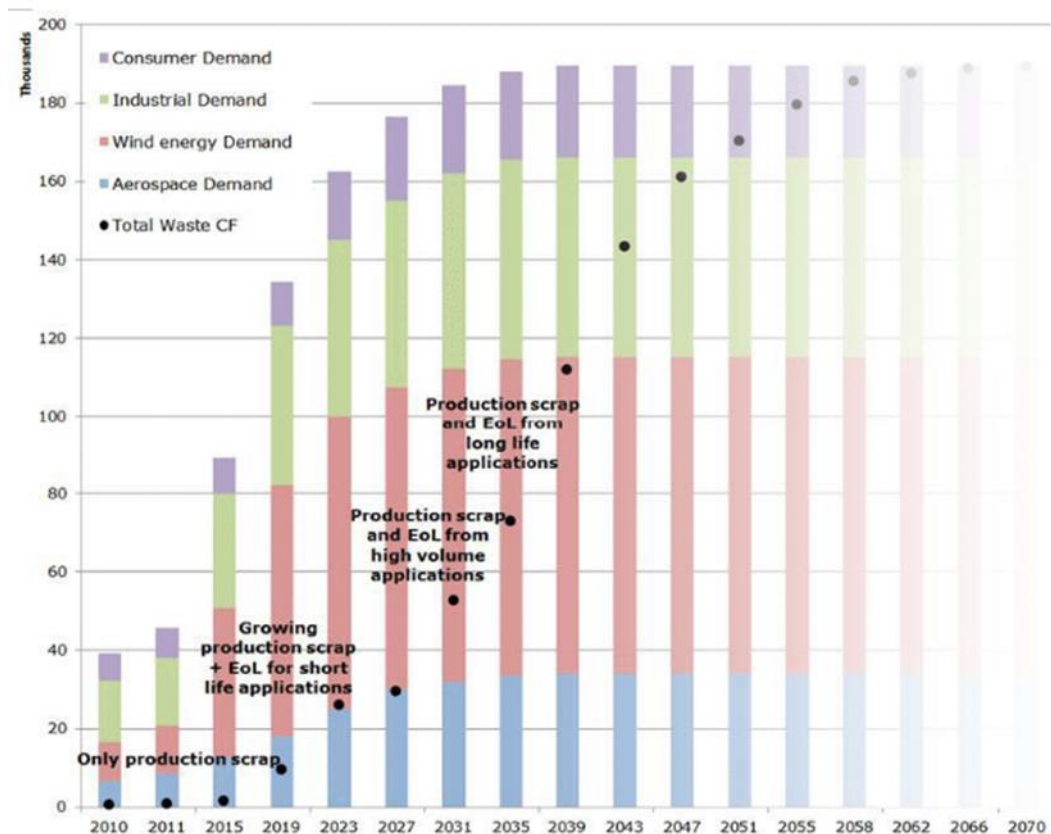
Fig. 2.3:   Graphic of composite demand and waste in kilotons per year. [Mel16]

2.2   Matrix

Composite materials are made of fibers as reinforcement and of different materials that work as a matrix. The matrix surrounds fibers and protects against chemical and environmental attacks. For fibers that resist strong loads the matrix must have less modulus and much more stretching than the reinforcement. The choice of the matrix is based on the chemical, thermal environmental, cost, performance and manufacturing requirements. The matrix establishes the operating temperature of the composite, as well as the manufacturing parameters to be used in their processing.

There are different materials used as matrix:

- Polymer matrix

- Thermosets curing

- Polyester resins

- Vinyl resins

- Epoxy

- Polyamides

- Polybenzimidazoles

- Phenolic and carbon matrix

- Thermoplastic matrix

- Metal matrix

- Ceramic matrix

2.2.1 Thermosetting polymeric matrix

Thermosets are typically liquid resins at room temperature. This liquid resin is then applied to a mould or a material for curing. The curing process takes place as bonds form and heat is present. These bonds change the basic nature of the material changing the once liquid resin into a solid material. Once cured the thermoset cannot longer be melted. Thermoset polymers have sites along the polymer chain that can be activated to become reactive. These sites react in a way that chemical bonds are formed between adjacent polymer molecules. This crosslinking formation is what cures the material and hardens it. When bonds form they restrict the motion of the polymer molecules to an increasingly greater amount. There are several disadvantages to thermosets, including: processing time, vapours, limited shelf life, inability to reprocess and a poor toughness.

The types of matrix material are:

Polymer: in this type of matrix, monomers are linked together into short chains called oligomers that are then bonded together leading to a polymer molecule. Many variations of polymeric matrix exist for predetermined properties. Some common thermosets include polyester, vinyl ester, epoxy, phenolic, cyano-acrylate and polyamide.

Polyester resin: is the cheapest and most widely used matrix in conjunction with fiberglass.

Epoxies: are the second most common thermosetting polymeric matrix materials. They have excellent adhesion, shear strength, fatigue resistance, strength and stiffness when compared to polyesters. The increased mechanical properties of epoxy are directly related to an increase in cost.

Polyamide: is the material used in the ITA. The procedure resembles a process involving fabric impregnation with thermoset resins, but it is adjusted to allow the use of polyamide pellets as the raw material. The dried polymer pellets are dissolved in acid under mechanical stirring for approximately four hours. Each ply of the carbon fiber is impregnated with the solution and stack up in groups of layers. The solvent is removed at room temperature for a couple of days and additional traces are removed at 80-100ºC. Each laminated composite is pressed using a hot platens press, following a temperature program that increases from 25ºC to 230ºC. The cooling is performed under pressure, at room temperature. There are obtained laminated plates with an average fiber volumetric ratio of 66%, that are processed into tensile and flexural shape specimens. [PPS16]

2.2.2 Thermoplastic

Thermoplastic composite materials are becoming more popular and have increased properties making them used in an increasing number of applications. Structural thermoplastics in particular have become a prevalent alternative to thermosets due to their enhanced mechanical properties, differences in processing capabilities, and manufacturing benefits.

Thermoplastic resins are solid at room temperature and are processed significantly differently than liquid thermoset resins. With appropriate pressures parts are fabricated with low void content and can be recycled. Thermoplastic composite have the added benefit of being able to be stored at ambient temperatures, so there is no need of refrigeration. Thermoplastics are heated and softened for application into a mould and then allowed to cool into the new shape. The great advantage of thermoplastics is that the shape is not an irreversible process. Within a certain temperature range thermoplastics may be melted again or heated and deformed again without that leads to sharp fluctuations in material properties. The ability to reform and reshape parts is beneficial in many applications and for recycling without damaging the fibers by high temperatures. However care needs to be taken to make sure temperatures are adequate for the design. [Ege17]

Tab. 2.3:   Properties of various non-reinforced matrix materials. [www17a]

Property	Polyesters	Epoxies	Polyam-ides	Phenolics	Thermo-plastics
Maximum use temperature (ºC)	79 – 141	93 – 177	204 – 316	149 – 204	171 – 232
Density (g/cc)	1.1 – 1.2	1.2 – 1.25	1.3 – 1.4	1.3 – 1.4	1.1 – 1.2
Tensile strength (MPa)	21 – 89	34 – 103	41 – 89	34 – 62	34 – 138
Tensile modulus (GPa)	0.2 – 0.4	0.4 – 0.5	0.3 – 0.4	0.6 – 1.2	0.2 – 0.5
Moisture absorption (%)	0.15 – 0.6	0.1 – 0.7	1.1 – 1.2	------	0.01 – 0.3

2.3   Nonwovens

EDANA, (The European Disposables and Nonwovens Association) defines a nonwoven as 'A manufactured sheet, web or batt of directionally or randomly orientated fibers, bonded by friction, and/or cohesion and/or adhesion', but goes on to exclude a

number of materials from the definition, including paper, products which are woven, knitted, tufted or stitchbonded (incorporating binding yarns or filaments), or felted by wet-milling, whether or not additionally needled.

2.3.1 Manufacturing process

Nonwovens can be subdivided based on the fiber layer into three groups: wetlaid, spunbond and drylaid nonwoven.

For wetlaids mainly short cut fibers, in a range of 5 mm to 30 mm are used. These are first dissolved in a strong dilution in water, similar to the paper production, and then placed over a sieve. A thermal or chemical solidification of the fibers then takes place. This kind of fleece is very dense, has isotropic properties due to the random fiber tray and thus achieved good strength values. In contrast, continuous fibers are used in the spunbond webs, which are spun only during the nonwoven production. For this purpose, the granules are fed into the spinning nozzles via an extruder. After that, a targeted deposition of the fibers can take place, whereby the properties can be defined more precisely. The solidification can be carried out here both thermally, chemically and mechanically, depending on the weight. Here, too, as with the wetlaids high strength and a high density are obtained. [AVK14]

The drylaid process used in the nonwoven compact-installation of the ITA is explained in next sub-chapter.

2.3.2 Preparation to the Dilo compact fabric conditioning

On the ITA available Dilo KO1.34290.16 ITA compact system (Dilo) the webs get dry by dry laying process of staple fibers, that is fibers of finite length made from rCF. In Fig. 2.4 the Dilo machine is shown.
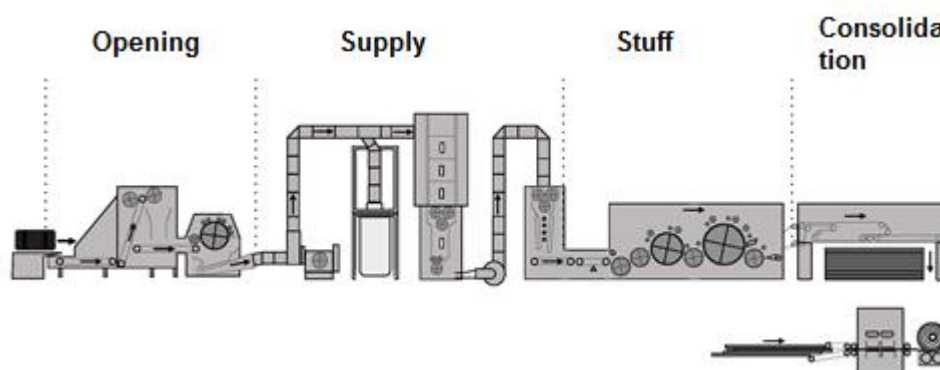
Fig. 2.4:   Side view of the Dilo machine used by the ITA. [Mar17]

In this method, the fibers delivered in bales are first opened and frayed. In a mixed bed, the required fiber composition is then produced from C fibers and PES. On the machine used in this work, this is done manually, but is produced by default in a mixing

chamber. After the feeding, the fibers are combed on the morel and transferred to the carding machine. There the fiber web is produced over the main drum and attached to their workers-turner pairs. In the successive laying, the web can then be settled to the thickness required for the desired fiber weight. For this purpose, several nonwoven layers are superposed, in different orientations, and weights up to 200 g/m^2 and more can be achieved. The orientation chosen for this is just as important as the fiber weight for the strength properties of the finished nonwoven.

To solidify, the mechanical version of the needling is used in the Dilo machine. Through a needle board, the fibers are looped from above and below each other. Depending on the strength of this entangled, the nonwovens are subsequently either very strong and thus only slightly pliability, or have a lower density and thus a higher pliable capacity. In contrast to chemical hardening, no additional binders are required in this variant. Thermal consolidation is limited mainly to polymer fibers. [Ege17]

2.4 Instruments of development methodology

In this chapter, the design process is presented as a procedure for the design and development of technical products. In Fig. 2.5 this cross-sectorial procedure is shown, which is divided into seven basic work steps. Between the seven work steps, the respective work results, such as the requirement list, the functional structure, the basic solutions, etc., are shown [PBF07].
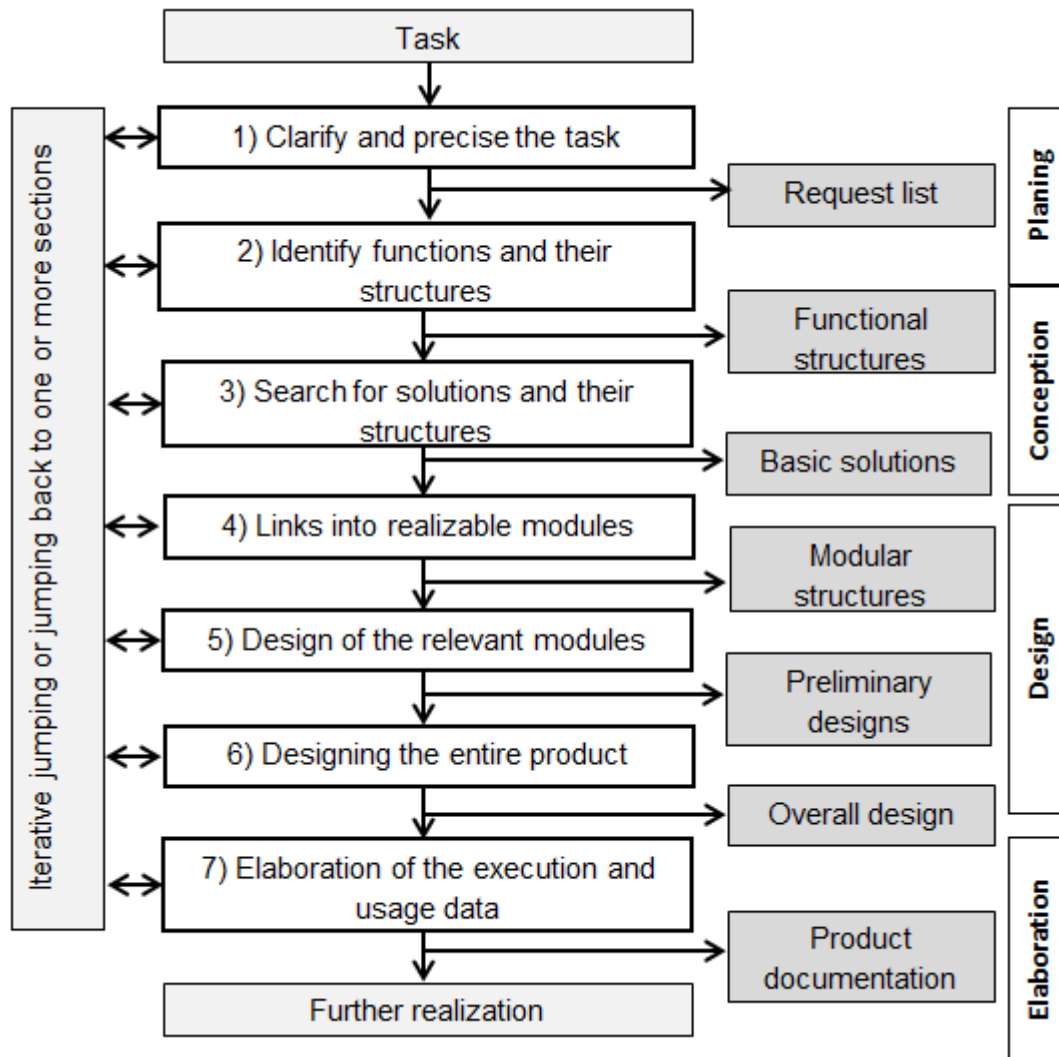
Fig. 2.5:   General procedure for developing and designing. [PBF07]

Request list

The requirements list is the first step in the process and is worked out together with the customer and the manufacturer at the beginning. All requirements are permanently documented so that a binding basis is established between both sides to the contract. Points that are not in the requirement list do not need to be considered for the construction.

Functional structure

From the requirement list, the elementary requirements are filtered and the functional structure is defined. The purpose of the functional structure is to solve problems that are simple and variant-solvable. For this purpose, the overall function is subdivided into sub-functions, as shown in Fig. 2.6.
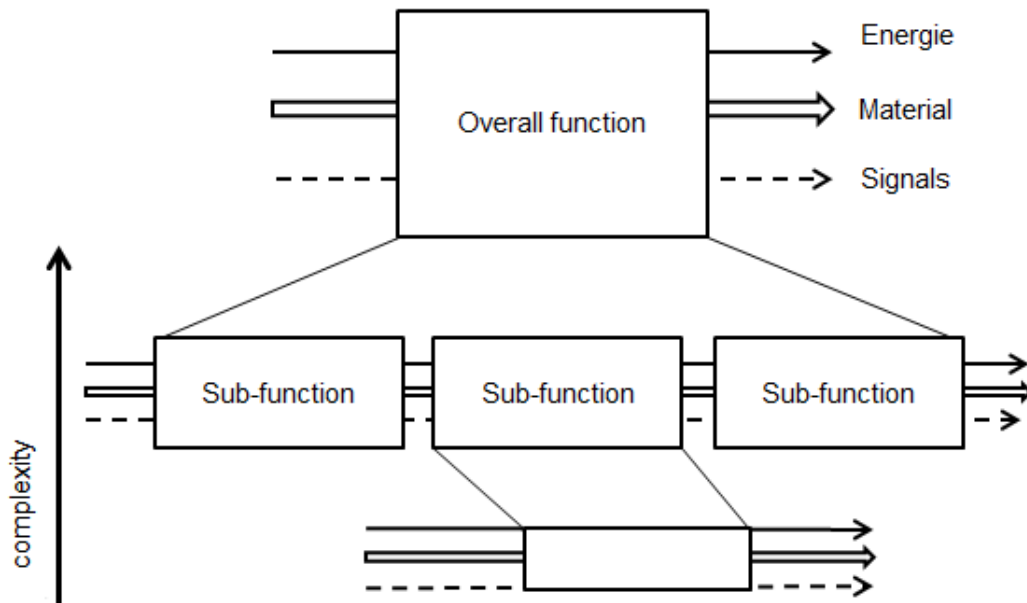
Fig. 2.6:   Overall function divided into sub-functions. [Fel13c]

The sub-functions are further decomposed and returned to functions. An elementary function is by definition the description of the primary function of a technical structure. Primary functions are functions which convert, for example, energy, material and / or signals. The return to elementary functions is helpful since various functions can be used for these functions. The functional structure must be neutralized so that solutions are not excluded at the beginning of the design process. [PBF07, Kol98]

Evaluation of concepts

The concepts have to be defined after the knowledge and conclusions obtained with the trials and all the theoretical approaches to solve the problem. The objective is to obtain a large number of solutions and developed them. To keep an overview, it is important to reduce this large number as early as possible to the practical concepts. The first containment already takes place when the active structures are set up, since a maximum of five concepts are selected for further evaluation. The assessment is carried out in this thesis with the aid of the value-in-use analysis. This is neutral and independent of external influences. To this end, the assessment criteria are defined in the first step. In order to take into account the influences of the evaluation criteria in the correct ratio, they are compared in a preference matrix. As a result, a weighting is calculated for each evaluation criterion. Then the concepts are evaluated through a point allocation from 0 to 4. Here 0 means an unsatisfactory fulfillment of the criterion of

evaluation and 4 stands for an ideal solution based on the evaluation criterion. The total value of each solution concept is the sum of the product of weighting and point allocation of the respective evaluation criterion. The highest overall value identifies the favoured concept, [PBF07, Rin14].

Vulnerability analysis

Vulnerability analysis reveals possible deficits in the design. Often it is possible to eliminate these deficits in further development. A graphical representation is used here in order to be able to easily identify weak points, in this work the so-called value profile is used, which is based on a bar chart. Fig. 2.7 shows an example of such a value profile. Each evaluation criterion is represented by a bar. The length of the bar corresponds to the selected value of the concept in relation to the criterion. The height of the bar reflects the weighting of the assessment criteria. The resultant area corresponds to the weighted partial values. This type of graphical representation makes it easy to determine which criterion has to be improved in order to increase the overall value. A balanced value profile is aimed at [PBF07]. With the vulnerability analysis, the final selection is made, of which of the concepts is further developed. [Rin14]
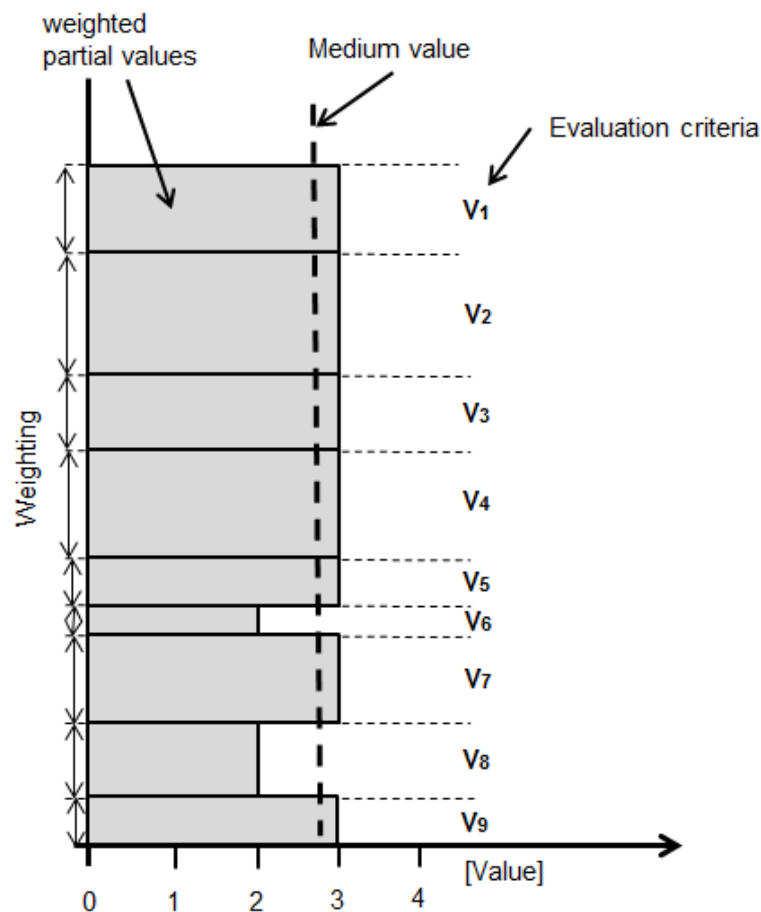
Fig. 2.7:   Vulnerability analysis through a value profile. [Fel13d]

3 Preliminary trials

It has been done four types of trials: heating up with the manual press, heating up with infrared oven, heating up with induction plates and heating up with hot air. For each of these trials it has been selected a way of cooling down and pressing. The possible way have been: cooling with a metal weight, with a hand-press and with three cooling tools that have a small pressure area.

3.1 Abstract

The aim of the present work is to figure out new effective process to do the pre-consolidation of the hybrid textile for the production of parts. This includes doing it faster and look for a continuous way of doing it in the future. The preform process is nowadays a manual and long process that needs labour and it is only available for discrete manufacturing. For this purpose it has been tried three other sources of heating like infrareds (infrared oven), induction (induction plates) or hot air (hot air gun). The results obtained with the hot air have been satisfactory for pre-heating in the pre-consolidation process because of the low time that it took to heat the surface in the trials. However to heat all the preform, not only the surface, the hot air seems the best options to improve the process and to reach the objective of a continuous process. On the other hand it has been shown that heating by induction is a long and inefficient way to heat the preform.

3.2 Introduction and objectives

The pre-consolidation process aims at transforming the nonwoven material into a preform that can be used to create the web based thermoplastic composite. To reach this objective the hybrid textile has to be heated till its melting point and then quickly cooled down and pressed before it gets stiff again.

The trials heating up with the DEMA Hand-press TP1400 have been done to see how the preform could be better done with the same method than before, proposed by [Ege17], but trying to decrease the production time. Another objective has been to have some samples that were currently used in the machine to then compare them with the preforms created with the new pre-consolidation process. Next step has been to try to have the same preform quality results in less time with the oven, the induction plates and the hot air. In these trials first it has been necessary to check if the new heating sources were able to heat the nonwoven textile, in the surface and inside it, and in a short time, less than 120 seconds. Moreover the heating temperature, the time of heating, the size of the surface pressed and the pressing time have been changed in order to find the optimal pre-consolidation process.

3.3 Trials heating with the DEMA Hand-press TP1400

Instruments

Nonwoven textile 40% rCF / 60% polyamide

DEMA Hand-press TP1400

Airtech MR1 separation film

Metal weight of 25 kg

Procedure

First trials have been made heating with the DEMA Hand-press TP1400 and then cooling down and pressing by contact pressure with a metal weight of 25 kg with a surface temperature of 22ºC during all the trials. The force applied has been:

$$F = 25 \text{ Kg} \times 9.8 \text{ m/s}^2 = 245 \text{ N} \tag{3.1}$$

in an area of:

$$A = 0.26 \text{ m} \times 0.29 \text{ m} = 0.0754 \text{ m}^2 \tag{3.2}$$

To prevent the sticking of the layers with the Hand-press and the cooling metal, the layers were covered with the Airtech MR1 separation film.

The variables of these trials have been the heating temperature; the preform has been heated at 280ºC, 300ºC and 320ºC. Secondly the heating time has vary between 180 and 40 seconds being the most common 60 seconds. Another parameter has been the number of layers heated at the same time in the same separation film in the hand-press. In Tab.1.1 it is written the layers used in each trial, the number between parentheses indicate that the layers have been already heated one time. Numbers without parenthesis indicate that the hybrid textile was heated for the first time. The last variable has been the time applying the pressure and cooling. The parameters of each trial are shown in Tab. 3.1.

Tab. 3.1:   Trials with manual press DEMA 1400

Trial	Heating temperature (ºC)	Heating Time (s)	Number of layers	Time till pressure (s)	Pressure time (s)	Force (N)
1	280	120	2	7	60	245
2	280	60	2	7	60	245
3	280	180	2	7	60	245
4	280	(60+60)+60	(1+1)=2	7	60	245
5	300	60	2	7	90	245
6	300	40	2	7	60	245
7	300	(40+40)+40	(2+2)=4	7	60	245
8	300	(60+60)+6	(2+2)=4	7	(60+60)+60	245
9	300	(60)+(60)+(60)+(60)	(1)+(1)+(1)+(1)=4	7	(60)+(60)+(60)+(60)	245
10	320	(80+80)+80	(2+2)=4	7	(60+60)+90	245
11	300	(60+60)+50 one side, turn +50	(2+2)=4	7	(60+60)+60	245
12	300	90 one side, turn +90	4	7	150	245

3.4   Trials heating up with infrared oven

Instruments

Infrared oven (Fig. 3.1).

1 Infrared oven composed of oven 1 (1a) and oven 2 (1b)

2 Pyrometer for the temperature measurement

3 Sliding tray 1 (close)

4 Sliding tray 2 (open)

5 Organovlies (inserts)

6 Device with heated retention matrices
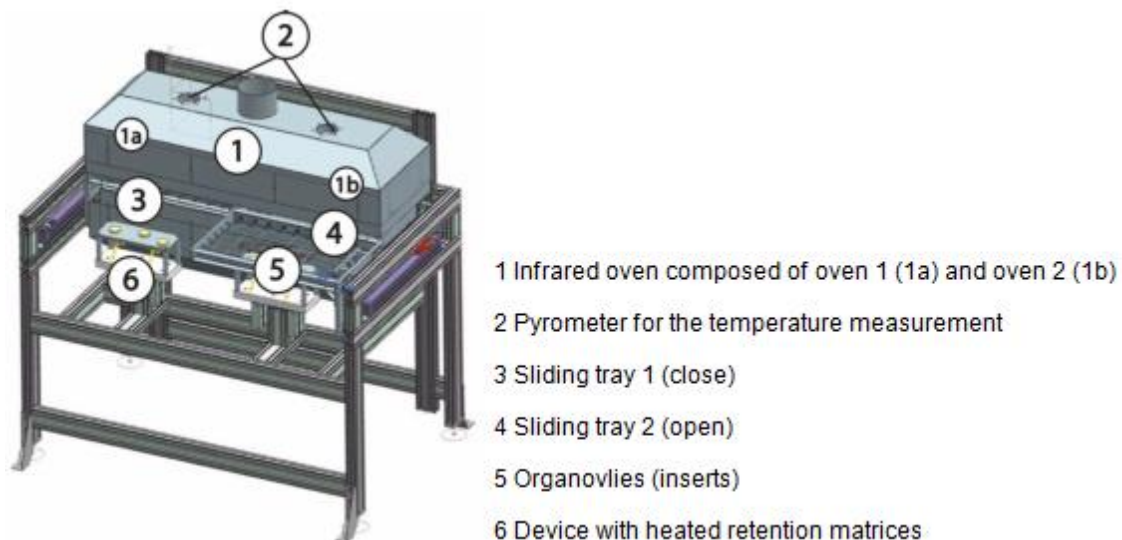
Fig. 3.1:   Infrared oven. [EnM16]

Metal grid

Nonwoven textile 40% rCF / 60% polyamide

Pressing tools used:

- Metal weight of 25 kg
- DEMA Hand-press TP1400
- Cooling and pressing metal tools M, T and P with different contact areas: 2.25 cm^2 (M), 7 cm^2 (T) and 10 cm^2 (P).

Caliper

Procedure

In these trials the heating source selected has been an infrared oven. The layer is put on the sliding tray and then introduce into the oven when this one is already at the desire temperature. On the first trials it has been shown that when the hybrid textile was heated in the infrared oven it started to blend so the solution has been to put a metal grid upper the material to do not permit the blending. This problem solved, the trials have started again with a temperature in the oven of 275ºC, higher than the melting temperature of 246ºC, testing a time between 60 to 10 seconds to try to find the best relation time/temperature to have a good preform in the least time possible.

For pressing and cooling the preform after the oven, three methods have been tested: the first one has been applying a contact pressure with a metal weight of 25 kg. For the second method the DEMA Hand-press TP1400 has been used. The third method has

been to pressure with a metal tool with a pressure area between 2 and 10 cm^2. Each type of pressing is explained in more details in the next sub-chapters.

3.4.1 Cooling and pressing with metal weight applying contact pressure

For this trial a force of 245 N has been applied with a 25 kg metal weight, with a surface temperature of 22ºC during all the trials, to cool and press the preform like in the trials of chapter 1.2.

The first trials have been made heating during 60, 30, 25, 20 and 10 seconds at the temperature of 275ºC to then can conclude which was the minimum time enough to make a preform similar to the ones used before. The pressure has been applied 10 seconds after the heating and during 60 seconds. These times have not changed. Trials have been made with one layer, with two layers already heated and pressed and with four (2 layers heated and pressed + 2 other ones). A layer before working on it and another after are shown in Fig. 3.2.
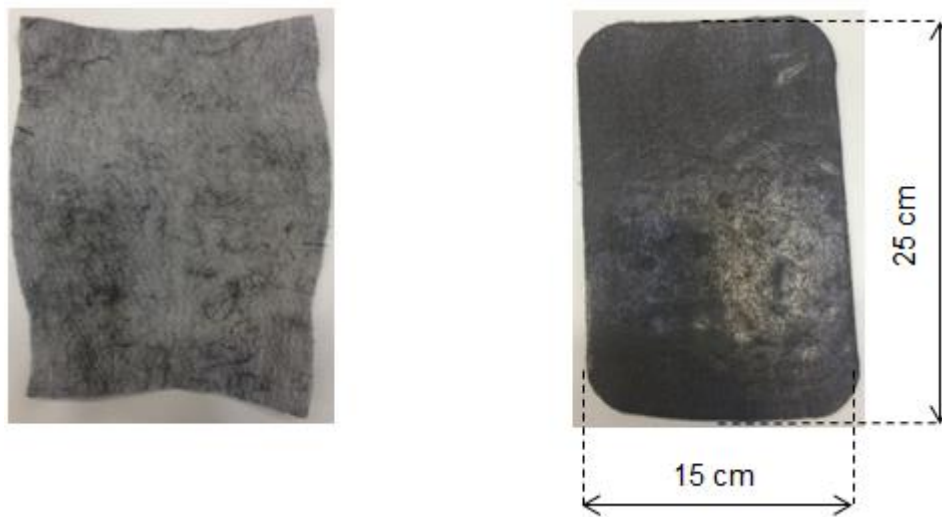
Fig. 3.2:   Hybrid textile before being heated and pressed (left) and preform after being heated and pressed (right).

The trial parameters and some notes about the results are summarized in Tab. 3.2.

Tab. 3.2:   Trials heating with infrared oven and cooling with metal weight pressure.

Trial	Heating temperature (ºC)	Time (s)	Number of layers	Pressure time (s)	Force (N)	Notes
H1	275	60	(1+1)=2	60	245	
H2	275	60	2	60	245	Pressure not uniform
H3	275	60	(1+1)+(1+1) =2+2=4	60	245	The layers do not stick. We should increase the time to 2 minutes and take a higher weight
H4	275	30	2	60	245	
H5	275	20	2	60	245	For one layer the stiffness is reduced than with 30 seconds. For two layers they do not stick.
H6	275	10	2	60	245	Not enough time to melt well.
H7	275	25	2	60	245	For two layers they do not stick.

Conclusions

After the trials it can be said that when the preform is heated at 275ºC in the infrared oven, it has to be at least 30 seconds to obtain a good aspect and stiffness. In Fig. 3.3 it can be seen the difference appearance between heating 20 and 30 seconds two pre-forms. In picture on the left the two layers are nearly separated while in picture on the right the two layers seem to be only one.

Fig. 3.3:   Two layers heated together in the oven 20 seconds (left) and 30 seconds (right).

3.4.2 Cooling and pressing with metal applying pressure with the DEMA Hand-press TP1400

In this trial the hand-press is used as pressing tool. It has been settled at 36ºC (the cooler it can be) for the first 8 trials and then, the temperature has been increased till 90ºC. The aim of this trial is to know how much the pressing tool can be heated before there is an influence in the quality of the preform and therefore that it will be needed to increase the pressure time to have again the quality wanted. These results will be useful later to realize if it is more convenient to increase the pressure time or to cool down the tool. The pressure time has been 5, 8, 10 and 20 seconds and the pressure was between 50 and 100 N. The heating temperature in the infrared oven has been settled at 275ºC during 30 seconds in every trial after the results seen in sub-chapter 1.3.1. All the parameters are showed in Tab. 3.3.

Tab. 3.3: Trials heating with oven and cooling and pressing with hand-press.

Trial	Heating time (s)	Number of layers	Pressure time (s)	T_u (ºC)	T_L (ºC)	Force (N)	Notes
P1	30	1	10	36	30	50-100	
P2	30	1	20	36	30	50-100	
P3	(30+30)+30	(1+1)=2	10	36	30	50-100	Good
P4	(20+20)+20	(1+1)=2	10	36	30	50-100	
P5	(25+25)+25	(1+1)=2	10	36	30	50-100	
P6	30	1	5	36	30	50-100	
P7	(30+30)+30	(1+1)=2	5	36	30	50-100	Not enough time to cool
P8	(30+30)+30	(1+1)=2	8	36	30	50-100	
P9	30	1	10	50	45	50-100	
P10	(30+30)+30	(1+1)=2	10	70	65	50-100	The thickness increases
P11	30	1	10	90	85	50-100	Same as 70ºC
P12	30	1	10	90	85	50-100	Same as 70ºC

There is a difference between the temperature of the upper pressing plate (T_u) and the lower (T_L) because the Hand-press only heat up the upper one.

Conclusions

These trials show that the optimal pressure time with the Hand-press at low temperature (between 20ºC and 40ºC) after heating 30 seconds the layer in the infrared oven is 10 seconds. In Fig. 3.4 it can be seen that applying the pressure for 20 or 10 seconds has similar results but that there is a difference when it is only applied during 5 seconds.
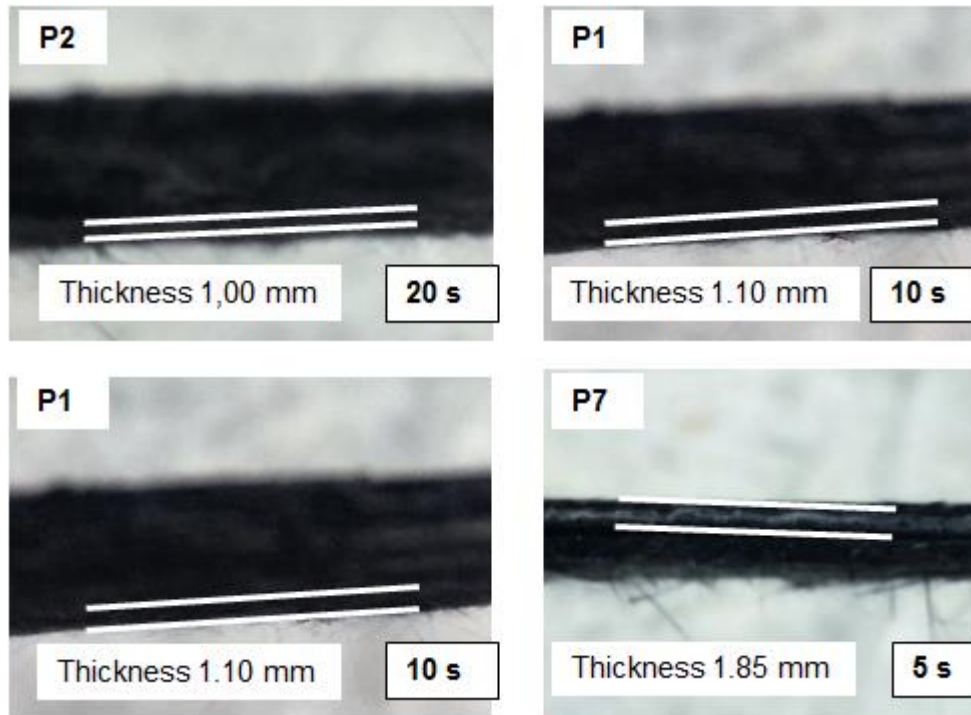
Fig. 3.4:   Final thickness of trials P1, P2 and P3.

For the cooling side, these trials show that when the pressing tool gets heated till 70ºC the results start to be worse, the thickness begin to increase, as it can be seen in Fig. 3.5. Another remark is that from 70ºC to 90ºC of the pressing tool the results are similar so it is not worth to cool it down in this range.

Fig. 3.5:   Final thickness with the hand-press at 90ºC.

3.4.3 Cooling and pressing with metal applying contact pressure in a reduced area

In these trials the pressure has been applied in a specific surface instead than in all the preform in three different ways: just pressing between 3 and 5 seconds, hitting the preform from a height of 10 cm, a speed of impact between 0.09 and 0.11 m/s and with a contact time of 2 seconds approximately. And finally pressing, and sliding the tool 2 cm. A schematic draw of each way is shown in Fig. 3.6.
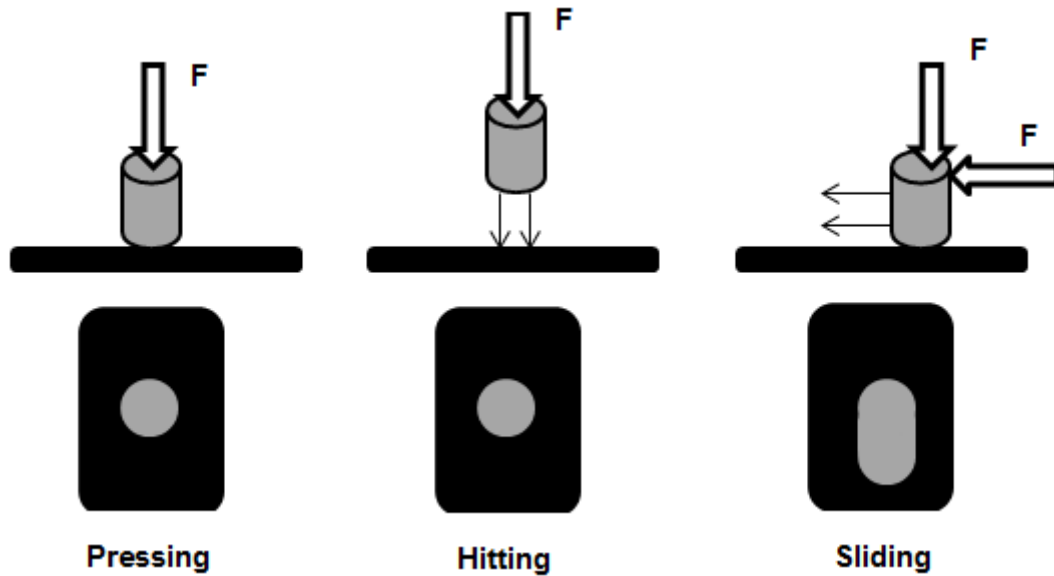
Fig. 3.6:   Schematic draw of each way of applying pressure used.

The heating temperature in the infrared oven has been of 275ºC during 30 seconds in every trial. Two cooling and pressing tools have been used, one with a contact area of 2.25 cm^2 (M) and the other with a contact area of 7 cm^2 (T). The pressure applied has been firstly between 40 and 50 N and then between 60 and 90 N. The last part of the trials has been to measure with an electronic caliper the final thickness of the preform (Fig. 3.7) to appreciate the quality of each process. In Tab. 3.4 every parameter are showed.

Fig. 3.7:   Schematic view of the final thickness of the preform measured

Tab. 3.4:   Trials heating with oven and cooling and pressing with metal applying pressure with tools M, T and P.

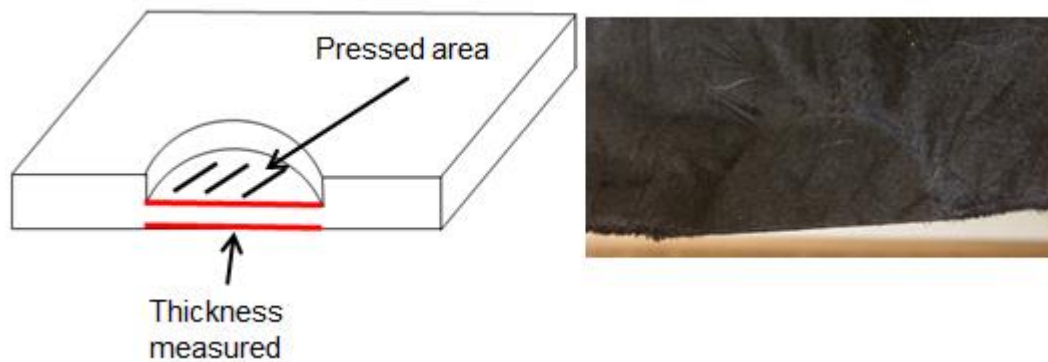| Trials	Layers	$T_{cooling}$ (ºC)	Mode of pressure	Pressure time (s)	Force (N)	$A_{pressed}$ (cm^2)	Final thickness (mm)
M1	1	22	Pressing	3	400-500	2.25	1.25
M2	1	22	Pressing	4	400-500	2.25	1.10
M3	1	22	Pressing	5	400-500	2.25	1.08
M4	1	22	Hitting	-	-	2.25	2.30
M5	1	22	Sliding	-	-	2.25	1.30
T1	1	22	Pressing	3	600-900	7	1.17
T2	1	22	Pressing	4	600-900	7	1.05
T3	1	22	Pressing	5	600-900	7	0.90
T4	1	22	Sliding	-	600-900	7	1.10-1.30
T5	-	-	-	-	-	-	-
T6	1	50	Pressing	5	600-900	7	1.20
T7	1	70	Pressing	5	600-900	7	1.30
T8	1	90	Pressing	5	600-900	7	1.50
T9	1	110 (>90)	Pressing	5	600-900	7	1.52

Looking at Tab. 3.4, from the three ways of applying pressure, it can be said that "Hitting" is not a good solution; the final thickness is the highest, more than 2 mm. "Sliding" could be a method to develop because the thickness obtain is nearly 1 mm in both trials done. The best method seems to be "Pressing" during 5 seconds to have a preform thickness of 1 mm. However 4 seconds could also being enough because the results are very similar, less than 0.20 mm of difference between trials M2 and M3 and between T2 and T3.

Another relevant data of these trials is that at 90ºC it seems that the thickness of the preform starts to increase. I has been measured 1.5 mm which is 50% more that when the tool is at room temperature, showed in Fig. 3.8. Therefore more trials have been done, all at 90ºC, to confirm that. Results are shown in Tab. 3.5 and in Tab. 3.6.
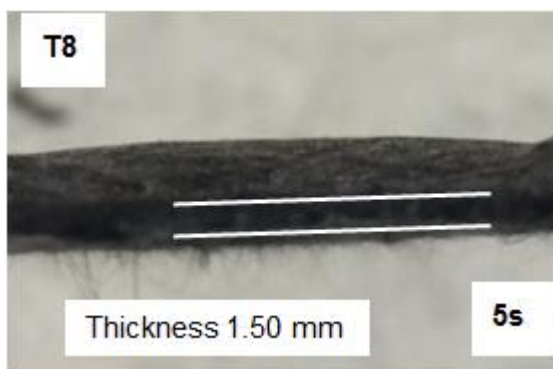
Fig. 3.8:   Final thickness of the preform after being pressed with the tool T at 90ºC.

Tab. 3.5:   Trials heating with oven and cooling and pressing with tool T at 90ºC.

Trials	Layers	$T_{cooling\ tool}$ (ºC)	Mode of pressure	Pressure time (s)	Force (N)	Thickness (mm)
$T90_1$	1	90	Pressing	3	600-900	1.65
$T90_2$	1	90	Pressing	3	600-900	1.40
$T90_3$	1	90	Pressing	3	600-900	1.90
$T90_4$	1	90	Pressing	5	600-900	1.50
$T90_5$	1	90	Pressing	5	600-900	1.60

Moreover a cooling and pressing trial with tool P at 90ºC has been made. Tool P has been pressed with the DEMA Hand-press TP1400 settled at 90ºC also.

Tab. 3.6:   Trials heating with oven and cooling and pressing with tool P at 90ºC.

Trials	Layers	$T_{cooling\ tool}$ (ºC)	Mode of pressure	Pressure time (s)	Force (N)	Thickness (mm)
$P90_1$	1	90	Pressing	3	500-1000	1.22
$P90_2$	1	90	Pressing	3	500-1000	1.20
$P90_3$	1	90	Pressing	3	500-1000	1.54
$P90_4$	1	90	Pressing	3	500-1000	1.30

3.5 Trials heating up with induction plates

Instruments

IFF induction plates EW200NTW

Nonwoven textile 40% rCF / 60% polyamide

Piece of metal

Airtech MR1 separation film

Procedure

Next trials have been done with two IFF induction plates that use the robot to heat the preform after the pre-consolidation process. The configuration of the induction plates can be seen in Fig. 3.9.
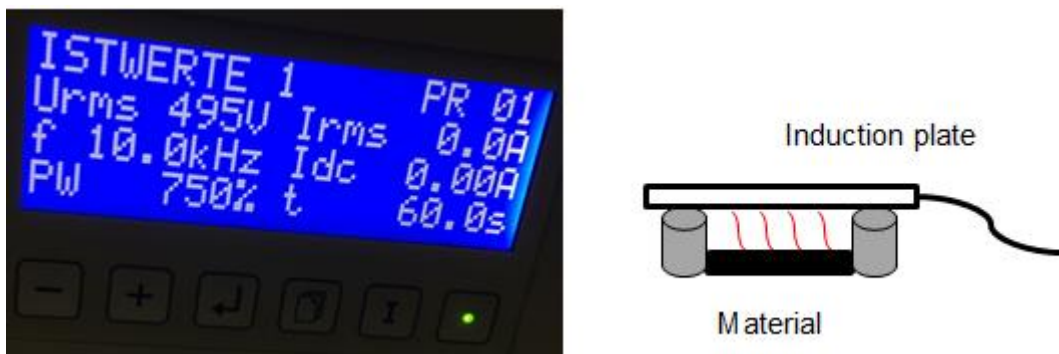
Fig. 3.9: Configuration of the induction plates (left) and schematic draw of the heating procedure at 20 mm (right).

First trial has been to heat up the hybrid textile for 30 seconds at a distance of 20 mm as shown in Fig. 3.9. Three more trials have been done heating again a hybrid textile and a preform already heated at the infrared oven and cooled and pressed with the metal weight of 25 kg, this time without distance between the material and the induction plates. In the first trials the preform has just been heated till 6ºC and in the trials heating without distance the results have been similar so any more trial has been done. Parameters are showed in Tab. 3.7.

Tab. 3.7:   Trials heating with induction plates.

T_0 (ºC)	T_f (ºC)	Time (s)	Distance to surface (mm)	Material
24	30	30	20	Hybrid textile
22	130	60	20	Piece of metal
25	40	30	0	Preform heated and cooled
25	50	60	0	Preform heated and cooled
24	38	60	0	Hybrid textile

T_0 is the initial temperature of the hybrid textile and T_f is the temperature after heating the preform.

Conclusions

After these trials it seems that the induction plates of the robot, currently specified to heat steal do not work efficiently with the preform. The induction plates heat quickly the metal but would need more than an hour to heat the hybrid textile. A solution could be to try the heating with other induction plates that are not so specific to heat steal or to vary the frequency parameter.

3.6   Trials heating with hot air

Instrument

Bosch hot air gun PHG 500-2

Nonwoven textile 40% rCF / 60% polyamide

Cooling tool T

Caliper

Procedure

Last trials have been done heating with a hot air gun and cooling and pressing with tool S. First the hybrid textile has been heated from a distance between 3 and 8 centimeters and then the next trial has been done heating without distance between the textile and the hot air gun which was heating at nearly 500ºC. Then the cooling down has been done with the tool T. In the first trials the material was only heated on the surface but the result without distance, showed in Fig. 3.10, was much better. The final thickness measured with the Caliper was between 1.06 and 1.20 millimeters which is a 10% of the initial thickness of the hybrid textile that was 1 cm.
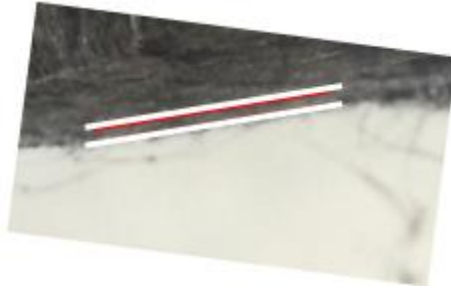
Fig. 3.10:   Final thickness after heating with hot air gun and cooling with tool T.

Conclusions

The thickness achieved with the hot air gun, nearly 1.1 mm, is a positive result because the thickness is reduced till a 10% of the initial one. However the heating temperature has been 500ºC, which is very high for the hybrid textile, that only needs 246ºC to melt, so it can be said that the hot air could be a good way to pre-heat the preform quickly in the surface and then combine with another heating source that finish to heat all the textile before cooling it down.

4 Theoretical design

In this chapter are presented theoretical instruments of development methodology, in chapter 4.1 the concept requirements are listed. Secondly in section 4.2 the functional structure is settled and divided into sub-functions. Next step is to define each of the concepts in chapter 4.3. In section 4.4 a review of the concepts is carried out and in chapter 4.5 a vulnerability assessment is created to select a final concept for further definition of it.

4.1 Request list

The list of requirements includes main features that provide information to find the relevant requirements. They are distinguished in two types: the mandatory ones, listed with (P), which describes the primary function of the system. And the requests (S) that contain information on requirements to be considered if possible. The requirements are listed as sub-items of each main feature and then summarized in the request list.

Temperature

The heating tools designed have to be able to heat at least till 300ºC to ensure that they can reach easily the melting temperature of the nonwoven material, 246ºC. Moreover they must heat up continuously and in a uniform way to permit the heating of all the part. The preform has not to be heated only in the surface but also inside, if not the pre-consolidation process will not be achieved satisfactorily.

Pressure

It is required that enough contact pressure (min a force between 60 and 150 N) is applied in the perpendicular direction of the preform after it has reached the melting temperature. Also the time passed after the heating process must be lower than 12 seconds to do not permit that the textile turns solid again.

Energy

The module shall not require exceptional demands on the power supply and the connections of the existing infrastructure of the ITA.

Safety

The heating sources must be closed and with all the hot cables cover by an isolating material to prevent possible accidents of the workers. Moreover it has to be at least one fire extinguisher in each heating machine.

Costs

The design must be made with the objective of develop a cost-effective solution. The running costs and the maintenance have to be reduced as much as possible.

Production

The production time must be as low as the costs permit it. Tools used should not have an excessive price. Furthermore the storage of the final preform must not take so much place.

Monitoring/sensors

Every tool should have a temperature sensor to know if in any moment there is an overheating.

Transport

It is important that the final preform is easy to transport because the nonwoven machine and the injection moulding press are not in the same place.

Maintenance

Ideally for any customer is that the unit designed is free of maintenance. This is not usually possible; nevertheless the hypothetical reparations should be done easy and quickly. This means that the main module can be disassembled and that the parts are easy to replace.

Recycling

The separation of the different materials which are not recycled in the same way have to be possible to accomplish the law.

4.2   Functional Structure

With the request list the basis for the further design process is created. In the following sub-chapters the functional structure is gradually built up. Here in section 4.2.1, the installation of the overall function is described. In this purpose, a description and the main flows are defined. In section 4.2.2 this overall function are divided into sub-functions which are considered as individual subsystems. The complete functional structure is finally compiled and the interaction between the subsystems described in section 4.2.3.

4.2.1 Building the overall function

The purpose of the process is to make the pre-consolidation part of the web. This includes a heating process of the hybrid textile followed by a cooling and pressing process and if possible a rolling or cutting and stacking process. Moreover the transport of the preform is also needed. In Fig. 4.1 it is shown the total function with input and output variables.
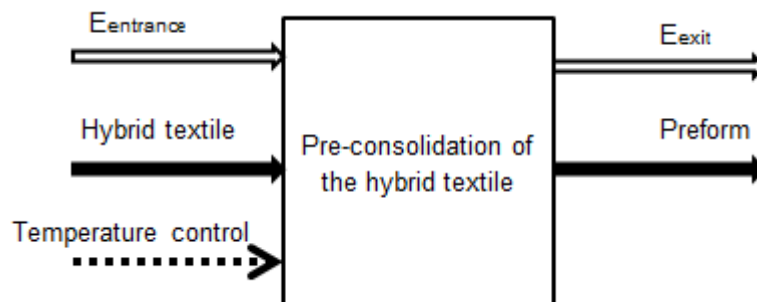

Fig. 4.1: Total function with input and output variables.

The preform is took from the nonwoven machine and then transported in a ribbon during the pre-consolidation process. First the preform is heated at least till the melting temperature between 245°C and 260°C. Secondly the web is pressed and cooled down and then rolled or cut and stacked.

4.2.2 Dividing the overall function into sub-functions

The next step is to divide the overall function into sub-functions. These sub-functions are considered as individual subsystems for a better overview. The subsystems considered are:

Heating (subsystem 1)

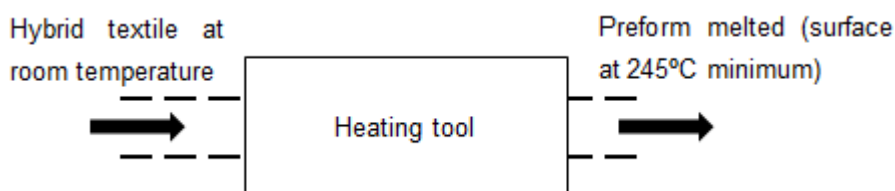The first subsystem processes the heating of the preform that have to reach the melting temperature.

Fig. 4.2: Subsystem 1: heating

Cooling and pressing (subsystem 2)

The second subsystem is the cooling and pressing action. A contact pressure is applied to cool down the preform. The pressure must be constant and uniform in the entire surface.
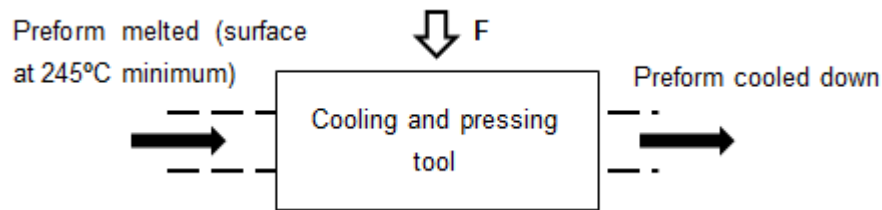
Fig. 4.3: Subsystem 2: cooling and pressing

Transport (subsystem 3)

The preform has to move from one operation to the next, this can be done automatically or manually. In the first case it can also be continuous (better if the pre-consolidation form structure is built after the nonwoven machine) or discontinuous if the heating process needs to be longer in time but not in length.

Fig. 4.4: Subsystem 3: transport

Cutting and stacking (subsystem 4a)

One option after cooling down the preform is to cut it and then stack it to have the preform already prepared to use in the machine which create the web.
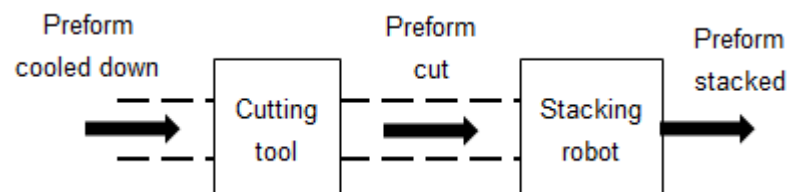

Fig. 4.5: Subsystem 4a: cutting and stacking

Rolling up (subsystem 4b)

The second option is to roll up the preform to permit an easy storage and future transportation to the cutting tool.
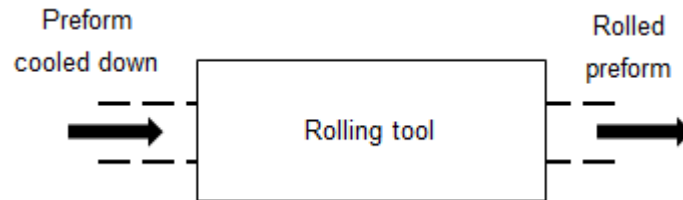

Fig. 4.6:   Subsystem 4b: rolling up

4.2.3 Complete functional structure

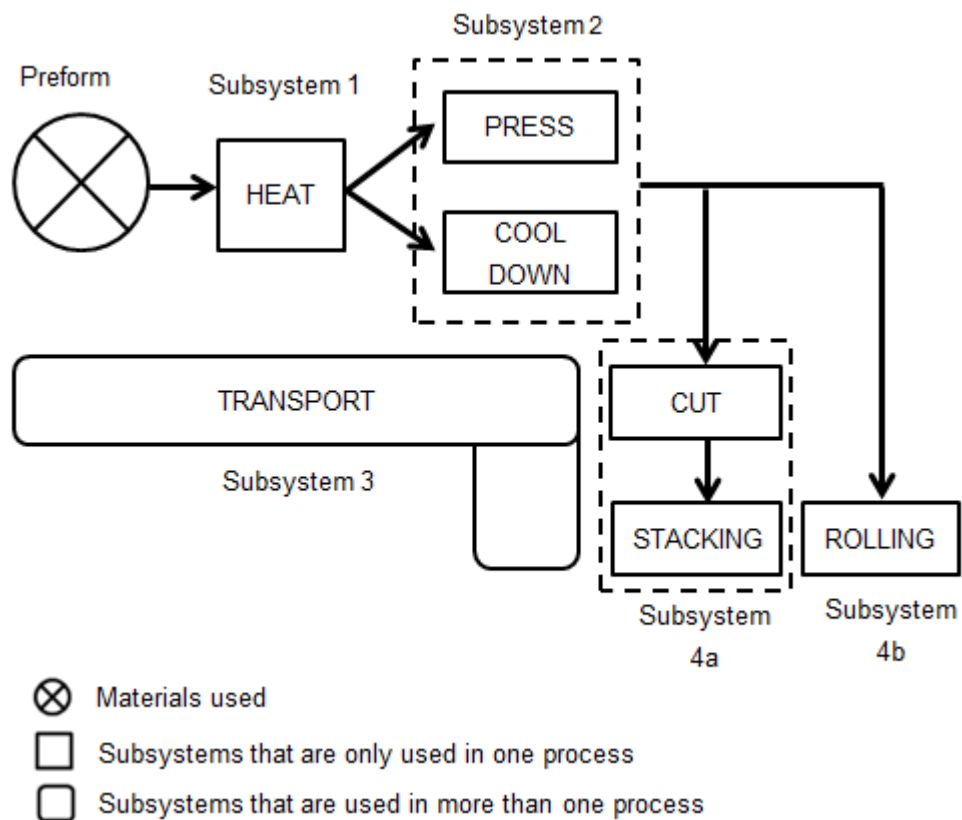In Fig. 4.7 the complete functional structure is summarized with all the subsystems.

Fig. 4.7:   Functional structure with subsystems.

4.3   Definition of the concepts

Six different concepts are proposed with subsystems 1 and 2 defined in each sub-chapter. However subsystem 3 is the same for all of them, the preform is transported during the process by a continuous conveyer belt. Finally subsystem 4 can be indistinctly chosen between 4a and 4b.

General consideration

A continuous belt is selected as subsystem 3 for the transport of the preform during the process in all the concepts. The main reason that this continuous process has been chosen instead of the use of a robot it is because it permits to assemble the pre-consolidation process at the end of the nonwoven machine that uses a continuous process too. Moreover a robot will increase the investment costs and the maintenance without improving the quality of the final preform. Another option considered has been to use the robot that put the preform into the injection moulding press, but there is not enough space to place a pressing and cooling tool and the press used for producing the final parts is not adaptable to the pre-consolidation process.

4.3.1 Concept 1

The subsystem 1, which processes the heating of the preform, is implemented by an infrared oven. For the next subsystem it has been selected a rolling press that includes two parallel rollers with the same dimensions.
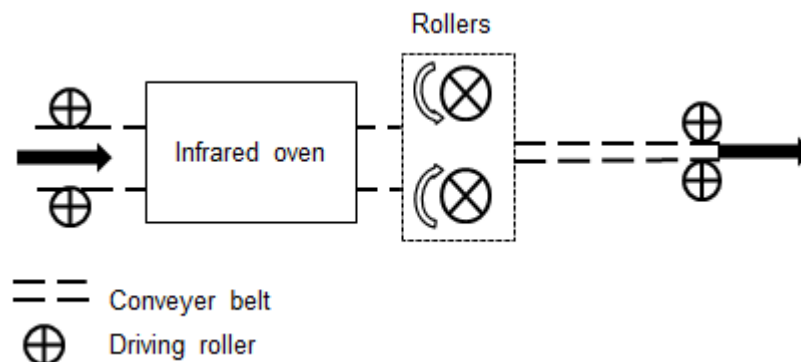

Fig. 4.8:   Concept 1 with infrared oven and rolling press

4.3.2 Concept 2

The second concept uses the same subsystem 1 as concept 1. However the system of pressing for cooling change and now the pressure is applied by a semi-continuous press.
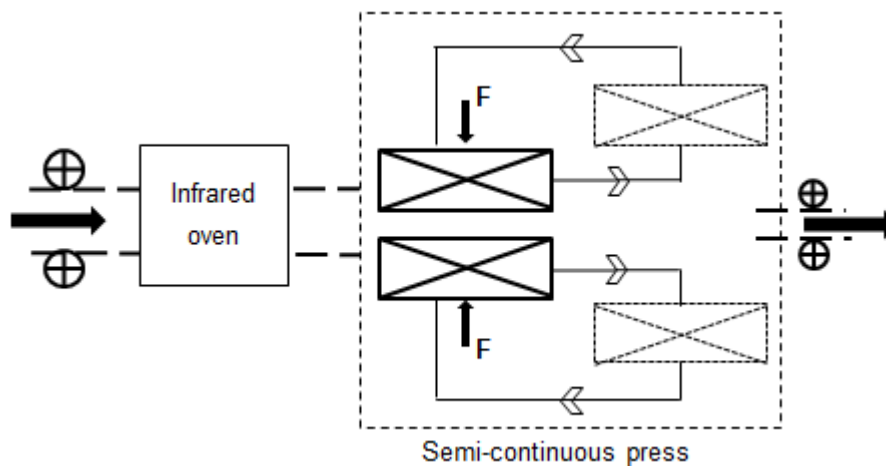
Fig. 4.9:   Concept 2 with infrared oven and semi-continuous press

4.3.3 Concept 3

This concept has a subsystem 1 composed of a hot air oven and an infrared oven. The subsystem 2 is the same that the one from Concept 1 with the rolling press.
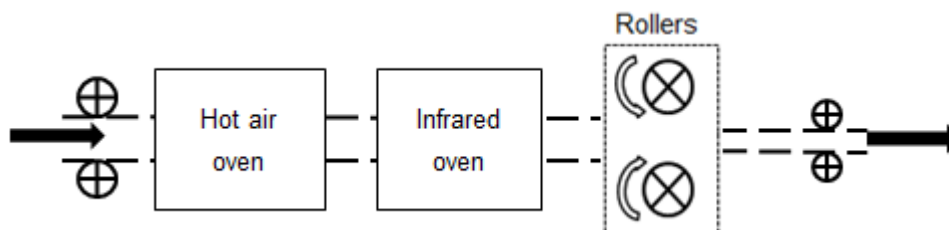
Fig. 4.10:   Concept 3 with hot air and infrared ovens and rolling press

4.3.4 Concept 4

The subsystem 1 of concept 4 is the same as concept 3, infrared oven after a hot air oven. Subsystem 2 is a semi-continuous press.

Fig. 4.11:   Concept 4 with hot air and infrared ovens and semi-continuous press

4.3.5 Concept 5

Concept 5 uses a specific hot air machine that recirculates the air and permit to pass it inside the textile so that it heats properly. The subsystem 2 is a rolling press like the one used in concept 1 and 3.
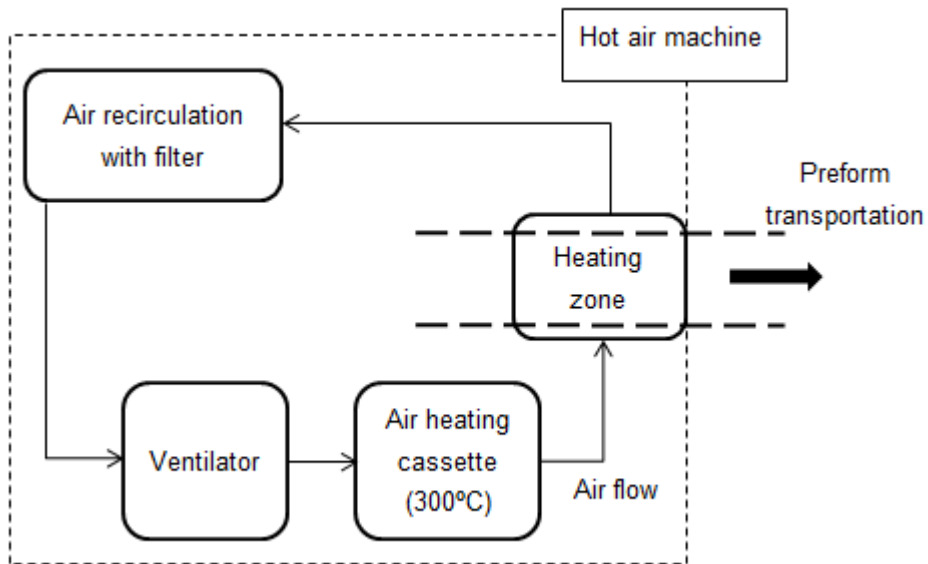
Fig. 4.12:   Specific hot air machine for Concept 5
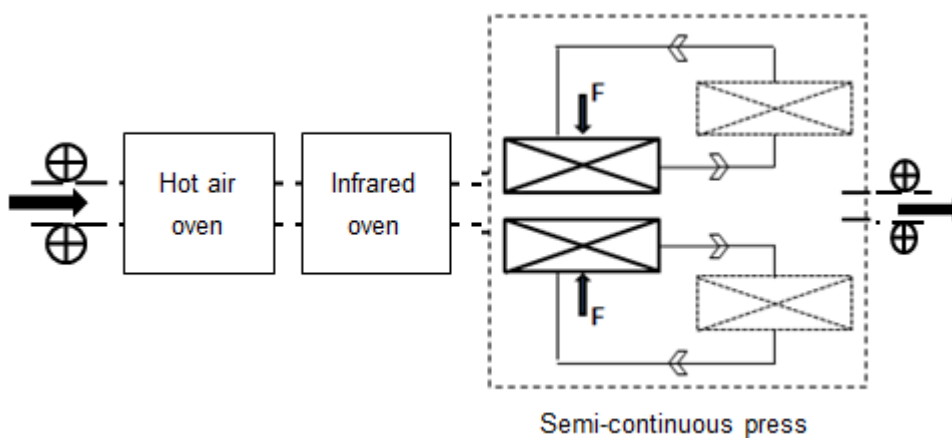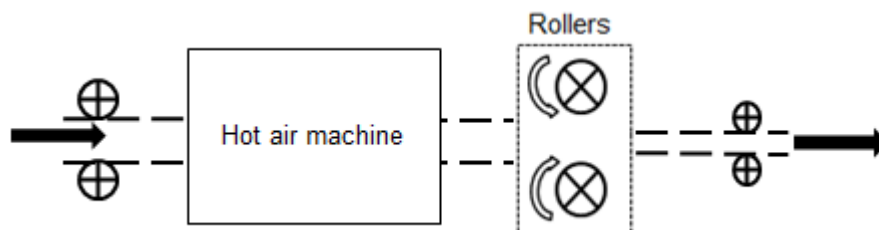

Fig. 4.13:   Concept 5 with hot air machine and rolling press

4.3.6 Concept 6

For concept 6 the same subsystem 1 as in concept 7 is used. The subsystem 2 is a semi-continuous press like in concept 2 and 4.
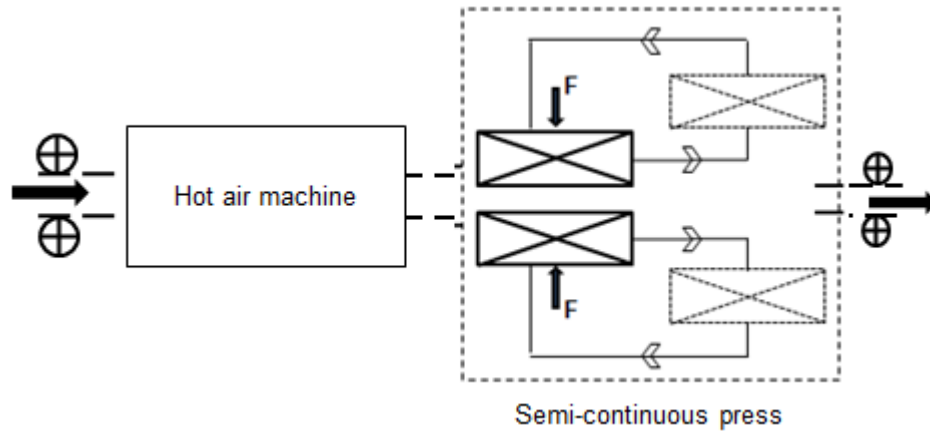
Fig. 4.14:   Concept 6 with hot air machine and semi-continuous press

4.4   Assessment of Concepts

To select the solution concept we used the evaluation criteria presented in Tab. 4.1: Evaluation criteria.

Tab. 4.1:   Evaluation criteria

1. SPEED
• High production speed
2. INVESTMENT COSTS   • Development costs   • Tooling costs   • Manufacturing costs
3. RUNNING COSTS   • Energy consumption   • Tools wear   • Labor needed
4. MAINTENANCE   • Durability of the designed components   • Quick and easy removability

5. MONITORING/OBSERVATION
 	
    • Central control unit
    • Visual control needed

6. SAFETY
 	
    • Quick stop option or safe mode
    • Good isolation of burning or electrifying cables

7. CORRECT HEATING
 	
    • Melting point achieved in all the preform
    • Part not burned
    • Uniform temperature distribution

8. COOLING AND PRESSING
 	
    • Uniform distribution of the force in all the surface
    • Minimum pressure between 60 and 150 Newton
    • Controlled temperature of the pressing tool
    • Pressure time

9. EFFICIENCY
 	
    • Low waste of energy
    • Recycling of the materials that are used during the process and have to be replaced by new ones

In order to determine the weighting factors of the individual evaluation criteria, a preference matrix is created. Fig. 4.15 shows the preference matrix with a total of nine developed evaluation criteria. These are pairwise compared. In the corresponding rhombus the number of the evaluation criteria is entered, which in direct comparison has the higher importance. For example, the desire for low investment costs (2) has a higher significance than the desire for a high speed process (1). Thus, in the corresponding rhombus the number 2 is entered.

Number	Evaluation criteria
1	Speed
2	Investment costs
3	Running costs
4	Maintenance
5	Control
6	Safety
7	Correct heating
8	Cooling and pressing
9	Efficiency

Fig. 4.15:   Preference matrix

The frequency of the corresponding numbers of an evaluation criterion in the preference matrix reflects the importance of the criterion. In order to normalize this, the frequency is in Tab. 4.2 divided by the number of all combinations (45) and there is a normalized weighting factor for each evaluation criterion.

Tab. 4.2:   Evaluation of the preference matrix

Evaluation criterion	1	2	3	4	5	6	7	8	9	Σ
Frequency	6	8	5	7	3	2	6	5	3	45
Weighting factor	0.13	0.18	0.11	0.16	0.07	0.04	0.13	0.11	0.07	1

The table shows that the evaluation criterion of the Investment costs (2), with eight nominations, has the highest importance of all criteria. Furthermore, the maintenance (4), with seven nominations has a great importance too. Less important in the following evaluation is the safety (6) followed by the Control (5) and the Efficiency (9).

After these results, it is clear that the focus is on the economic aspects which are the most important for the customers. However the good functionality of the process (speed, temperature, pressure) seems also important and plays a subordinate role. The safety and control do not be so important because the present design is a proto-type and the focus is on reaching a good quality product taking care of the costs.

In the following rating scheme (Tab. 4.3), the numerical values are fixed and each of them associated with one meaning. The scale used is from 0 ("unsatisfactory") to 4 ("ideal"). Often it is not possible to assign a value to a qualitative evaluation criterion. For this reason, the concepts are compared between each other and not with an ideal solution. The comparison with an ideal solution would be an absolute comparison. The scale of importance when comparing thus changes to "well below average" to "well above average".

Tab. 4.3:   Evaluation scheme with numerical values and their meanings

Points	Importance	Significance when comparing
0	Unsatisfactory	Well below average
1	Just about acceptable	Below average
2	Sufficient	On average
3	Good	Above average
4	Ideal	Well above average

The concepts are evaluated against the criteria and the metrics from the evaluation scheme. The description is divided into a definition of evaluation criterion and the subsequent comparison of the more significant concepts together. The respective score is entered in Tab. 4.4 and multiplied by the corresponding weighting. The sum of the results is the respective total value, which is entered in the last line for each concept.

Tab. 4.4:   Concept comparison analysis

N. i	Criterion	Wt. fct.i	Cpt1		Cpt2		Cpt3		Cpt4		Cpt5		Cpt6	
			V.i,1	Wt.i.1	V.i,2	Wt.i.2	V.i,3	Wt.i.3	V.i,4	Wt.i.4	V.i,5	Wt.i.5	V.i,6	Wt.i.6
1	Speed	0.13	3	0.39	3	0.39	3	0.39	3	0.39	4	0.52	3	0.39
2	Investment costs	0.18	3	0.54	3	0.54	2	0.36	2	0.36	2	0.36	2	0.36
3	Running costs	0.11	3	0.33	3	0.33	2	0.22	2	0.22	3	0.33	3	0.33
4	Maintenance	0.16	3	0.48	3	0.48	3	0.48	3	0.48	3	0.48	3	0.48
5	Control	0.07	3	0.21	3	0.21	3	0.21	3	0.21	3	0.21	3	0.21
6	Safety	0.04	3	0.12	2	0.08	3	0.12	2	0.08	3	0.12	2	0.08
7	Correct heating	0.13	3	0.39	3	0.39	4	0.52	4	0.52	3	0.39	3	0.39
8	Cooling and pressing	0.11	3	0.33	2	0.22	3	0.33	2	0.22	3	0.33	2	0.22
9	Efficiency	0.07	3	0.21	3	0.21	2	0.14	2	0.14	4	0.28	3	0.21
	Total value= ΣVt.i,j		3.00		2.85		2.77		2.62		3.02		2.67	

N. = number of criterion; Wt.fct. = Weighting factor; V. = value of the criterion; Vt. = total value; Wt. = Wt.fct. × V. The explanation of each value is shown in A.1.

4.5   Vulnerability Analysis

The vulnerability analysis in this work is represented by a value profile. There are two concepts with very similar total values, Concept 1 (3.00) and Concept 5 (3.02), but the first one has the same value (3) in every criterion so it will be better for a comparison to see the good and bad points of the other concepts. Therefore Concept 1 will be directly compared with the concepts with different ways of heating and cooling and pressing.

In Fig. 4.16 the concept 1 is compared with the Concept 2 that has a different pressing tool. From the figure, it appears that the Concept 1 is balanced overall. It has a high rating in each criterion and every rating is equal or higher than the one from Concept 2. In concept 2 the weaknesses are the safety (V6) and the cooling and pressing (V8). The more important is the cooling and pressing because it affect directly in the production of the preform. The safety has not a bad score (2, sufficient) and can be improved with some extra protection of the semi-continuous press.
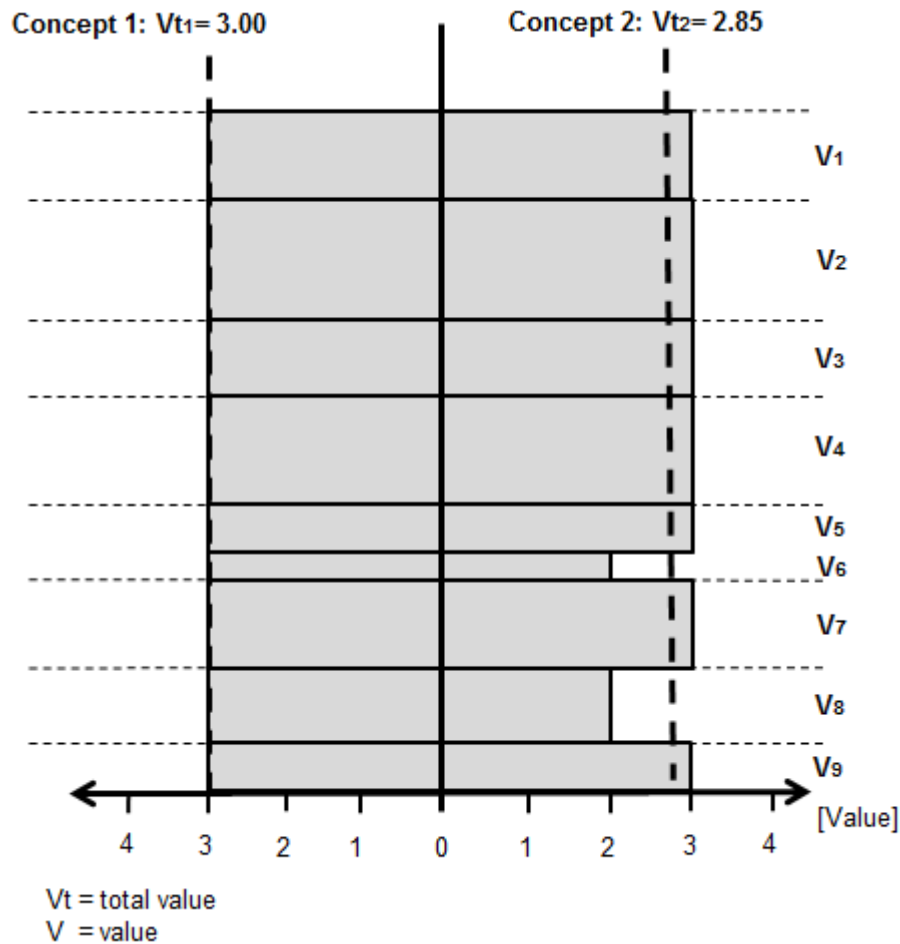

Fig. 4.16:   Vulnerability analysis Concept 1 and Concept 2

In Fig. 4.17 the Concept 1 is directly compared to the Concept 3 which has the same way of cooling and pressing but different heating method. Concept 3 has some better rated criterion and other worse than Concept 1. Concept 3 has a remarkable good score in correct heating (V7), which is very important in the pre-consolidation process. However it has a weak point in the economical field, with the investment costs (V2) and the running costs (V3). The efficiency (V9) is also inferior because of the use of two machines for heating.
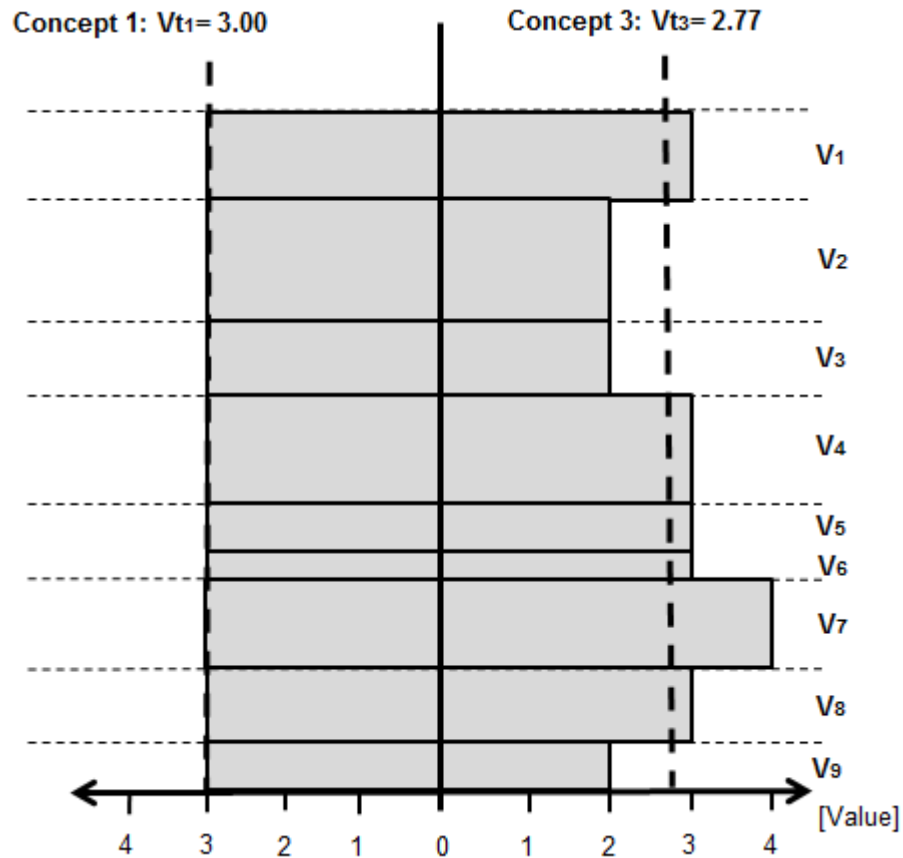
Fig. 4.17: Vulnerability analysis Concept 1 and Concept 3

In Fig. 4.18 Concept 1 is directly compared to Concept 5 which has a different way of heating but the same tool for cooling and pressing. In Concept 5 the scoring of the speed (V1) and the efficiency (V9) are higher which means that it is able to heat faster using less energy. On the other hand the weakness is the investment costs (V2) because of the fact that the machine has to be built specific for this process. However the machine can be designed after an existing machine so that its production price decreases.
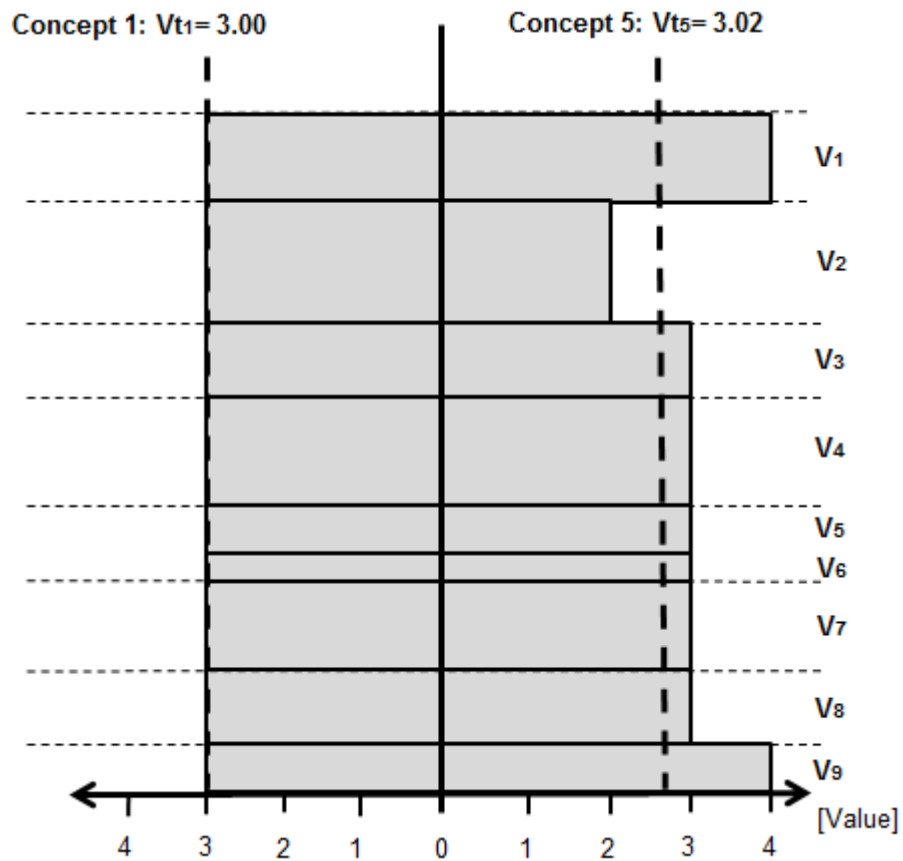
Fig. 4.18:   Vulnerability analysis Concept 1 and Concept 5

Summarizing Concept 3 has the inferior rating and is the one with the more weaknesses. Between Concept 1 and Concept 5 there are a lot of similar advantages but Concept 5 could be the best option for the future because its major weakness, the investments costs (V2) seems to have a possible solution.

5 Development of the concept

This chapter describes the steps of the design for the concept 5. The dimensioning and the configuration of each of its individual components are explained in the next sections. The hot air machine for the heating process is explained in chapter 5.1, the rolling press for the cooling and pressing process is defined in chapter 5.2, the rolling process to get the material in rolls is described in chapter 5.3 and finally, in chapter 5.4, the conveyors for the transport process is defined.

5.1 The heating process

A hot air machine is used for the heating process. The components of this machine are an air recirculation system with a filter, an air heating cassette to heat the air up and a ventilator. In Fig. 5.1 every part of is shown.
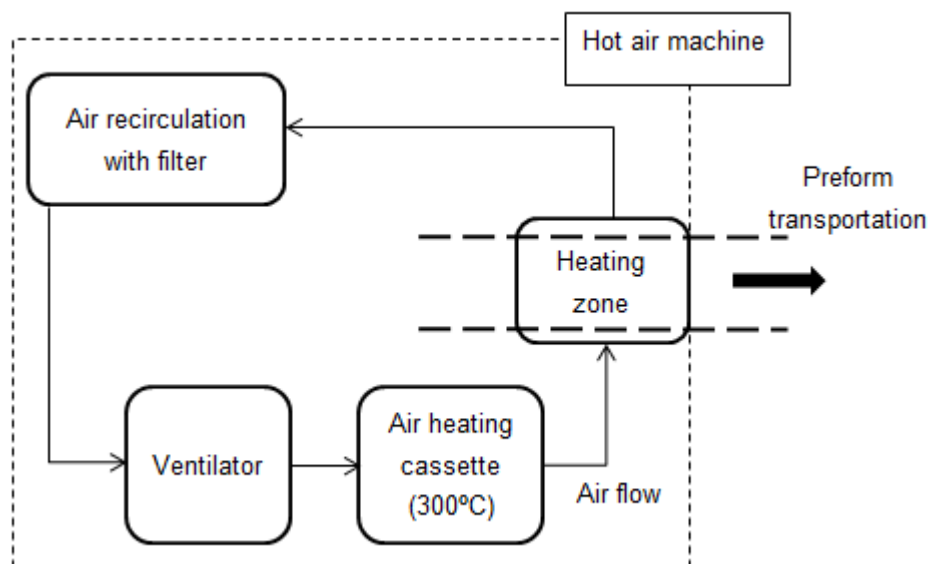

Fig. 5.1:   Components of the hot air machine

Air recirculation with filter

The hot air after heating the hybrid textile has to be cleaned of possible particles. For this purpose a filter resistant to high temperatures is needed. The filter is not regenerated because the carbon fibers need to be heated till 2 000ºC to get burned and this temperature is very far from the 300ºC settled in the process. In Fig. 5.2 the recirculation system with the filter is shown.

$$\dot{V}_{air}$$

Filter

$$\dot{V}_{air}$$

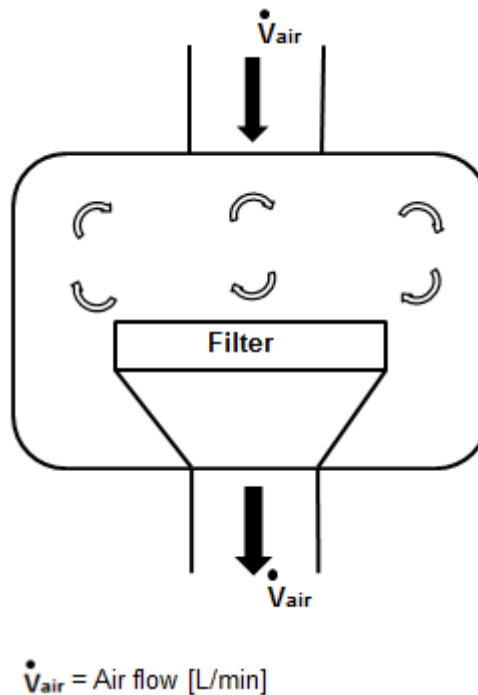$$\dot{V}_{air} = \text{Air flow [L/min]}$$

Fig. 5.2:   Air recirculation with filter

Air heating cassette

To heat the air after the recirculation till the temperature wanted of 300ºC, an air heating cassette is used as the one shown in Fig. 5.3. The cassette permit to heat air up to 800ºC, so there is any problem to reach the temperature needed.

$\dot{V}_{air}$ = Air flow [L/min]
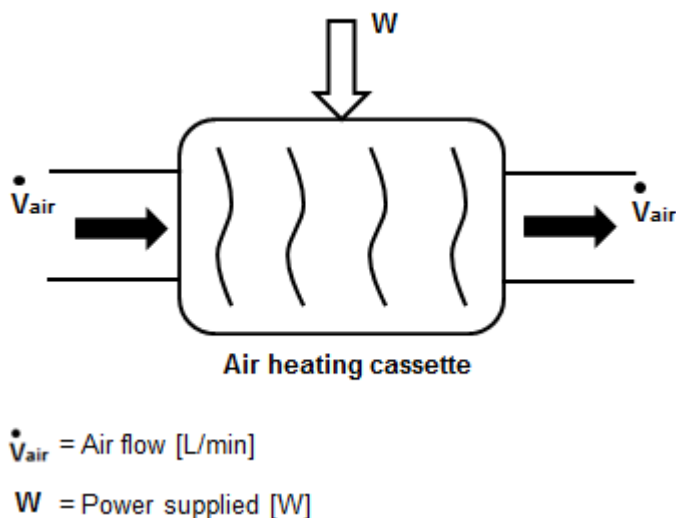
W = Power supplied [W]

Fig. 5.3:   Air heating cassette

The power needed to heat the air till 300ºC can be deduced from Fig. 5.4 depending on the air flow wanted. In the trials of chapter 3.5 with the hot gun the flow has been between 24 m³/h and 30 m³/h through an area of:

$$A = \pi \times R^2 = \pi \times 0.02^2 m^2 = 1.26 \times 10^{-3}\ m^2 \qquad (5.1)$$

So the speed of the flow has been:

$$V = A \times v \longrightarrow v = \frac{V}{A} = \frac{27\ m^3/h}{1.26 \times 10^{-3}\ m^2} = 21\ 428.6\ m/h \qquad (5.2)$$

The flow can expected to be between 20 000 and 25 000 m/h.

For the area wanted of

$$A = 1 \times 0.2\ m^2 = 0.2\ m^2 \qquad (5.3)$$

the flow should be

$$V = A \times v = 0.2\ m^2 \times 21\ 428.6\ m/h = 4\ 285.72\ m^3/h \qquad (5.4)$$

The flow that has been taken into account is between 4 000 and 5 000 m³/h.

And the power has been obtained from the curves of Fig. 5.4. With the air at 200ºC the power needed to heat a flow of 1 400 m³/h is 100 kW so the flow of the process has been obtained interpolating the numbers between 200 and 400ºC.

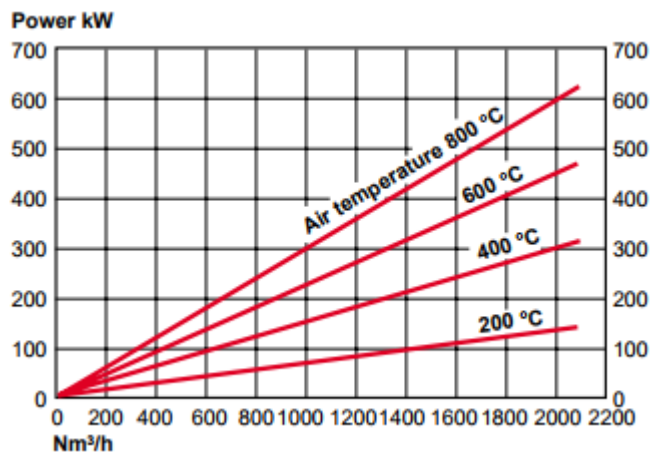The power needed by the air heating cassette is 465 kW.

Fig. 5.4:   Diagram of the needed power for different air temperatures and flow when starting from room temperature from the catalogue of Kanthal. [www17c]

Ventilator

To generate the necessary air flow that penetrate the preform and heat it inside, a tubular and axial ventilator is needed. The flow needed is the one calculated before, between 4 000 and 5 000 m³/h. The ventilator is shown in Fig. 5.5.

$\dot{V}_{air}$ = Air flow [L/min]

W   = Power supplied [W]
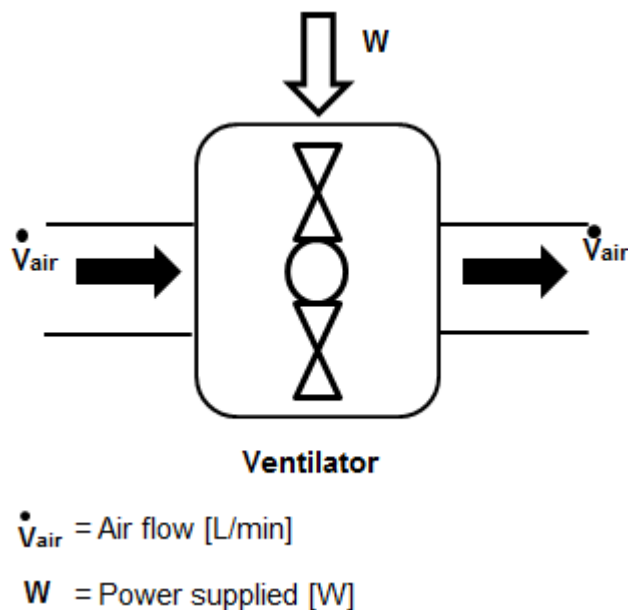
Fig. 5.5:   Ventilator

To move this flow the power supplied must be:

$$W = V \times hp \times g = (\frac{4200}{3600}) \, m^3/s \times 40 \, Pa \times 9.8 \, m^2/s = 457.33 \, W \qquad (5.5)$$

The flow losses (hp) value has been taken from Fig. 5.6.

The power needed can expected to be between 400 and 600 W.
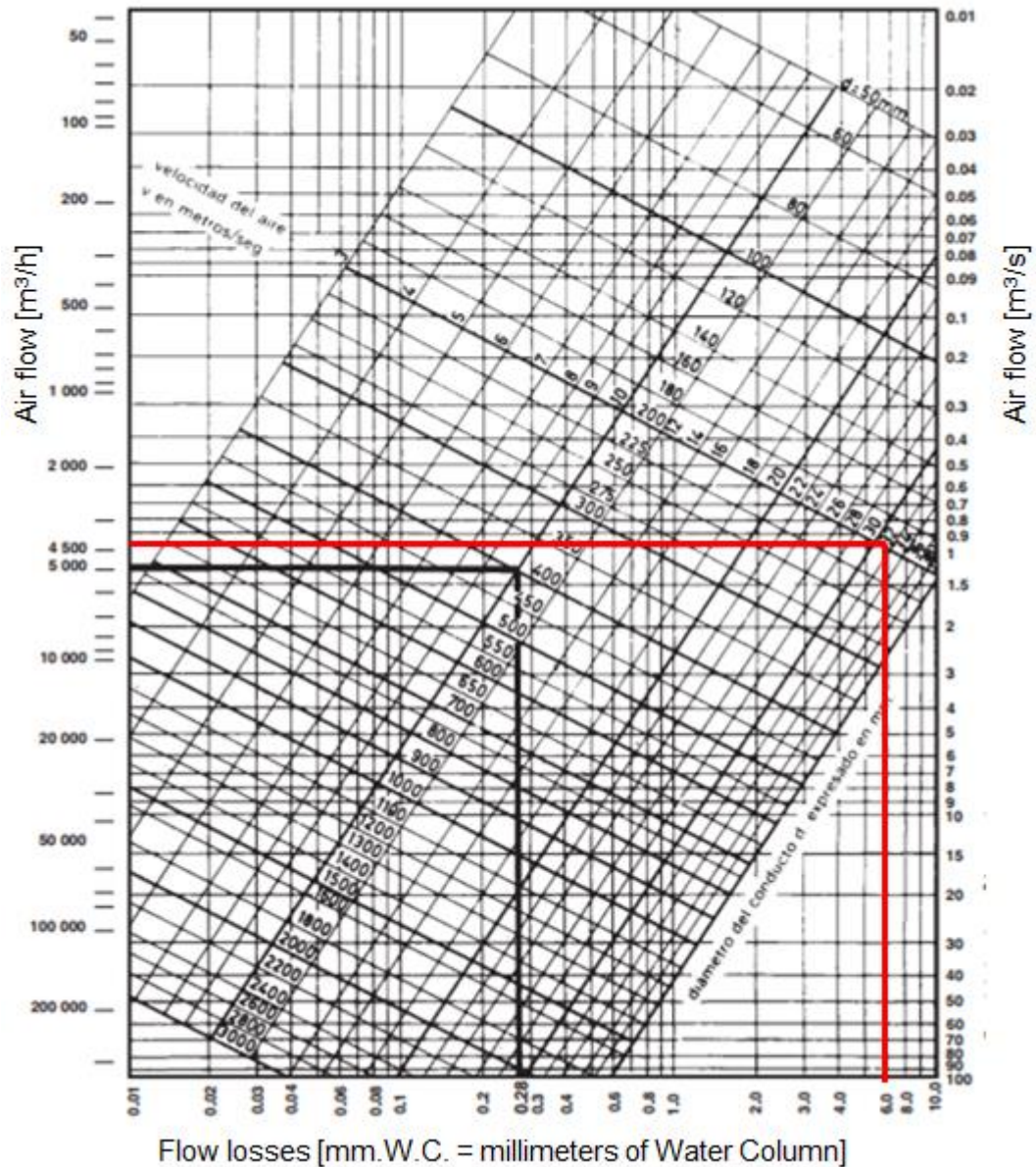
Fig. 5.6:   Plot of flow losses in circular duct. [www07]

5.2   The Cooling and pressing process

In Concept 5 the way of cooling and pressing is using a rolling press. The parameters of the press are the previous thickness (h_0), the final thickness (h_f), the lineal speed of the rollers (V_r), the projected length of the contact arc (L_p) and the contact angle (α) defined by the arc which surface of the rollers is in contact with the preform. The forces applied will be explained later. In Fig. 5.7 these dimensions and parameters of the rollers and material are shown.
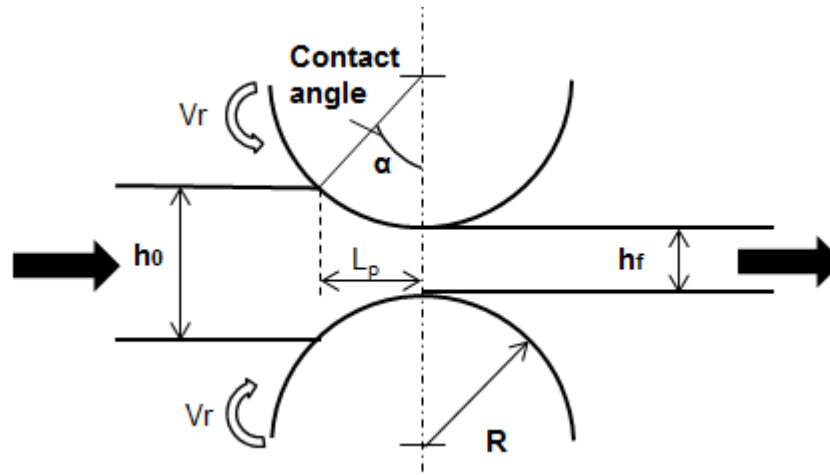
Fig. 5.7:   Dimensions and parameters

The relationship between the diameter of the rollers, the contact angle and the absolute reduction magnitude is expressed by the formula:

$$h_0 - h_f = D \times (1 - \cos \alpha) \tag{5.6}$$

so the absolute reduction magnitude rises with the increasing of the rollers diameter.

And the maximum reduction possible is defined by the formula:

$$[\Delta h]max = R \times \mu^2 \tag{5.7}$$

Where:

$$\mu = \tan \alpha \tag{5.8}$$

The rollers apply pressure on the material to reduce the thickness, so a force is required perpendicular to the contact arc, or perpendicular to the plane of the sheet, since the arc is very small in relation to the size of the roller. The rollers rotate in opposite directions so that the material flows between them, exerting forces of compression and shearing, originated by the friction that occurs between the rollers and the textile. The rollers speed (Vr) is applied electronically and both rollers are synchronised by gears to permit the best precision.

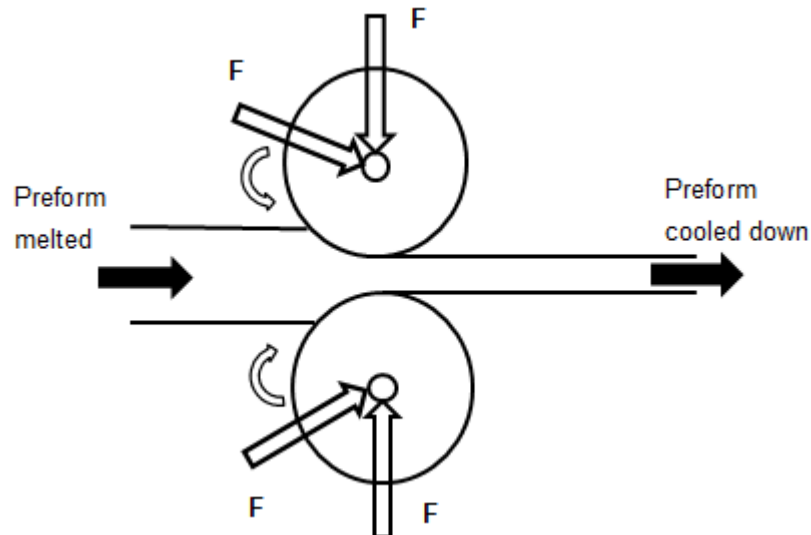Fig. 5.8:   Forces in the rollers press

Data of the pre-consolidation process here designed

Initial thickness of the hybrid textile produces by the nonwoven machine: ho = 10 mm, the same as the one used in the preliminary trials

Final thickness needed: hf = 1 mm, the same as the better obtained in the preliminary trials in sub-chapter 3.4.3.

Radius of the rollers: R = 0.15 m

Calculations

Reduction:

$$\Delta h = h_0 - h_f = 10 \text{ mm} - 1 \text{ mm} = 9 \text{ mm} \tag{5.9}$$

Projected length of the contact arc:

$$L_p = \sqrt{R \times \Delta h} = \sqrt{0.15 \text{ m} \times 0.009 \text{ m}} = 0.038 \text{ m} \tag{5.10}$$

Contact angle:

$$h_0 - h_f = D \times (1 - \cos \alpha)$$

$$\alpha = \text{arcos} \left(1 - \left(\frac{h_0 - h_f}{D}\right)\right) = \text{arcos} \left(1 - \left(\frac{10 \text{ mm} - 1 \text{ mm}}{300 \text{ mm}}\right)\right) = 14° \tag{5.11}$$

So the contact angle has to be 14° at least.

The force of the rollers is calculated from the preliminary trials with the reduced area pressing tool T (sub-chapter 3.4.3). The pressure of the trial is deduced:

$$P_{\text{tool T}} = \frac{F}{A} = \frac{750 \text{ } N}{7 \times 10^{-4} \text{ m}^2} = 10 \times 10^5 \text{ Pa} \tag{5.12}$$

The contact area of the rollers is (wi = width of the material):

$$A = L_p \times wi = 0.038 \text{ m} \times 1 \text{ m} = 0.038 \text{ m}^2 \qquad (5.13)$$

So the force of the rollers is:

$$F = P \times A = 10 \times 10^5 \text{ Pa} \times 0.038 \text{ m}^2 = 38\,000 \text{ } N \qquad (5.14)$$

The force of the rollers can expected to be between 35 000 and 40 000 N.

Lineal speed of the rollers: from the preliminary trials of sub-chapter 3.4.3, before mentioned, the time of pressing (t_P) needs to be between 3 and 5 seconds so:

$$Vr = \frac{L_p}{t_P} = \frac{0.038 \text{ } m}{4 \text{ } s} = 0.01 \text{ m/s} \qquad (5.15)$$

The lineal speed has to be between 0.008 and 0.02 m/s.

Angular speed of the rollers:

$$w = \frac{Vr}{R} = \frac{0.01 \text{ m/s}}{0.15 \text{ m}} = 0.07 \text{ rad/s} \qquad (5.16)$$

Power needed:

$$W = T \times w = \frac{L_p}{2} \times F \times w = \frac{0.038 \text{ m}}{2} \times 38\,000 \text{ N} \times 0.07 \text{ rad/s} = 50.54 \text{ W} \qquad (5.17)$$

5.3   The transport process

The transport of the material is done by a conveyor which is put into operation through the motor system; the movement to the belt is imparted by the driving drum, through the transmission system. The belt is the traction member of the conveyor and at the same time the material transport. The preform is automatically deposited therein by the nonwoven machine which supplies the material constantly to the conveyor. At the end the material is rolled. Fig. 5.8 shows the transport system.
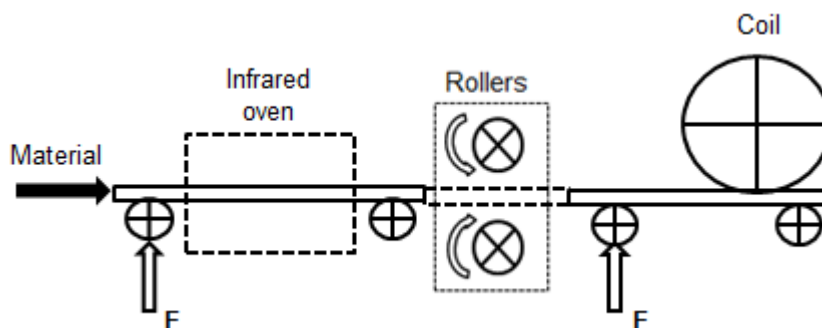

Fig. 5.8:   Transport process

The speed of the conveyor is defined by the speed needed in the infrared oven and in the rollers. It is adjustable increasing or decreasing manually the power that arrives to the driving drums and it is constant.

The power needed can expected to be between 100 and 400 W as it is said in the Axmann catalogue [www17d].

5.4 The rolling up process

After cooling down the material, it is rolled up in big rolls to facilitate the transport. The preform can be bended till 20 degrees, so the rolls have to have a diameter higher than 15 centimeters. The diameter chosen for the calculations is 20 centimeters.

Calculations

Angular speed of the roll:

$$w = \frac{v_2}{R} = \frac{0.05 \text{ m/s}}{0.20 \text{ m}} = 0.25 \text{ rad/s} \tag{5.18}$$

$$w = 0.25 \frac{\text{rad}}{\text{s}} \times \frac{60 \text{ s}}{1 \text{ min}} \times \frac{1 \text{ rev}}{2 \times \pi \text{ rad}} = 2.4 \text{ rev/min} \tag{5.19}$$

Perimeter of the roll:

$$P = 2 \times \pi \times R = 2 \times \pi \times 0.20 \text{ m} = 1.26 \text{ m} \tag{5.20}$$

So to roll up 1 meter of preform:

$$\frac{1}{1.26} = 0.8 \text{ rev} \tag{5.21}$$

Time to roll up 1 meter:

$$t_r = \frac{0.8 \text{ rev}}{2.4 \text{ rev/min}} \times \frac{1 \text{ h}}{60 \text{ min}} = 0.006 \text{ h} = 21.6 \text{ s} \tag{5.22}$$

The time to roll 1 meter can expected to be between 20 and 25 seconds.

The energy consumption can expected to be between 50 and 100 W as it is shown in the catalogue from Dimatra. [www17e]

5.5 Total production and energy consumption

The production time of 1 meter of preform is the same time as the rolling up time of 1 meter (between 20 and 25 seconds). So the total production (Pr_T) is:

$$Pr_T = \frac{1\ m}{22\ s} \times \frac{3\ 600\ s}{1\ h} = 163.64\ m/h \qquad (5.23)$$

The total production can expected to be between 140 and 180 m/h of preform.

If the speed of the process (v_T) needs to be increased, then the lineal speed of the rollers (V_r) also, to do that it is necessary to increase the angular speed of the rollers (w) or the radius of the rollers (R).

The energy consumption is:

$$E_T = E_H + E_V + E_P + E_{Tr} + E_R = 465\ W + 500\ W + 60\ W + 250\ W + 80\ W \qquad (5.24)$$
$$= 1\ 355\ W$$

The total energy consumption of the pre-consolidation process can expected to be between 1 200 and 1 500 W.

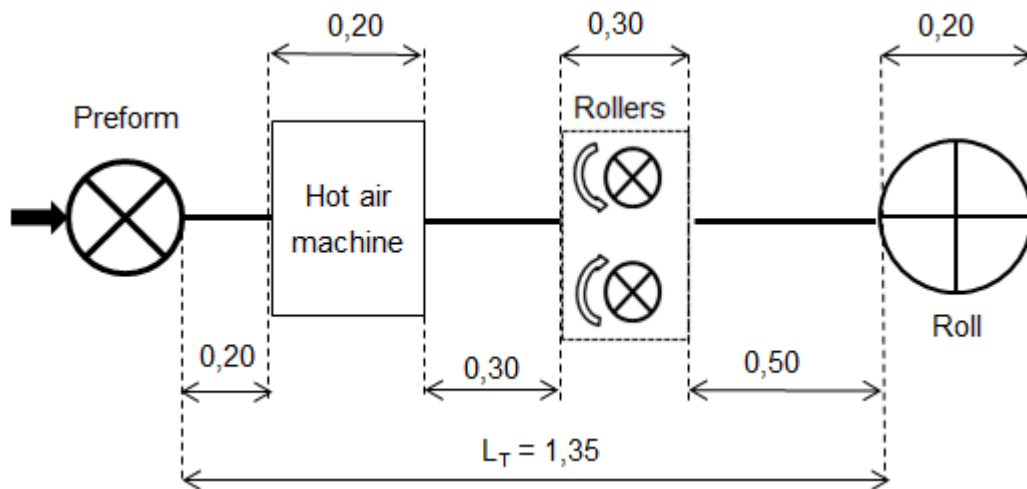The length of the pre-consolidation process is shown in Fig. 5.9.

Fig. 5.9: Distances of the pre-consolidation process in meters.

6 Summary and Outlook

The ITA developed a process to create an rCF part from RCF nonwovens with a thermoplastic matrix. This process is divided in three steps: the nonwoven process, the pre-consolidation process and the moulding and injection process. (At the moment the three steps are divided in different places but the pre-consolidation process can be adapted at the end of the nonwoven machine.)

The pre-consolidation process of the hybrid textile is needed to have a preform workable for the injection moulding press. To achieve a good quality of the preform, the textile has to be heated till the melting point and then quickly cooled and pressed. This process needs to be updated to another more efficiently and faster that allows a more automated overall process.

To develop the new pre-consolidation process some preliminary trials about the way of heating and cooling and pressing have been performed and a theoretical design has been done. For the design, first of all the list of requirements has been defined and then the functional structure of the pre-consolidation process. Using the theoretical knowledge and the preliminary trials six concepts have been defined and evaluated depending on some concrete criteria. Then the most interesting have been compared by value profiles.

The chosen concept heats the textile with a hot air machine that heats the preform into its core, then a rolling press is used to do the pressing and cooling process and finally a roll helps to storage the preform obtained. During the process the material is guided by an automatic conveyer belt. In Fig. 6.1 the hot air machine composed by a ventilator, an air heating cassette and an air recirculation system with filter is shown.
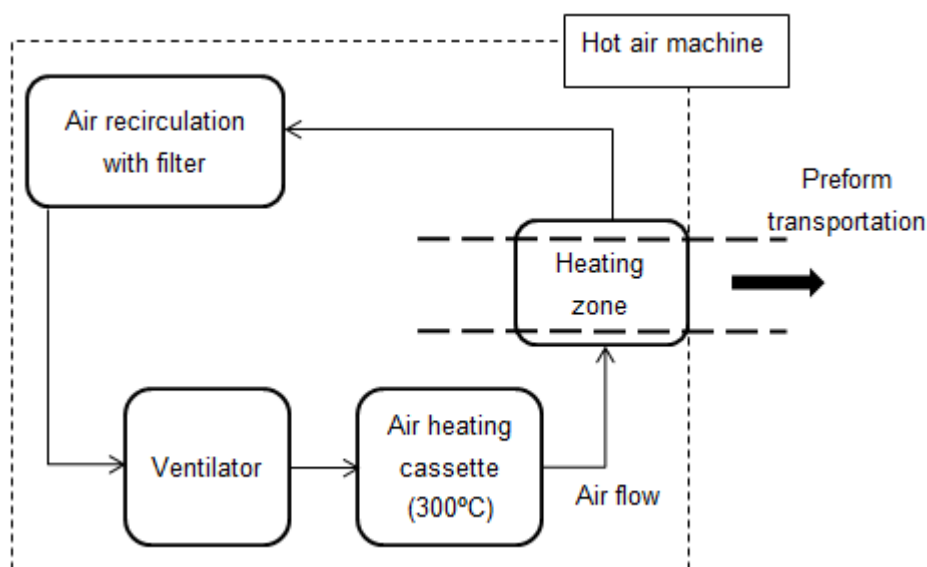

Fig. 6.1:   Heating system of the developed concept

Each of the machines that compose the concept is described and the calculations of their parameters are done. These calculations are based on the results obtained in the

preliminary trials of chapter 3. The air flow and the heating time of the hot air machine are calculated after the trials with the hot air gun and the dimension, the force and the speed of the rollers are based on the trials with the reduced area pressing tool. With the developed concept, the pre-consolidation process is turned into a continuous process and achieves a production between 140 and 180 m/h of preform.

Next step to be done should be the CAD design of the pre-consolidation process to be able to have a simulation of the continuous process and give a better estimation of the process times and speeds.

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7 Appendix

A.1: Explanation of values for each concept of Tab. 4.4.

	Value explanation
Concept 1: infrared oven and rolling press	This concept has the same value (3, good) in each of the criteria because both of the machines used are already developed so the costs and efficiency are optimized and the security rules are accomplished. Moreover the way of heating with the infrared oven has been tested in the trials of chapter 3.2 with good results.
Concept 2: infrared oven and semi-continuous press	This concept has similar criteria values as concept 1. However the cooling and pressing value is lower (2, sufficient) because the press used is a semi-continuous one which can damage the textile with its movement by creating wrinkles or can leave some surface not pressed because of an offset between the press and the textile. The safety is also worse because the semi-continuous press can damage something or hurt someone with its movement.
Concept 3: hot air and infrared oven and rolling press	In this concept there is two ways of heating so the correct heating value is the maximum (4, ideal). On the other hand the investment and running costs values decreases because the hot air oven is an additional expense that is not in Concept 1 and 2.
Concept 4: hot air and infrared oven and semi-continuous press	The values for Concept 4 are similar as the values from Concept 3 because it has the same way of heating. The safety and cooling and pressing values are lower because of the semi-continuous press (same reason as in Concept 2).
Concept 5: hot air machine and rolling press	Concept 5 has the higher value in speed because the hot air machine is a fast way of heating so the process takes less time. The efficiency has also the best value because the machine do not needs more energy than the other tools for heating and has better results. On the other hand the investment costs have a lower value because the hot air machine is specific for that process so it is more expensive to develop it.

	Value explanation
Concept 6: hot air machine and semi-continuous press	In this concept the safety and the cooling and pressing values are lower (2) because of the semi-continuous press. Meanwhile the investments costs value is also lower (2) due to the hot air machine.

8 Statement of academic honesty

I hereby declare to the best of my knowledge that this thesis contains no material previously published or written by any other person. The work submitted in this thesis is the product of my own original research, except where I have duly acknowledged the work of others.

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City, Date   Signature