Alternative Manufacturing Route of Fibre Metal Laminates

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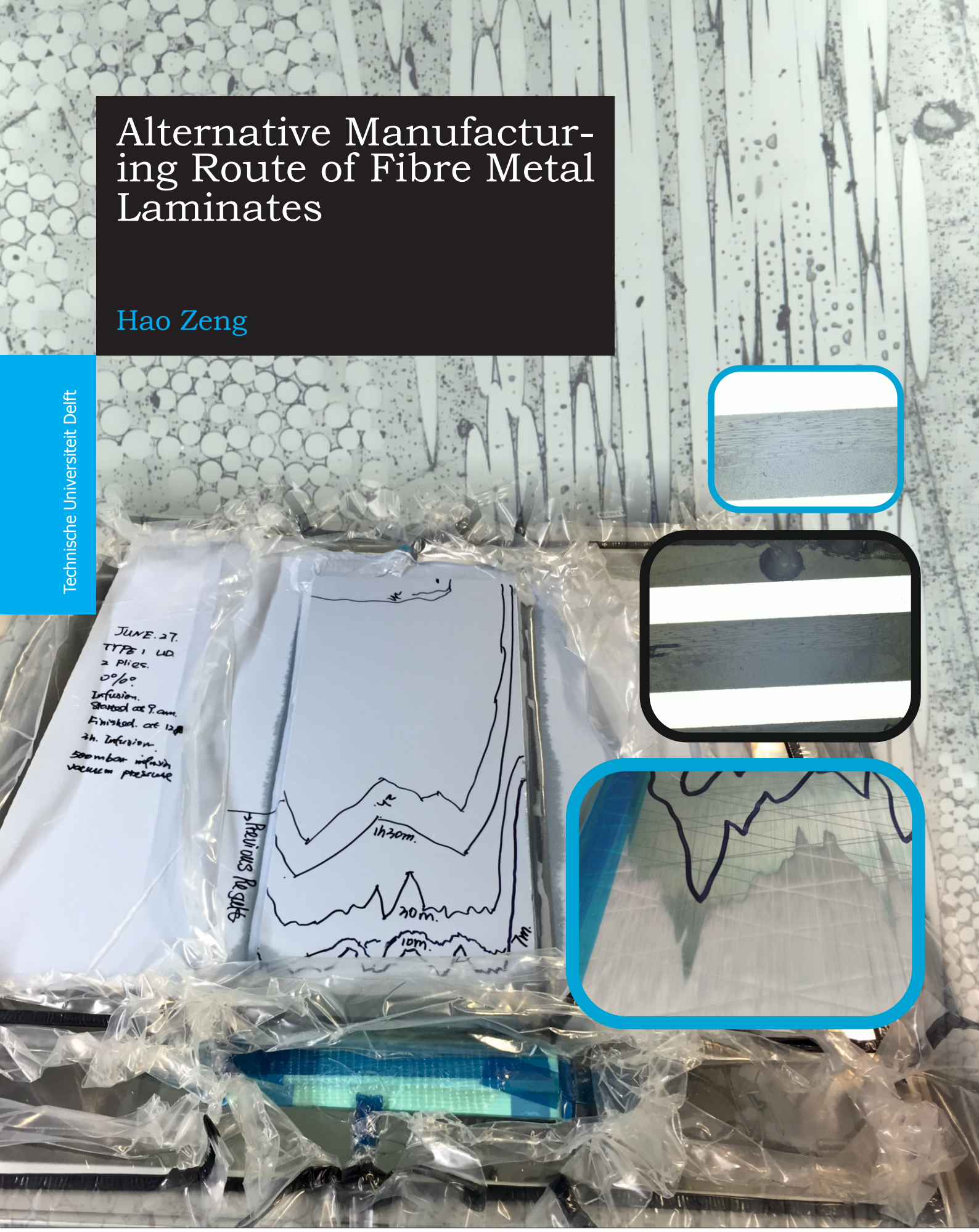

TU Delft Delft University of Technology

Challenge the future

Alternative Manufacturing Route of Fibre Metal Laminates

by

Hao Zeng

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Abstract

Fibre metal laminates (FML) are manufactured by stacking metal sheets and fibre reinforced prepreg in an alternating fashion, and curing it in an autoclave. The most well-known FML is Glare, which has been successfully applied on Airbus A380 for its fuselage skin. It consists of aluminium sheets and glass fibre prepregs. FMLs have a better impact and fatigue performance compared to the bare metal and are therefore more damage tolerant. The drawback of Glare is the high manufacturing cost because of the use of an autoclave and the expensive prepregs. This study investigates the feasibility of vacuum infusion for the manufacturing of FMLs to reduce costs, while keeping an acceptable fibre volume content of 45% to 60%. An experimental approach is taken to explore the manufacturing process to determine under which conditions an infusion is possible, and to analyse which process parameters influence the duration of the infusion. Three variables: resin viscosity, vacuum infusion pressure and the reinforcement permeability are identified from Darcy's law, which can influence the infusion process. The experimental data was gathered through multiple infusion process tests by adjusting these variables. Because the resin flow on the composite layers cannot be monitored visually through the metal sheets, glass plates are used to investigate these variables' effect on the process. Through the analysis of the experimental data, the vacuum infusion process including the material selection, equipment and processing details are determined. Aluminium and dry glass fibre sheets are used to conduct the Vacuum Infusion process. The product is used to verify how the process parameters adhere to actual FML product fabrication. It can be concluded that during the experimental study, the Vacuum Infusion process has successfully been applied on the manufacturing of Fibre Metal Laminates with a satisfying fibre volume content of 54% to 65%, and a voids content of 0.5% to 1.5%. By extrapolating the experimental infusion length curves, it was estimated that under the current conditions a maximum infusion length of 1.4 m most likely is possible when infused over the 0° direction, and a maximum infusion length of 1.0 m is expected to be possible when infused over the 90° direction. The total manufacturing cost of Vacuum Infusion process was found to be reduced 43% compared to the autoclave manufacturing process. These results show that vacuum infusion is a promising technique for the manufacturing of low cost FML, and it opens a door for future research on this topic to reduce the manufacturing cost of Glare.

Contents

1

Introduction

1.1. Background and motivation

Fibre Metal Laminates (FML) are a family of hybrid composite materials which consist of stacked thin metal sheets and fibre reinforced resin matrix layers. With the advantage of both metal and fibre components, FML provide excellent mechanical properties such as high strength, low density, great corrosion resistance, fatigue resistance and impact resistance. As a representative FML family member, Glass fibre reinforced aluminium laminate (GLARE) has been developed with thin aluminium alloy layers (typically 0.2 to 0.4 mm) with alternating uni-axial S-glass fibres with epoxy matrix composite layers. GLARE has been applied on the upper fuselage panels and the vertical fin of the Airbus A380 since 2005 [1]. However, various investigations indicate that the manufacturing of FML reveal a high overall cost and it limits the applicability. Therefore, the manufacturing cost study of FML draws sufficient attention from researchers [2–4]. Although there is a great amount of articles published studying FML mechanical properties, the attention for a cost reduction of the manufacturing method is still limited. So, the purpose of this study is developing a cost effective manufacturing method with a similar fibre volume content as the GLARE material.

1.2. Research objective and research questions

The main research objective is to ”Explore the feasibility of vacuum infusion for the manufacturing of FML to achieve a low-cost alternative manufacturing route, while maintaining a high fibre volume content and the ability of fabricating large products.” The research questions following the research objective are listed below:

1. What are the parameters influencing the infusibility of the laminate, and in which way do they influence the process?
    - In which way does the fibre architecture/orientation influence the process?
    - How does the pressure difference influence the infusibility?
    - How does the processing temperature influence the infusion process?
2. How does the resin flow-front travel through the laminate during the process?
    - How can the resin flow be visualised?
    - How fast does the resin travel through the fibre preform?
    - What is the shape of the resin front line?
3. What is the maximum infusion distance that this method could achieve?
    - Where do dry points occur?
    - What are the limiting factors for the infusion distance?

4. Which infusion parameters lead to the highest material quality (e.g. fibre disturbance due to infusion, fibre volume and voids content?
5. How much is the cost compared to the traditional manufacturing method?

1.3. Methodology

An experimental methodology is designed to adapt the Vacuum Infusion process to manufacture Fibre Metal Laminate structures with the following stages:

1. Experimental setup of infusion tests;
2. Fibre reinforcement permeability comparison between two types of dry fibreglass unidirectional tapes preforms;
3. Testing various vacuum infusion levels;
4. Resin viscosity influence by changing the processing temperature;
5. Influence of Fibre orientation between unidirectional and cross-ply configuration.
6. Difference between single composite layer infusion and multiple composite layers infusion
7. Vacuum infusion Fibre Metal Laminates manufacturing test and quality inspection

Furthermore, the cost estimation of the Vacuum Infusion(VI) processed FML will be conducted to compare it with the traditional Autoclave(AC) FML process. In this study, the experimental study will develop a reliable and repeatable experimental setup for VIFML, and provide the fibre volume content void content in order to study the product quality. The cost estimation result on VIFML manufacturing process will be compared with the ACFML process.

1.4. Report outline

Chapter 2 provides the literature study and determines the VI process for the alternative method research in this project. Chapter 3 theoretically investigates the parameters involved in Darcy's law and their influence on the infusion process. Chapter 4 introduces the experiment test matrix design and the detailed experimental set-up. Chapter 5 demonstrates the experimental results for the infusion process test matrix, the effect of infusion processing time and the product fibre volume and voids content is demonstrated. The influencing factors including vacuum level, resin viscosity and fibre architecture are discussed. Chapter 6 extrapolates the experimental results towards the industrial application of the vacuum infusion process of FML. Chapter 7 explains the cost model applied to this study, the cost of the VIFML manufacturing is compared with the ACFML fabrication process. Chapter 8 gives the conclusions and the recommendations of this study.

2

Literature Review

In Chapter 2, three major factors that influence cost are identified and discussed for the traditional manufacturing method of Fibre Metal Laminates (FML): long cycle time, expensive raw materials, and expensive equipment cost. Different Out-of-autoclave (OoA) manufacturing processes are reviewed and analysed for making Fibre Metal Laminates. A literature review has been conducted while keeping in mind the economic aspects in developing Fibre Metal Laminates. Various studies have been performed for fabricating FML material with reduced autoclave times or with perforated metal sheets. However, almost no studies can be found on fabricating continuous fibre metal laminates without using an autoclave. Following a brief literature of various OoA methods, the Vacuum Infusion(VI) process is selected as an alternative to the traditional autoclave manufacturing of Fibre Metal Laminates. A relationship known as Darcy's law is used to describe the performance of liquid flow through a porous medium. It is introduced briefly and used to study and improve the infusion process.

2.1. Identification of current Fibre Metal Laminates manufacturing methods, and cost drivers

The traditional manufacturing method of FML consists of the lay-up of glass fibre reinforced prepreg and thin aluminium sheets as raw materials and curing them in an autoclave. Taking GLARE as an example, the general FML composite structure production includes the following steps:

- Raw material preparation: The surface of the thin metal layers are pre-treated with an acid solution to improve the bonding between composite and metal surface. The prepreg is defrosted from the freezer and trimmed according to the dimensions of the product.
- Layup and vacuum bagging: After the tooling has been cleaned and a release agent has been applied, the metal sheets and the trimmed prepreg are placed in an alterlating fashion by manual operation. A vacuum bag is made over the tooling surface and applies a uniform pressure on the product via vacuum application.
- Curing process: The tooling together with the vacuum bag is loaded into the autoclave, and the curing process is performed by the autoclave program. The curing cycle of FML production may last 4 to 6 hours, including temperature rising phase (0.5 h), high temperature dwell phase (approximately 3 h) and cooling down phase (1 h). During the curing process, the autoclave pressure should be maintained ranging from 300 kPa to 600 kPa [4, 5].
- Demoulding: After the product is cooled down to room temperature, the tooling is unloaded from the autoclave, and the product is removed from the vacuum bag.

Reviewing the general manufacturing steps, three cost drivers are identified. Firstly in the raw materials preparation steps. S-glass fibre embedded in epoxy matrix prepreg is used for the traditional FML manufacturing. Prepreg is the term used to present reinforced materials pre-impregnated by the resin matrix used for composite manufacturing. Prepreg could be used during the manufacturing process

and result in very high fibre volume content of 60% to 65% in the final product. However, this material is more expensive than adding the cost of dry fibre, resin and curing for the same amount due to the pre-impregnated fibres. Thus, raw material cost is considered as one cost driver for this study. Secondly, the tool cleaning, preparation and materials trimming are conducted for building the vacuum bag. During these steps, the labour is high due to the manual operations. The labour time is identified as another cost driver at this moment. Thirdly, a cure cycle is chosen based on the selected matrix resin system of the prepreg materials and takes place in an autoclave. The autoclave demands high acquisition and maintenance costs, and also requires high-quality tooling that can last multiple curing cycles. A curing cycle consists of the continuous holding of vacuum level and positive pressure together with controlling the temperature rising and cooling rate, also the dwelling time. Therefore, a long curing time leads to high energy cost.The manufacturing flow is also demonstrated into sequential steps during the process as in Figure 2.1, where the cost drivers are identified from the related actions on the right side of Figure 2.1. Note in Figure 2.1, the manufacturing flow chart is a demonstration of simplified technical and economic factors. The steps from the flowchart indicated in the shape of rhombus can vary due to different product designs and the one indicated in the rectangular shapes are fixed in practice [6].

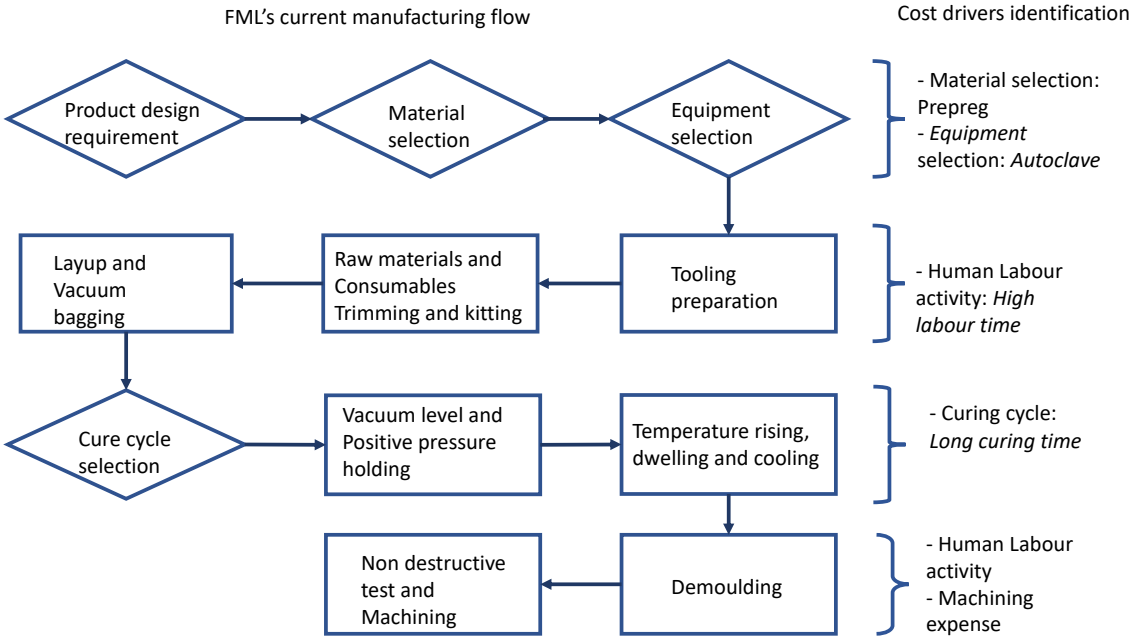


Figure 2.1: Flow chart of FML current manufacturing flow chart and the key manufacturing cost drivers[6]

2.2. State of the art of Out-of-autoclave techniques

This section provides information on most of the OoA technologies that are used on industrial, and lab scale. These methods are compared to the conventional autoclave methods concerning the raw material, the equipment and the process. The advantages and disadvantages are compared and evaluated for the application on FML. An alternative composite manufacturing technology would be chosen as the essential study object aiming at overcoming the disadvantages of the traditional autoclave methods.
To overcome the challenges brought by autoclave curing methods, out of autoclave manufacturing technologies are popular for producing economical aerospace structural and non-structural composites components [4]. One of these advanced fabrication approaches is Vacuum Infusion combined with oven curing, microwave curing or curing at room temperature. This Section gives an overview of three popular OoA methods as potential routes for FML production.

2.2.1. Oven/Vacuum Bag Only (VBO) processes

The primary idea of the Out-of-autoclave method is obtaining a product with low void content (less than 1 %) without using an autoclave. Without the high positive pressure curing environment, the alternative

equipment would not need to use compressed nitrogen and could be operated and maintained at a more economical cost. Thus, a convection oven can be used for the vacuum bag only (VBO) process. In comparison to the autoclave, an oven is much more cost-effective for the curing process. To achieve the low void content like the autoclave product, the prepreg for the oven curing VBO process are specifically designed with a different prepreg system for the entrapped air and breathing volatilise out during the curing process. The OoA prepreg is partially impregnated before curing so that the air permeability of the prepreg is not the same on the cross-sectional area, as it shows in Figure 2.2. Then the initial dry edge area of the OoA prepreg provides better extraction for the entrapped air and volatile, and the remaining part of the fibre reinforcement will wet out during the curing process, as Figure 2.3.

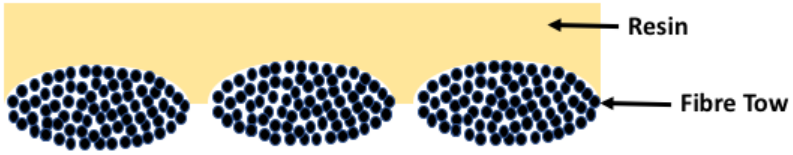


Figure 2.2: A sketch of OoA prepreg system before curing

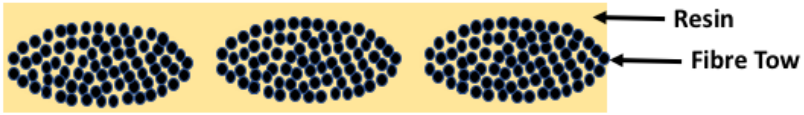


Figure 2.3: A sketch of OoA prepreg system after curing

The raw materials used in VBO processes are specifically designed OoA prepregs, which have an ensured uniform resin distribution, avoiding both dry spots and resin rich spots. During the manufacturing process, the vacuum bagging material types, and the stacking sequence are the same with autoclave curing. However, the vacuum quality plays a more critical role in the product. Presently, available OoA prepreg materials are equally expensive as prepreg materials that need to be cured in an autoclave to achieve equivalent quality like the autoclave product. However, for OoA the lower tooling cost and equipment cost provide a more economical solution compared to autoclave curing methods. VBO processes utilise the vacuum bagging materials, and oven curing equipment. The pros and cons are listed in Table 2.1.

Table 2.1: Pros and Cons for Vacuum Bag Only Process

Pros	Cons
Easy to use; Low investment; Long history of application in industry; Applicable to pre-forming and infusion processing; Multiple parts per cure cycle possible; Batch processing.	Long process time including heating and cooling; Lower heat transfer rates than an autoclave; Relatively high energy consumption; Batch processing per cure cycle.

Vacuum bagging method combined with oven curing is available to investigate fibre metal laminate processing. However, it needs to be used with an autoclave for the superior mechanical properties. For GLARE laminates fabrication, both composite prepreg and thin aluminium sheets are stacked in an alternating fashion on the tooling surface and then cured in an autoclave with the curing cycle of continuously high pressure (maximum 6 bar) and curing temperature of 120 °C [7]. The autoclave provides a high-pressure environment facilitating the air and emission dissolution during the process. This reduces the void content of the product, allowing the product to achieve the excellent mechanical property for aerospace structure. An autoclave curing method is a mature technology to offer high quality products, but is costly to purchase, operate and maintain in comparison with other curing methods.

2.2.2. Resin Transfer Moulding (RTM)

Resin Transfer Moulding (RTM) is a closed mould and out-of-autoclave (OoA) composite manufacturing process. In a RTM process, the resin and fibres are separated as raw materials. Resin Transfer Moulding (RTM) is a technique for fabricating complicated composite structures, with precise dimensional tolerance, high strength, and the process provides excellent product quality for aerospace applications. The RTM process begins with placing the dry fibre preform in the mould, then the moulds are closed and clamped or placed in a press. A resin in liquid state is injected into the moulds (typically at high pressures between 5–7 bar), displacing the air and venting it at the edges of the closed mould. The mould and resin can be preheated before injection, or the mould can be heated after injection to cure the resin. The typical RTM process setup is illustrated in Figure 2.4.

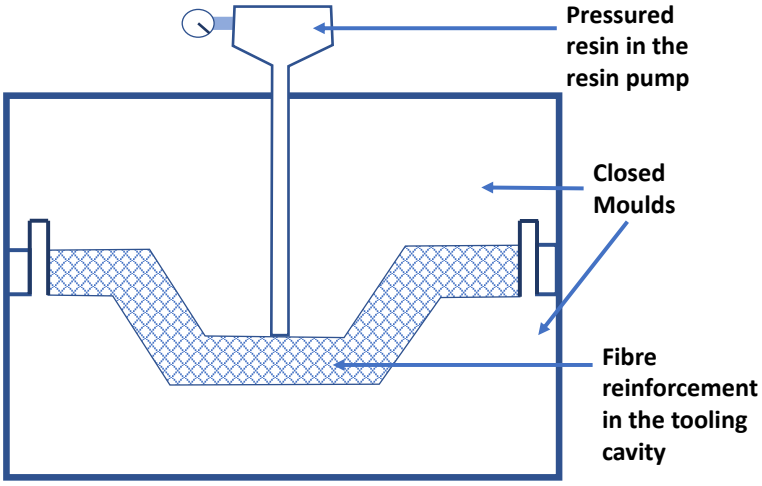


Figure 2.4: A sketch of RTM process Setup sketch with closed mould and resin pump

Research on RTM FML has been conducted experimentally in the past. Experiments on RTM manufacturing FML product might be possible, and the fibre volume content is relatively high like 50% to 60% [5]. However, there is not much literature published about RTM processing FML details.

2.2.3. Vacuum Assisted Resin Moulding (VARTM)

Vacuum Assisted Resin Transfer Moulding (VARTM) is similar to RTM process with closed moulds, but with a vacuum bag sealing on the top of the stiff moulds to assist the mechanical clamping [8]. The VARTM process setup is described in Figure 2.5. In VARTM process, a double matched mould is applied to create a cavity for the dry fibre preform. Instead of the high pressure (commonly 700 kPa) resin injection used in RTM process, VARTM process utilises the vacuum to facilitate resin flow into a fibre layup by using the vacuum bagging method. After the impregnation, the composite part can be cured at a high temperature in an oven with an optional post cure. Compared with RTM process, VARTM process achieves the fibre impregnation at lower pressure level(vacuum) with the use of the vacuum bagging application and results in the fibre volume fractions of 50 % to 60 % of the final composite product [9].

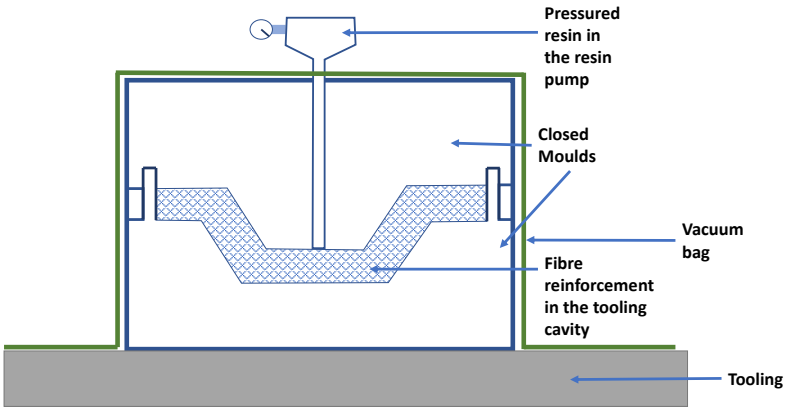


Figure 2.5: A sketch of VARTM setup with vacuum bagging and resin pump

VARTM has been applied for manufacturing FML at NASA Langley Research Centre in 2009 [10]. However, the process in that research uses perforated thin aluminium sheets with hole diameters of 0.4 mm to create flow pathways for the resin to impregnate the fibre laminates. The VARTM process can be seen in Figure 2.6. The result of that research shows the possibility of resin infusion through this method. But for the conventional GLARE structure, the holes in the metal sheet act as crack initiators demonstrated in durability tests [11].

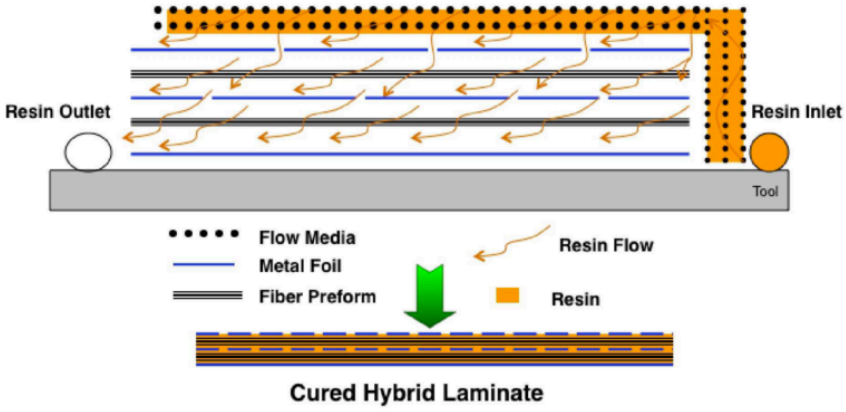


Figure 2.6: VARTM process illustration from courtesy of the NASA Langley Research Centre in 2009 [10]

2.2.4. Vacuum Infusion Process (VI process)

The Vacuum Infusion (VI) process is a method of manufacturing laminates by preforming the dry fibre reinforcement under vacuum and utilising the pressure differential to infuse the resin through the fibre preform. In the VI process, dry reinforcements are placed in the mould and a vacuum bag is sealing the reinforcement on the tooling surface, then vacuum is used to compact the dry fibre reinforcement and remove the air. Resin is introduced and the vacuum draws it through the reinforcement. The VI process setup is described in Figure 2.7.

The products made by the VI process have higher fibre volume content (typically 50 % -60 %) compared to other VBO processes (approximately 40 %) and lower void content (less than 1 %), which makes that the VI process produced parts show higher strength than most open-mould processed products with the same thickness. Lastly, the VI process is able to manufacture large, highly integrated structures at economic cost.

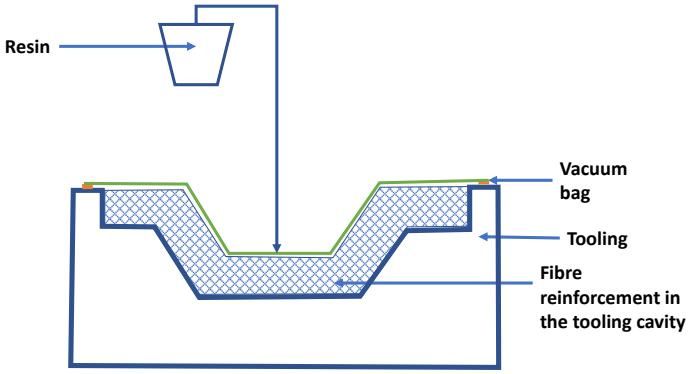


Figure 2.7: A sketch of VI process setup

2.3. Alternative manufacturing methods selection

The aim of this study is investigating an alternative manufacturing method for FML to reduce the fabrication cost while keeping a high fibre volume fraction and low void content.

2.3.1. Raw materials comparison

The VBO process relies on the OoA prepregs with special micro structural characteristics to obtain precise dimensional tolerances and low porosity. Therefore, the VBO process demonstrates the capability to fabricate the competitive components with autoclave-quality under oven curing. Prepregs consist of fibre reinforcement as thin sheets impregnated with the matrix resin. Usually, it has a limited shelf-life at a storage temperature of subzero. The pot life is also consumed during the thawing time before the prepreg is used. The manufacturing cost and the additional cost for packaging and handling is very high. Regarding the fact that the prepreg is expensive due to the pre-impregnation process, the straightforward idea is that the alternative plan can be based on dry fabric and neat resin. The prepreg cost, packaging and handling can potentially be reduced to 40%. There are a few concerns regarding these alternative materials. Thus, these factors are considered throughout this study. One concern would be whether the fibre volume content would be too low, this could be solved by selecting a proper processing route. Changing the manufacturing route will also influence the cost. Then a study on the state-of-art of Out-of-autoclave methods is performed, which is not necessarily using prepreg.

2.3.2. Tooling comparison

Both RTM and VARTM processes use a closed mould consisting of two matching moulds (female and male) during the manufacturing. Typically, the moulds for RTM process are mechanically clamped, and VARTM process mould is vacuum clamped. Eventually, the resin is injected using vacuum assist into the mould cavity for both methods. With the higher pressures applied during the process and strict tolerance for matching tooling set, the tooling cost is also increased for larger mass and more precise manufacturing and even larger storage space demanded. The tooling used in VBO and VI processes are open moulds which are single-sided male or female mould, which are significantly smaller mass and easy producing.

2.3.3. Equipment comparison

A conventional oven is the important equipment used for OoA composite curing during the manufacturing process. An oven has lower capital investment, operation and maintenance cost than an autoclave.

2.3.4. Cycle time comparison

The cycle time for autoclave curing usually is about 6 hours or longer. It is relatively long processing time, but not unacceptable because a batch of products with the same cure cycle could be cured together. However, a long cycle time increases the tooling cost for curing large batches for mass

production. The investment of the tooling and equipment is one of the major cost drivers during the autoclave fabrication [3].

VBO process with OoA prepreg might need longer cycle times for achieving a product with a low void content by slowly extracting the entrapped air. The cycle times are increased due to tool mass. These are a direct result of the need to overcome these higher moulding pressures. RTM and VARTM processes use closed mould sets, and these moulds have larger mass compared to the open mould which is used by VI and VBO processes. The larger mass of the mould also leads to longer cycle times set-up due to the heating up energy.

2.3.5. Overall comparison among Out-of-Autoclave (OoA) processes

In the previous sections, factors of equipment cost, tooling cost, cycle time and raw material cost are compared among the OoA processes mentioned in this study. Hereby, an overall comparison among the processes is performed to select a new routine for manufacturing FML. Factors about feasibility, materials cost, tooling are considered to perform the comparison with the traditional autoclave curing method and mentioned OoA methods. The factors are summarised in Table 2.2.

Table 2.2: Autoclave and Out of Autoclave composite manufacturing methods Process comparison table

Item	**Tooling**	**Raw materials**	**Equipment**	**Product quality for manufacturing FML**
Autoclave method	Open mould	Prepreg	Autoclave	Successful in commercial aircraft structure application[5]
VBO	Open mould	OoA prepreg	Oven and autoclave	part's quality with minimal void content (<1%)[4]
RTM	Closed moulds with joints	Dry fibre and resin	Resin pump and a press and oven (optional)	Void content too high[5]
VARTM	Closed moulds with vacuum clamp	Dry fibre and resin	Resin pump and oven (optional)	The holes with 0,4 mm diameter in the metal sheets act as crack initiators[10]
VI	Open mould	Dry fibre and resin	Oven (optional)	No research conducted yet

The result of the fibre volume fraction from autoclave methods is 13 % higher than the RTM methods due to extra pressure [12].

2.3.6. Research method selection

In general, RTM, VARTM and VI processes could be classified as members of the Liquid Composite Moulding (LCM) principle. Contrary to the prepregs, the fibre reinforcement are initially dry, and resin as matrix material must be injected or drawn through the fibres during processing. The impregnation driving force in LCM is usually provided by pressure difference. Resin transfer moulding (RTM) and Vacuum Assisted Resin Transfer Moulding (VARTM) utilises relatively high processing pressures from the inlet resin feed line, where the inlet pressure in VI process is the atmospheric pressure level. High operating pressure techniques require matched moulding (two or more part moulds) in RTM and VARTM, while vacuum infusion is usually done using a flexible membrane (e.g. polymer foil) on the mould. These technologies are popular for its economic effect and large product size [3]. The pros and cons are listed in Table 2.3.

Table 2.3: Pros and cons for LCM processing

Pros	Cons
Cheaper raw materials compared with prepreg; Can be combined with various heating and curing equipment; Large size and complex configuration of product.	Difficult resin flow prediction For pressurised systems (RTM): - Tooling investment is high - Long cycle time For vacuum based systems: -Only single side of tooling surface -Leakage is fatal to the product.

Vacuum infusion process has the similar experimental set-up of open mould combining with vacuum bagging method like VARTM method. However, the infused resin is not pressurised. So far, no preliminary studies are focusing on VI fabricating the FML. Therefore, the processing viability is an interesting topic to be explored in this study. The process is also well known for the potential unpredictable resin flow behaviour, and its complexity for positioning the resin feed and the vacuum lines, and high risk of failing in the vacuum system integrity.

2.4. A brief description of Darcy's law

This section gives a short description of Darcy's law. Later, in Chapter 3 Darcy's law is used to estimate the infusion of the plates with a fixed length of 50 cm, and to identify the parameters that influence the infusion process most. Research has shown that the flow of a liquid through a permeable medium can be defined by a relationship, which is known as Darcy's law[13]. Darcy's law can be expressed by the equation 2.1

$$q = \frac{KA(p_1 - p_2)}{\mu l} \tag{2.1}$$

In Equation 2.1, q represents the volume of flow rate, K represents the permeability of the dry fibre reinforcement, A is the cross-section area where the resin flow is travelling through, $p_1 - p_2$ represents pressure difference across the laminate length. μ is a dynamic value represents the value of the resin viscosity, l is the distance that the resin has to infuse[1]. The permeability of the dry fibre preform is one of the main factors influencing the infusion speed and distance in the laminate. Permeability is defined as "the property of something that can be pervaded by a liquid" [14]. From Equation 2.1, the variables are identified influencing the vacuum infusion process. By adjusting these variables during the experiments, the vacuum infusion process for FML can be altered to overcome problems, and optimise results. Thus, these variables are used for the process control to guide the experiment design in this study.

2.5. Infusion process monitoring

During the infusion experiments, the resin front line positions could be observed by human eyes through the glass plates, so the resin front line positions are recorded every 2 minutes after the infusion starts. As the resin travels away from the inlet, it will encounter resistance from the reinforcement, and eventually slow down. It is always important to monitor resin flow paths over time. This can be done with a stop watch, and a marker. The timer is started when the resin is first introduced into the laminate. At regular intervals, the bag is marked for the resin's position. This information is especially helpful for further infusion experiments to determine whether small changes in the set-up have a noticeable effect. And the vacuum level is constantly checked and recorded during the process to ensure that the vacuum bag is not leaking.

2.6. Visual inspection

A fundamental and essential inspection method for composite products is visual inspection. Impact damage or severe dis-bonding would be spotted during visual inspection with a good light source. Thickness is one of the basic physical properties used to control the quality of many textiles and synthetics. In this study, thickness measurement is performed after the fully cured samples obtained.

A film thickness measurement gauge of Model AK 63 from the company Karl Frank Weinheim Birkenau is used to record the thickness result, as it is illustrated in Figure 2.8. This equipment is easy to operate and the thickness of the samples can be measured with an accuracy of 0.01 mm for the range of the thickness up to 10 mm.

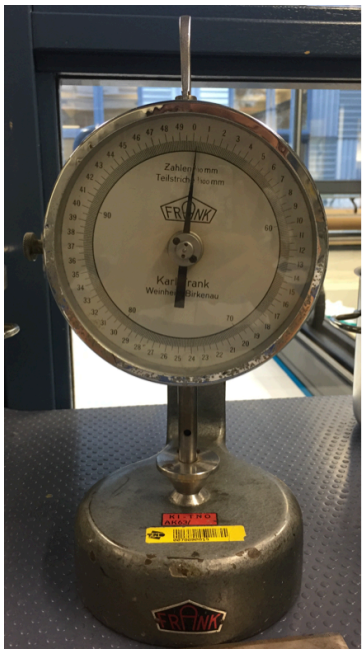


Figure 2.8: Thickness Gauge

2.7. Fibre volume content and void content inspection

Optical microscopy is used to determine the fibre volume content and void content for multiple samples. Each sample is cut into squares with the size of approximately 1.5 cm by 1.5 cm for the microscopy samples. The cross sectional photos would be taken and Leica QWin software is used to detect the fibre volume content and the void content. Samples of composite layers are prepared according to the instruction manual, well sanded and polished to eliminate the scratches on the cross-sectional surface. Leica QWin software is an image processing and analysis software which is designed to solve quantitative analysis tasks on the photo graph obtained from external equipment. Leica QWin provides the measurement of the volume fraction of the fibres, resin and void contents of the cross sectional samples. Pictures of the samples cross section are taken and measured by Leica QWin software.

3

Darcy's law: a theoretical parameter sensitivity analysis

3.1. An introduction to Darcy's law

Vacuum infusion process is typically performed in such a way that the resin can flow through the thickness. This results in a significantly shorter infusion time then infusing over the length of the part. To accommodate a through the thickness infusion an flow mesh is used. A flow mesh is a typical consumable material during the conventional vacuum infusion process, which promotes the resin to distribute and flow over the reinforcement preform area. Usually the flow mesh is a net structure made of knitted plastic wires or cast plastic film. However, in this study, the resin infusion has to infuse the composite layers over the length of the aluminium sheets for FML structure, thus, the flow mesh is absent in the process, and the resin is infused following the direction from the resin inlet to outlet.

The flow of a steady 1-dimensional liquid flow through a permeable medium can be defined by a relationship, which is known as Darcy's law [13]. Darcy's law can be expressed by Equation,

$$q = \frac{KA \cdot \Delta P}{\mu l} \tag{3.1}$$

in which, q represents the volume of flow rate, K represents the permeability of the dry fibre reinforcement, A is the cross-section area where the resin flow is travelling through, ΔP represents pressure difference across the laminate length. μ is a dynamic value representing the resin viscosity, l is the distance that the resin has to travel [1]. In SI units, the flow rate of 1 m^3/s, is defined as a fluid flowing through a permeable medium with a permeability of 1 μm^2, a cross-sectional area of 1 m^2, and fluid viscosity of 1 $Pa.s$ under a pressure gradient of 1000 Pa/m. Equation 3.1 can be rewritten as follows,

$$\frac{dl}{dt} = \frac{K}{\mu\varepsilon}\frac{\Delta P(t)}{l(t)} \tag{3.2}$$

in which the flow though the porous medium is described as a function of time. In this equation ε is the porosity. When integrating Equation 3.2 and substituting the fibre volume percent for the porosity, it is possible to obtain a theoretical estimate for the infusion time for the infusion distance l with the following equation [15],

$$t = \frac{l^2 \cdot \mu}{2K} \cdot \frac{(1 - V_f)}{\Delta P} \tag{3.3}$$

In this equation V_f is the fibre volume fraction. ΔP can be described with the following equation

$$\Delta P = P_a - P_{out}, \tag{3.4}$$

in which P_a is the ambient pressure, and P_{out} is the applied vacuum pressure at the outlet. The capillary driving pressure was neglected in the estimate.

3.2. Sensitivity of infusion parameters on the infusion time

In this section, the sensitivity on the infusion time is studied for the change in resin viscosity, permeability [14], applied vacuum level and fibre volume fraction. At the end of this section the main parameters driving the infusion speed for a pre-determined length of 50 cm are identified, and the results are extrapolated for infusing a 300 cm part. In Table 3.1 an overview is shown of parameters that influence the infusion time defined by Equation 3.3. The same table shows some typical value ranges for the parameters. These ranges will be used to find their influence on the infusion time.

Table 3.1: Selection of parameters influencing the infusion time according to Darcy's law in Equation 3.3.

Parameter	**Symbol**	**Range**	**Comments**
Resin viscosity	μ	130 - 1040 [mPas] [16]	Depends on resin and T [K]
Permeability	K	$5 * 10^{-10} - 10^{-10}$ $[m^2]$ [17–19]	In-plane flow
Vacuum level	P_{out}	50 - 500 [mBar]	Applied outlet vacuum
Fibre volume fraction	V_f	0.40 - 0.60 [-]	N/A
Infusion distance	l	0.5 [m]	Taken as a starting point

In order to study how sensitive the infusion time is to the different process parameters, a reference case with corresponding parameter values is used in Table 3.2. In Section 3.2.1, this sensitivity is studied by altering one parameter at a time for a fixed infusion distance of 50 cm and plotting the infusion distance with respect to the time.

Table 3.2: Reference values taken for estimating infusion time with Equation 3.3.

Parameter	**Reference value**	**Figure addressing parameter change**
l	0.5 [m]	N/A
K	10^{-10} $[m^2]$	Figure 3.1
P_{out}	50 [mBar]	Figure 3.2
μ	520 [mPas]	Figure 3.3
V_f	0.5 [-]	Figure 3.4

3.2.1. Results

Figure 3.1 shows the sensitivity of the infusion time on the change of the permeability, while all other parameters are kept constant and equal to the reference case shown in Table 3.2. The permeability value is shown for the range of $5 \cdot 10^{-10}$ to 10^{-10} m^2. It can be seen that when the permeability is improved with a factor 2 from 10^{-10} to $2 \cdot 10^{-10}$, the infusion time halves from 60 min to 30 min. Further improving the permeability with also further decreases the infusion time with the same factor. Thus, the permeability is a very important factor.

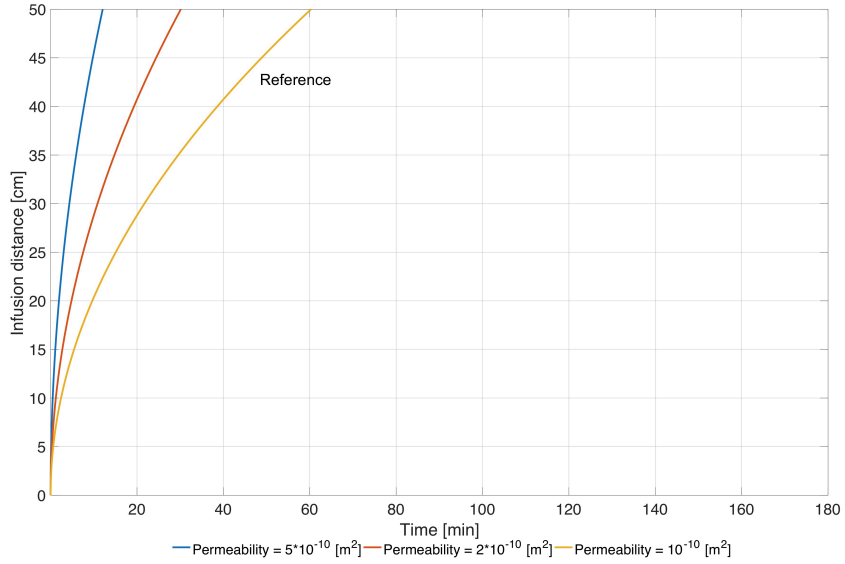


Figure 3.1: Calculated infusion time for a 50 cm infusion distance using Equation 3.3. Permeability value is changed from the reference value to understand the influence on the infusion time.

Figure 3.2 shows the sensitivity of the infusion time on the change of the applied vacuum level, while all other parameters are kept constant and equal to the reference case shown in Table 3.2. It can be seen that for a vacuum infusion with an applied vacuum level of 50 mBar the infusion time is 60 min, increasing vacuum level with a factor 2 to 100 mBar, slightly affects the infusion time with only 4 min. When changing the vacuum to 500 mBar the infusion time is decreased significantly to 115 min. However for such high vacuum levels it can be expected to that the vacuum bag is not tight anymore and may introduce resin runners.

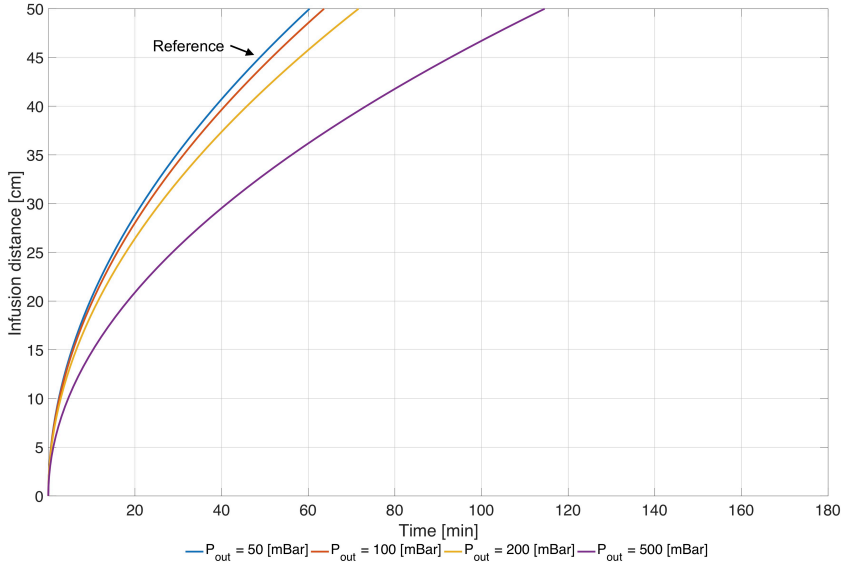


Figure 3.2: Calculated infusion time for a 50 cm infusion distance using Equation 3.3. The applied vacuum level value is changed from the reference value to understand the influence on the infusion time.

In Figure 3.3 the sensitivity of the infusion time on the change of resin viscosity is shown, while all other parameters are kept constant and equal to the reference case shown in Table 3.2. It must be noted that the pot life of a resin is not taken into account for the calculation. It can be seen that approximately reducing the viscosity by 50 % of the resin by for example heating up the resin or by selecting a low viscosity resin, highly impacts the infusion time. When lowering the viscosity from 520

mBar with a factor 2, also the infusion time reduces with a factor 2. However, it must be noted that when a resin is used at an elevated temperature also the pot life reduces significantly. Thus, when selecting a strategy to change the viscosity, this must be taken into account.

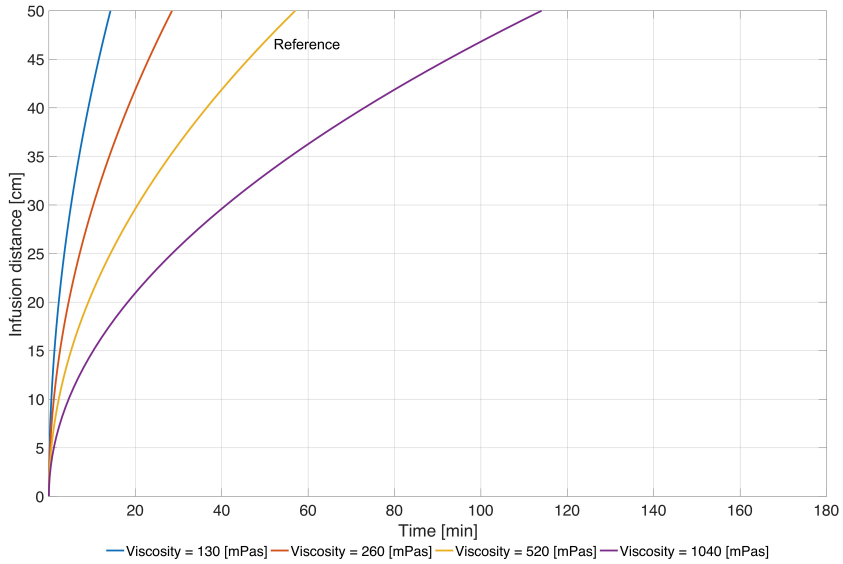


Figure 3.3: Calculated infusion time for a 50 cm infusion distance using Equation 3.3. The viscosity value is changed from the reference value to understand the influence on the infusion time.

Figure 3.4 shows the sensitivity of the infusion time on the change on the fibre volume fraction (called porosity in Darcy's law), while all other parameters are kept constant and equal to the reference case shown in Table 3.2. When taking a fibre volume fraction of 0.50, which is very normal for a vacuum infusion, the infusion time can be calculated to be 64 min. There is not that much room for change in fibre volume fraction. The higher the fraction of fibres the faster the infusion. However a fibre volume fraction higher than approximately 0.60 cannot be achieved with vacuum infusion. The change in infusion time from a fibre volume fraction of 0.50 to 0.60 is only 7 min.

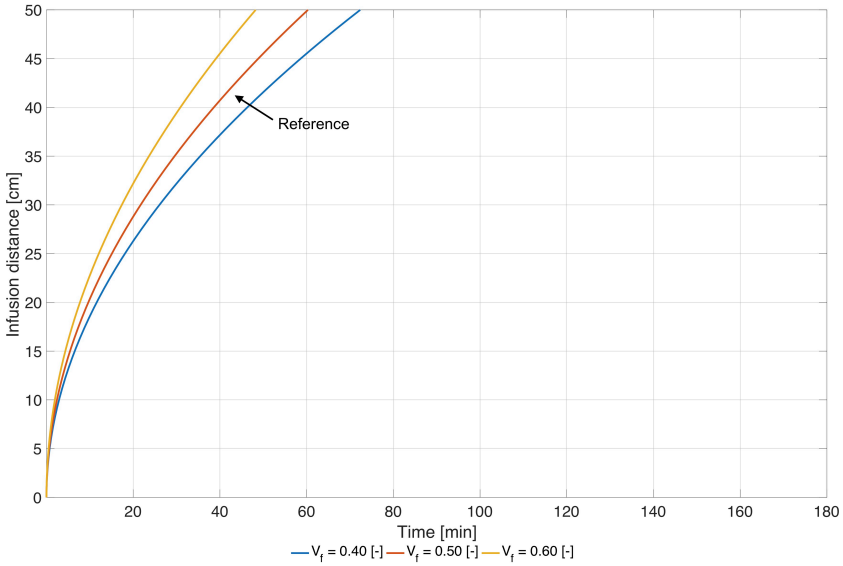


Figure 3.4: Calculated infusion time for a 50 cm infusion distance using Equation 3.3. The parameter values are taken from the Table 3.2 as a reference. The fibre volume fraction was changed from the reference value to understand the influence on the infusion time.

In Table 3.3 the best combination of the parameter values that decreased the infusion time are sum-

marised. These values can be seen to be realistic, but also optimistic. These values are used in Figure 3.5 to extrapolate the potential for infusing larger structures.

Table 3.3: Infusion parameter values found to give a shorter infusion time. The ideal (theoretical) case.

Parameter	Ideal value
μ	130 [mPas]
K	$5 \cdot 10^{-10}$ $[m^2]$
V_f	0.6 [-]
P_{out}	50 [mBar]

In Figure 3.5 the infusion time is plotted for the reference values from Table 3.2 and for the improved case with parameter values found to reduce the infusion time from Table 3.3. The infusion distance on the Y-axis is shown up to 300 cm, to get a feeling for infusion larger structures. It can be seen that to infuse a 50 cm structure for the reference it takes 60 min, while for the improved case in theory it takes approximately 4.5 min. Even in the most ideal case the figure shows that for infusing a distance of 300 cm it will take at least 2.5 hours. Which is a very long infusion time, and would require a thorough study on resins that have a low viscosity and a long pot life to avoid gelling before the infusion finished.

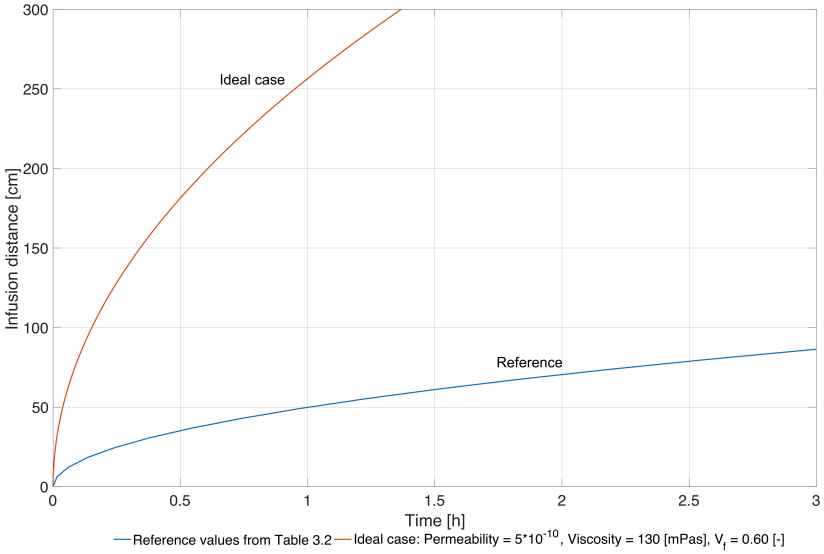


Figure 3.5: Calculated infusion time for a 300 cm infusion distance using Equation 3.3 for the reference case from Table 3.2 and the improved case from Table 3.3.

3.2.2. Discussion

The results presented in Section 3.2.1 showed that the permeability of the preform has a large impact on the infusion time. Selecting a preform with a high permeability will lead to the shortest infusion times. Since this parameter has such a large impact in the infusion time, it crucial to select a suitable preform. The applied vacuum level on the other hand has less impact on the infusion time. Changing the vacuum from 100 mBar to 50 mBar only reduces the infusion with a couple of minutes on a total infusion time of around 60 min. Thus, it can be concluded that applying a vacuum level even lower than 50 mBar will almost not affect the infusion process. When decreasing the vacuum level even lower, it might be possible that voids are created in the product due to extra degassing of the resin. The viscosity of the resin was found to have a very large impact on the infusion process. Therefore, it will be important to select a low viscosity resin. Besides, it might be helpful to elevate the temperature of the resin during the infusion to even lower the viscosity further. A problem that might arise is the fact that when increasing the temperature of the resin, the pot life reduces significantly. A rule-of-thumb is that the pot life of the resin reduces with a factor of 2 with every increase of 10 °C. The fibre volume fraction was found to have very limited effect on the infusion time. The fibre volume fraction to get an acceptable mechanical performance will be between 0.40 to 0.60, and the difference between these

cases on the infusion time is very low. When extrapolating the findings for the parameters values in the infusion time, it was found that even in the most ideal case it will take almost 1.5 hours to infusion over a distance of 300 cm, which might make it very challenging on infusion larger structures. Selecting the right preform with a high permeability together with low viscosity resin was also found to be crucial. The results obtained are experimentally tested in Chapters 6 by adjusting the infusion parameter values during experiments of infusion plates over a length of 50 cm. In Section 5.10 the experimental results are discussed and compared to the results in this Chapter.

4

Experimental Setup: Process Design and Development

This chapter describes the experimental setup of the vacuum infusion process focusing on manufacturing Fibre Metal Laminates in a laboratory environment. The materials selection, equipment, tooling and the process steps are explained.

4.1. Raw materials

FML structures consist of monolithic thin aluminium sheets and composites layers made from a fibre reinforced epoxy matrix. Currently, Glare is made of a prepreg consisting of unidirectional glass fibres and FM 94 adhesive resulting in a nominal fibre volume fraction of 59 % and a 0.127 mm-thickness. In the VI manufacturing process in this study, the composite layers are made by infusing dry fibre glass sheets in the form of unidirectional tapes with an epoxy resin.

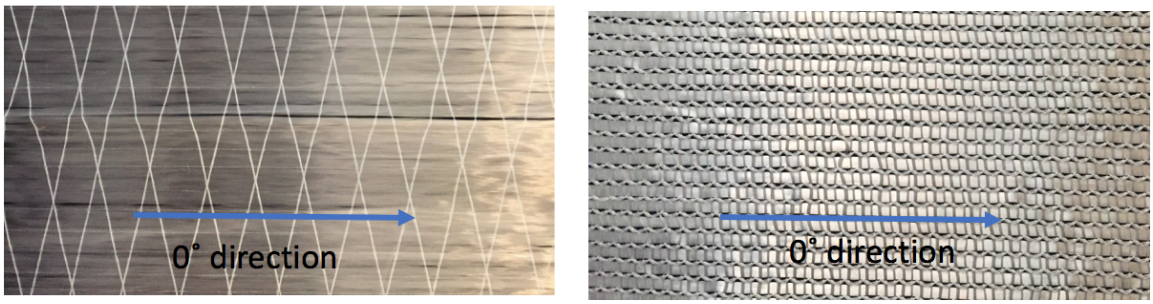
4.1.1. Reinforcement selection

The reinforcement is provided in the form of dry glass fibre unidirectional tapes. Two types of unidirectional fibreglass tapes were used in this study. SAP 4593, shown in Figure 4.1a, unidirectional (UD) tape is represented with the product number of U-V-E-228 g/m^2, from the company of SAERTEX, with areal weight of 228 g/m^2 [20]. SAP 4593 unidirectional tapes have NonWoven unidirectional tape structure. The fibres are aligned uniformly in transverse direction and there are Nylon wires holding the fibres on one side of the fibre sheet. SAP 3318 unidirectional tape, shown in Figure 4.1b, has the product number of U-E-397 g/m^2, also from the company of SAERTEX. The areal weight of the material is 397 g/m^2 [21]. The unidirectional tows are oriented along the warp direction of the sheet and bound together by continuous stitches. The fibre tows are twice as wide as the gaps in-between the tows. Some technical data of the material SAP 4593 and SAP 3318 are presented in Table 4.1.

Table 4.1: Technical Data of Dry Fibreglass materials [20, 21]

Item	**Supplier Information with areal weight**	**Ply thickness**
Type 1 Unidirectional Tape	Supplier code: U-V-E-228 E-fibreglass (Width 1500mm), SAERTEX	0.25 mm
Type 2 Unidirectional Tape	Supplier code: U-E-397 E-fibreglass (Width 635mm), SAERTEX	0.37 mm

When comparing the two yarn structures shown in Figure 4.1, it seems that Type 2 in Figure 4.1b has a better permeability compared to the yarn structure of Type 1 in Figure 4.1a. The stitchings to keep the fibre bundles together in Figure 4.1b create channels in between the 0° fibre bundles supporting the flow of resin. Therefore, it can be expected that the Type 2 fibre preform can be infused in a shorten infusion time.



(a) Type 1 UD tape: SAP 4593

(b) Type 2 UD tape: SAP 3318

Figure 4.1: Yarn structure photo of dry glass fibre UD-tape

4.1.2. Resin selection

The resin selection is another key aspect of the VI process. Typically, a low viscosity will benefit the infusion, as it infuses easier into the reinforcement. Epikote resin 04908 is selected for this study because of the low viscosity with excellent wetting and adhesion characteristics on dry fibreglass. Epikote resin 04908 with the curing agent Epikure 04908 is a low viscous epoxy resin system, which is designed for infusion applications of fibre glass sheet. The processing temperature ranges between 25 °C to 35 °C. The curing time is 24 hours at room temperature or 4 to 6 hours at 80 °C [16]. The pot life is 300 ± 50 minutes at 25 °C. The pot life reduces with factor of 2 when the temperature rises at every 10 °C. The technical details of the resin and the hardener are summarised in Table 4.2. In Appendix A the pot life and the estimated viscosity of the resin are shown in three graphs for room temperature, $35°$C and $45°$C.

Table 4.2: Technical data of the resin and hardener used for experiments

Property	Unit	EPIKOTE Resin 04908	EPIKURE Curing Agent 04908
Viscosity at 25 °C	mPa·s	500±250	10±5
Density at 20 °C	g/cm^3	1.15±0.02	0.93±0.02
Mixing viscosity at 25 °C	mPa·s	130±10	
Pot life at 25 °C	minute	300±50	
Curing cycle	hour	24h at room temperature or 4 to 6h at 80 °C	

4.1.3. Aluminium sheets selection

To obtain a homogeneous and even oxide surface, the aluminium sheets are anodised and then primed to improve the corrosion protection for further bonding. The same aluminium sheets of Al2024 with the thickness of 0.4 mm as for traditional Glare are chosen for this study.

4.2. Consumables

Consumable materials have been used throughout the entire manufacturing process to provide an airtight vacuum bag, and making sure not to contaminate the fabrication environment with resin or fibres. The type and amount of required consumables in this study, is based on several trials, and specifically chosen for the VI process. The selection is listed in Table 4.3.

Table 4.3: Consumables list

Item	Supplier and Model number	Description
Vacuum foil	Airtech WL5400	Airtech WL 5400 foil is an aerospace-grade, multi-layer mono nylon vacuum bagging film suitable for cure temperatures up to 150°C.
Tacky tape	Airtech	Tacky tapes are used to hold and seal the bagging medium to the tooling surface. 150°C tacky tapes are selected for this project.
Pressure Sensitive Tape	Airtech Flashbreaker 1	The pressure sensitive tapes are used for holding down the raw materials, consumables and position thermocouples during the vacuum bagging process.
Ventilation Materials	Saertex	The essential requirements of a good breather/bleeder for the fabric are temperature resistant, adequate to withstand the required curing temperatures; good drape ability enabling it to form closely to the contours of the mould and good permeability to solvent vapours.
Release Agent	Marbocote 227	Release Agent is used for providing a solution to prevent the composite bonding to the tooling surface relevant for the de-moulding process.
Flow Mesh	DIANET HT	Flow mesh is a knitted thermoplastic membrane supplied for providing a high permeability resin path.
Release Film	Airtech	Release films serve the purpose of preventing foreign materials, from becoming integrated into the finished product.
Spatula	N/A	Spatula made of wooden sticks in the size of Width of 3cm and Lenght of 20cm and Thickness of 0.5cm are used to mix resin and the hardener.
Markers	N/A	Markers are used for marking the resin flow front position and profile.
Inlet and outlet tubes	N/A	Vinyl tubes are usually used for inlet and outlet tubes which are strong and flexible to resist collapse under vacuum application during the infusion, with 10 mm inner diameter allowing for maximum flow during infusing process.
Tube Line Clamp	N/A	Resin Infusion Tube Line Clamps are used to clamp the inlet and outlet tubes during certain parts of the vacuum infusion or vacuum bagging processes.

4.3. Equipment

The equipment used during the vacuum infusion process is listed in Table 4.4.

Table 4.4: Equipment and tooling list

Item	Description
Vacuum pump	The vacuum pump is used for creating the vacuum level in the vacuum bag. There is a vacuum gauge which is connected to the vacuum pump to measure and monitor the vacuum level inside the vacuum bag.
Resin Trap	A resin trap is placed at the vacuum line to contain the excess resin in case that the resin could damage or destroy the vacuum pump.
Tooling table	A specially designed table with glass plates and a mirror bottom for observing the infusion process is used in this study. The size of the glass table is W 100cm *L100 cm*H120 cm.
Glass Plates tooling	Glass plates with the dimensions of 20 cm width, 50 cm length and 1 cm thickness are used for this study to monitor the resin flow in the composite layers during the experiments.
Heat Blanket	To test various temperature influences on the infusion process, a heat blanket is used for providing a uniform temperature over the tooling.

4.4. Tooling and setup

The general experimental setup is illustrated in Figure 4.2. The study begins with a group of experiments aiming at adjusting the setup for a stable and reliable process, and then to develop the prototype of vacuum infusion method for fibre metal laminates. At the beginning of the experimental study, two glass plates are replacing the aluminium sheets in the FML structure to study the resin flow behaviour during the infusion process. The glass plates are transparent, which could be used to observe the fluid flowing through the reinforcement from both sides. In this study, experimental setups were made on an infusion demonstration table, as it is shown in Figure 4.3. This table consists of a glass plate on the top as the layup tooling and a mirror placed under an angle of 45 ° in order to monitor the resin flow behaviour through the glass plate. In this laboratory scale study, the composite samples are made in the form of rectangular layers with the size of 200 mm wide by 500 mm long, and the size of the square layup tooling table has sides of 750 mm long.

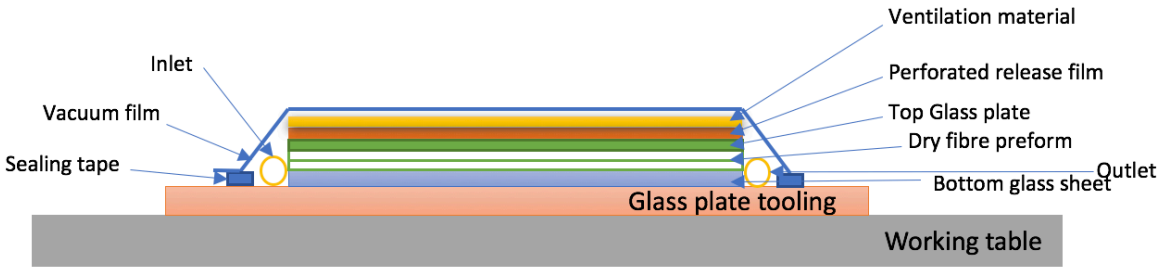


Figure 4.2: Experiment setup schematic sketch

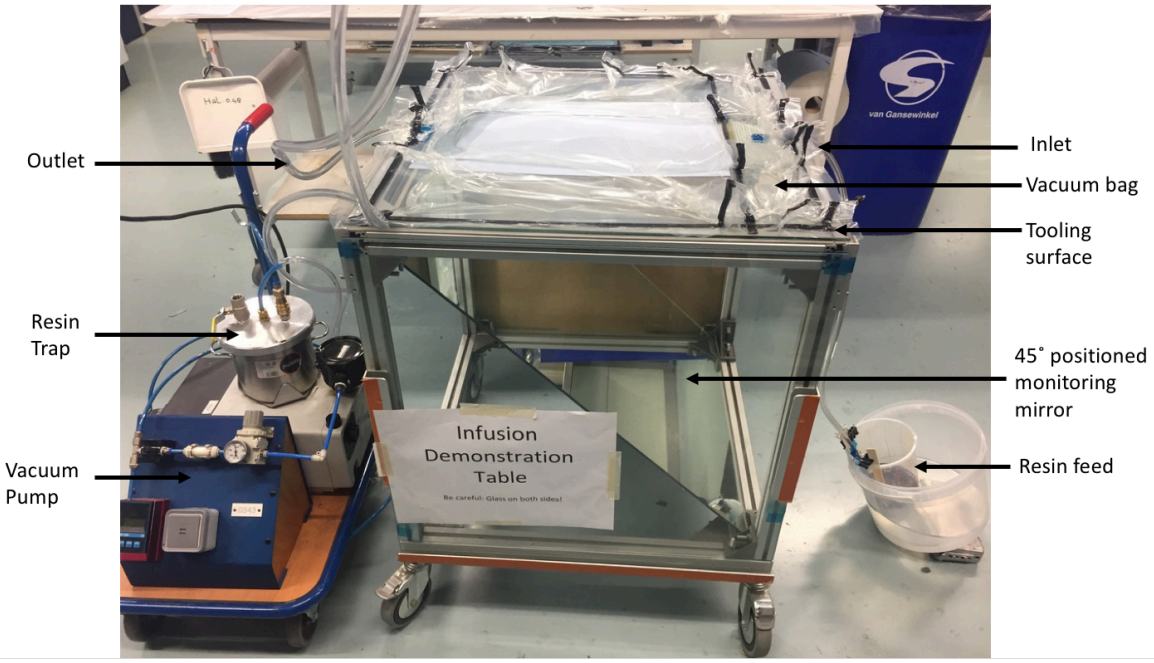


Figure 4.3: Experiment setup of VIFML

4.5. Process steps

VI process utilises the pressure difference between the environmental air pressure and the vacuum level created in the vacuum bag. The applied vacuum compacts the dry fibre preform to the open mould, and draws the resin into the fibre preform. A step-by-step VI manufacturing process is described below, followed by a detailed explanation of the experiments.

- **Step 1: Tooling preparation**

  The glass plate used as layup tooling should be rigid and have a good surface finish without any visible damage, because the damage could cause leakage or unacceptable product surface defects. The size of the tooling should provide a large enough area for the placement of sealing tapes and infusion tubes. The tooling should be cleaned by using resin removal agent and methanol to remove the contamination and grease. The release agent Marbocote 220 is applied on the tooling surface after cleaning to be able to remove the infused product from the tooling.

- **Step 2: Raw material preparation**

  Two types of unidirectional tapes are chosen as the reinforcement material in the vacuum infusion. The dry fibre glass, and the aluminium sheet will be trimmed to the desired size and shape. For the dry fibres this is done by an automated Gerber prepreg cutting machine.

- **Step 3: Resin feed lines and Vacuum lines setup**

  Resin will be supplied from a standing bucket which is also used to mix and degas the resin. The resin feed line is placed in the bucket for getting the resin into the laminate. The resin feed line has to be installed before finishing the vacuum bag. The vacuum lines are extended within the sealed bag. In order to achieve continuous and complete infusion throughout the entire laminate, the resin must flow to all corners of the laminate.

- **Step 4: Layup and vacuum bag building**

  The dry fibre pre-from and the aluminium sheet are placed on the tooling in the predetermined sequence and orientations. Subsequently, the vacuum bag is built. The vacuum bag should offer sufficient space for the tubes, but should not have large wrinkles, that can potentially facilitate resin runners. The vacuum bag should also be fully air tight. After the preparation of the vacuum bag is completed, the vacuum line and the resin feed line can be connected. The resin always

tends to fill in the open spaces that are still present under the vacuum, and the resin takes the path with least resistance. So sufficient pleats should be made around the edges of the vacuum bag, hence, there will be sufficient amount of the vacuum bagging film, which could be tacked into all the existing bridging corners of the open mould. As a result, the potential resin runners are eliminated in the vacuum bag.

- **Step 5: Vacuum pump connection and leaking check**

  The resin is infused from the inlet by applying vacuum on the outlet by a vacuum pump. Attaching the vacuum pump and ensuring proper vacuum are important steps to be conducted. The vacuum level applied on the outlet is maintained at 50 mBar during the infusion process, the value of 50 mBar is commonly used for VI process in laboratory tests and commercial usage. Once the vacuum pump is attached, the vacuum should be switched on, and any possible leakage needs to be found before starting the infusion. This is required for the further infusion performance and the product quality.

- **Step 6: Resin preparation**

  A two component epoxy including Epikote 04908 and the corresponding hardener Epicure 04908 is used for infusion. This is a low viscosity resin typically used for vacuum infusion processes. Epikote 04908 and Epicure 04908 mixture has a pot life of approximately 300 min at room temperature, and the capability of de-moulding in 24 hours at room temperature. Once everything from the previous steps is ready, the resin can be mixed with the hardener according to the ratio given by the manufacturer and the mixture can be degassed.

- **Step 7: Infusion**

  The resin bucket is connected to the resin feed line, and the inlet is opened to start the infusion. The resin should flow through the resin feed line, and get into the vacuum bag quickly. The resin is allowed to travel until the entire laminate is saturated, and sufficient resin exited into the resin outlet. It should be visible that the resin travels through the entire product and flows into the outlet tube for at least 30 cm in length. Then the resin feed line should be closed again, and then the vacuum level at the outlet should be decreased to 500 mBar, therefore, the pressure gradient over the laminate between the resin feed line and the vacuum line could be eliminated. The vacuum level should be maintained at 500 mBar to stabilise the uniform pressure over the laminate until the resin sufficiently cured.

- **Step 8: Curing**

  According to the technical sheet of Epoxy 04908, curing time is 24 hours at room temperature or 4 to 6 hour at 80 °C in the oven.

- **Step 9: De-moulding** After the product is cured, the vacuum pump is turned off, and the vacuum bag is removed to obtain the product. Afterwards the tooling is cleaned for the next experiment.

4.6. Preliminary goals to obtain a stable process

In this study, the process should become stable to produce fully cured products without severe debonding or delamination, the fibre volume content would be expected to be minimum 55 % and the void content should be at most 2 %.

4.7. Development of the experimental setup improvement

The experiment setup introduced in Section 4.4 is the basic setup for the VI process. To achieve a stable and repeatable experimental setup for FML manufacturing, the vacuum bagging structure has been improved based on the fundamental vacuum bagging setup for VI processes. The problems and related solutions for the setup are explained in this section.

4.7.1. Flowmesh placement strategy

At the beginning, resin and vacuum lines are placed without the addition of any ”in bag extension material”, such as the spiral tubes. As a result, the resin will travel from the inlet to the outlet through a

very narrow path like sketched in Figure 4.4. Once the resin is infused and travelled through this narrow path to reach the outlet, the remaining area of the reinforcement would not get infused anymore, because the resin keeps flowing to the outlet to the resin trap following the path of the least resistance.

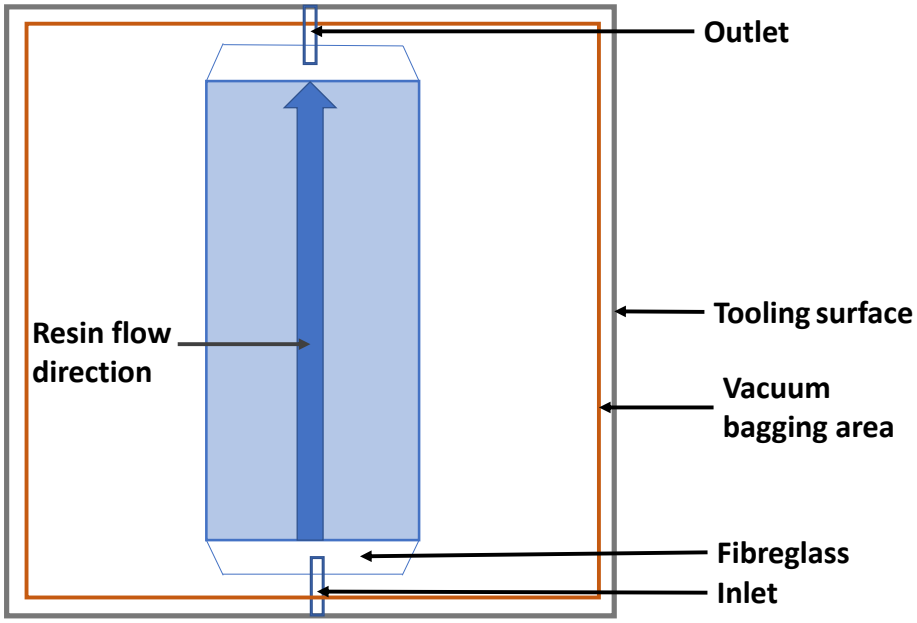


Figure 4.4: Resin infusion though a narrow path sketch

In general, spiral tubes are connected to the inlet and outlet to create a uniform front flow, as seen in Figure 4.5. In this study, spiral tubes also have an extra resin trap at the inlet area within the vacuum bag due to the FML sample's structure. The extra resin leads to unexpected leakage and also to the difficulty of demoulding.

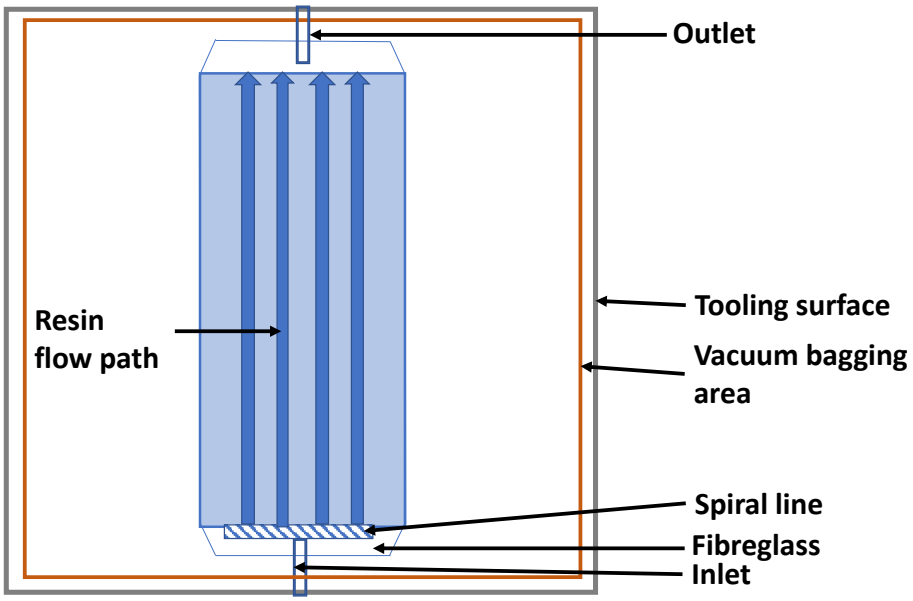


Figure 4.5: Vacuum infusion with the spiral line extension

Eventually, a small piece of flow mesh is placed over the fibre reinforcement at the inlet area to provide

a uniform resin front. This setup is demonstrated in Figure 4.6. The flow mesh could offer a fast route for the resin to infuse and it also promotes a uniform front by its own configuration.

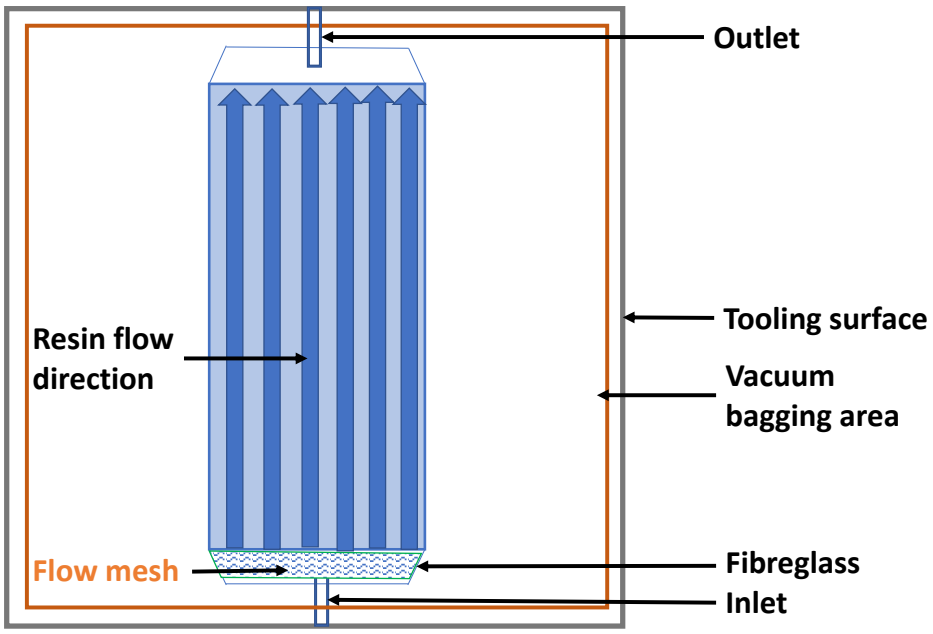


Figure 4.6: Vacuum infusion with partial flowmesh application sketch

4.7.2. Leak tightness control

Leakage is fatal to the composite product during the VI process. Once any leakage happens during the infusion process, the resin will flow to where the leakage occurs, and it will not follow the expected flow path within the fibre preform. Therefore, the dry fibreglass sheet would not get infused. In addition, the leakage would reduce the relative pressure at the resin front flow, which means there is no sufficient driving force to infuse the dry fibre preform. The leakage will also draw the already infused resin out of the fabric when the resin is still viscous. Thus, it can be concluded that a leakage check is essential to the vacuum infusion process. Detecting and sealing all the leaks is very important in this study before starting an infusion. A vacuum test over a 20 minute period is performed to ensure the infusion process can be conducted in a controlled way.

4.7.3. Edge dam, and automated cutting fibreglass

During the VI process, the resin tends to flow faster towards the area where the permeability is higher. The open space permeability is higher than the fabric permeability, thus, the resin would flow along the corner area along the glass plates radii or the aluminium plates during the infusion step. This phenomenon causes unexpected resin runners to the outlet without infusing the composite layers during the process. Therefore, a large dry area will be formed due to the resin runner issue like in Figure 4.7.

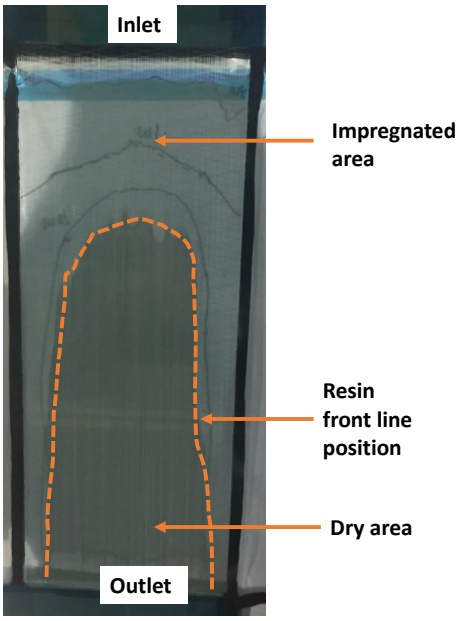


Figure 4.7: Photo of undesired runners occurred during VI process

The fibreglass sheet was previously trimmed by manual operation. This could not be performed very precisely. Therefore, the fibreglass sheet did not fit the glass plates or aluminium sheets perfectly, causing the resin to flow faster along the edges of the fibreglass sheet in between the two transparent glass plates or metal sheets. This resulted in a only partially infused fibreglass sheet. These two issues resulted in an unacceptable product. The misfit of the fibre sheet is easily solved by using an automated prepreg cutting machine instead of hand cutting. Furthermore, edge dams made of sealant tapes are applied along the sides of the plates to stop the resin that tends to fill in all possible corners. The edge dam are made of tacky tapes applied along the edge of the glass plates or aluminium sheets. In Figure 4.8 it can be seen that the edge dam separates the vacuum bagging area, and isolates the fibre sheet as the air appalling path through the area between glass plates. Hence, combining the usage of resin edge dam method and precisely cutting fibre sheet leads to better resin infusion result and less resin waste during the manufacturing process.

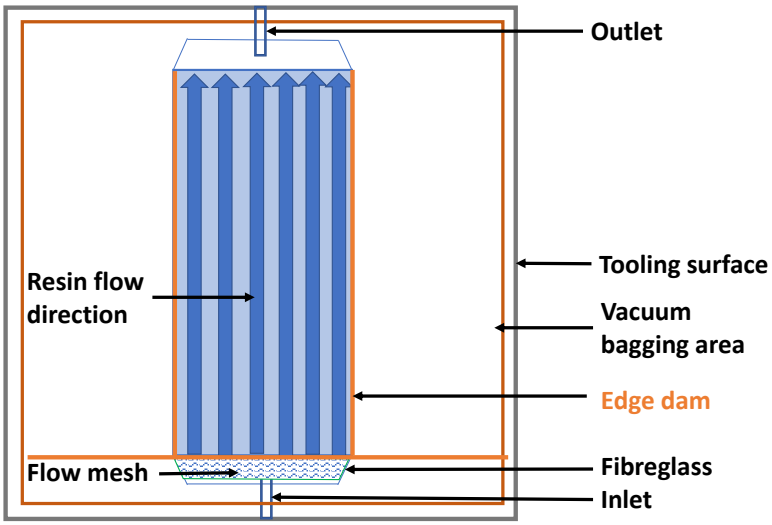


Figure 4.8: Vacuum infusion with edge dam in the vacuum bag application sketch

4.7.4. Vacuum bagging structure layout adjustment

The vacuum bagging process in this study is taking more effort than other vacuum bagging processes for the traditional autoclave methods for flat panels. For the traditional autoclave method, in general, the vacuum bagging film is 1.5 times larger than the compacting area, which could be used to form pleats along the circumstance of the bagging area. A pleat is a typical technique for folding the vacuum bagging film upon itself bonded together by tacky tapes, as shown in Figure 4.9.

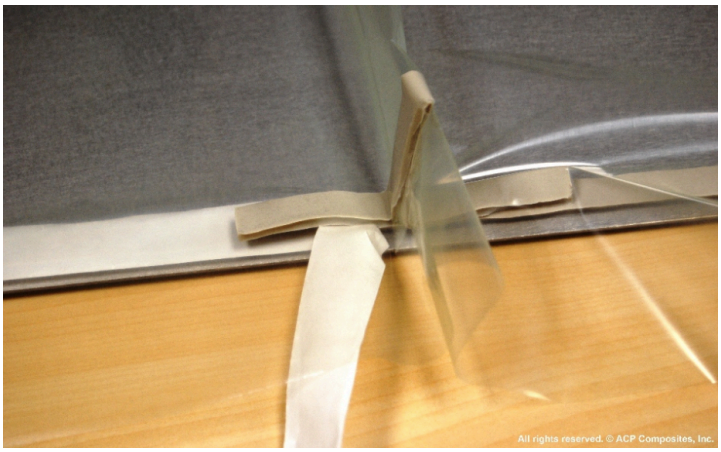


Figure 4.9: Vacuum Bag Pleats Photo [22]

Pleats assist the vacuum bagging foil to form uniformly along the parts profile, providing an even vacuum level over the product. Deciding the location of pleats before completely sealing the vacuum bagging foil is an easy strategy to prevent potential leakage or undesirable vacuum bag wrinkles. The issue of corner bridging is highly likely to occur when the vacuum bag is too tight. The usage of pleats is an excellent way to avoid this issue. Additionally, vacuum pleats and eliminating the leakage of the bag, completely isolate the fibreglass as the only ventilation material and resin flow path. Thus, pleats are more applied for the vacuum bagging of VI FML manufacturing than the conventional vacuum bagging method on the same contour of the tooling. Therefore, extra pleats are made to allow the vacuum bag to successfully seal along the edges, and to ensure the vacuum bagging film follows the product curve. Allowing all the vacuum bagging film to fill all the corners to ensure that a sufficient, and uniform pressure is applied on products surface.
In this study, more pleats are made along the edges of the samples to isolate the resin flow path through the fibre sheet. The final setup of the vacuum bagging structure is shown in Figure 4.10.

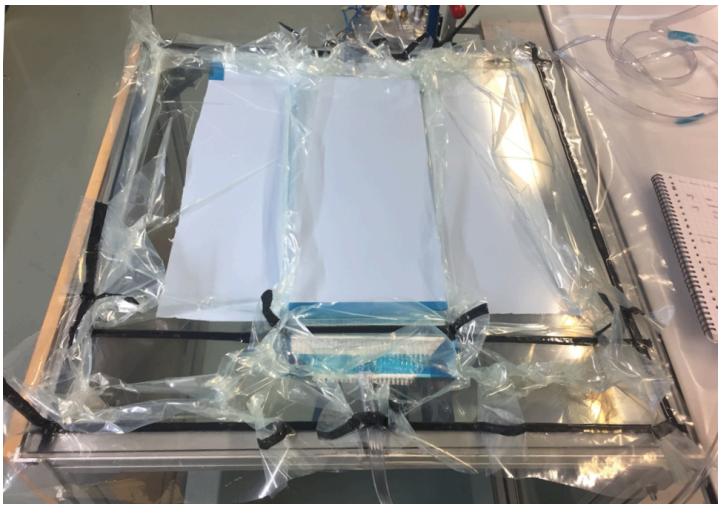


Figure 4.10: Vacuum bagging demonstration with extra pleats structure

The area of the vacuum bagging film is taken twice the size of the tooling surface for VIFML manufac-

turing. Firstly, an extra sealant tape is applied along the lateral direction of the resin flow direction to ensure that the fibres between aluminium plates are the only flow path material for the vacuum resin. As it can be seen in Figure 4.10, the extra sealant tape separated the vacuum bagging area into two separate parts where only limits the vacuum is applied through the fibre preform. It ensures that the resin will flow along the fibre preform and eliminate runners caused by big wrinkles on the vacuum foil. Secondly, extra pleats are made around the inlet and outlet tubes, each corner of the tooling surface and along the radii of the sample. These pleats provide sufficient vacuum foil which could be tacked into all the small open space on the tooling and the product. Thus, the potential runners can be prevented for the infusion.

4.7.5. Visual flow front tracking

Numerous techniques exist to trace the flow front such as the use of fibre optic sensors, pressure transducers or ultrasound measurements. However, the most commonly employed method remains visual monitoring through transparent tooling. The fibre metal laminates are obviously not able to employ this method, thus, the primary experiments to adjust the manufacturing parameters are carried out in a setup using glass plates instead of metal sheets. With these glass plates, the resin front line's position, and shape can be observed. In order to reduce the scatter, multiple points will be recorded of the resin front line position and the shortest distance position is recorded during testing.

5

Test Matrix, Experimental Results and Discussion

In this chapter, first the test matrix is presented followed by the experimental results. Afterwards the results are analysed and discussed. The results regarding the influence of vacuum infusion pressure, processing temperature and fibre architecture are shown, and the effect of fibre architecture on the permeability in liquid composite moulding is investigated. At the end of this chapter in Section 5.10 the experimental results are discussed and compared to the theoretical results obtained in the theoretical sensitivity analysis from Chapter 3.

5.1. Development of the Test Matrix

During the VI process, different variables influence the experimental results. The variables that influence the infusion process were identified in Chapter 3 to be: the permeability related to the reinforcement and layup-structure, the resin viscosity, and the vacuum infusion pressure. A test matrix is designed by using the method of One-Variable-At-a-Time approach. The experimental matrix in Table 5.1 consists of 17 tests. It was designed to test the influence of the variables on the infusion process, and find a stable and reliable manufacturing process. The test matrix is designed to observe the influence of the three factors mentioned from Darcy's law, the permeability difference, vacuum infusion pressure, and the resin viscosity. The test matrix shows possible combinations of the variables with different values. Each sample size is 200 mm wide and 500 mm long. The layup-sequence is also listed in the test matrix in Table 5.1. Three different composite lay-ups were used: [0°/0°], [0°/90°], and [90°/90°]. These lay-ups are used to study the influence of the lay-up on the infusion process in Section 5.2. The influence of the applied vacuum is studied in Section 5.3. In Section 5.4 the effect the processing temperature on the infusion process is studied. The influence of the fibre architecture on the process is studied in Section 5.5. Four main groups of experiments are conducted to study the influence of the variables on the infusion process. These setups are explained as follows:

- **Group 1: Single Composite layer in between two glass plates.** The influence of the fibre architecture, vacuum level changing and resin viscosity (by changing the temperature) on infusion speed is studied in this group.
- **Group 2: Two composite layers among three glass plates.** The infusion speed differences between the two composite layers are studied in this group.
- **Group 3: Single composite layer in between two aluminium sheets.** By utilising the infusion speed data from the test results of the first group, the infusion speed and the different friction effect between fibres to glass plates and fibres to aluminium sheets are studied and evaluated.
- **Group 4: Two composite layer among three aluminium sheets.** By combining the infusion speed data from previous groups, the infusion speed of different layers of composites among multiple aluminium sheets is tested.

Table 5.1: Test Matrix

Single Composite Layer in between Two Glass Plates				
Test Item	Dry Fibre Sheet Type	Composite Orientation in Each Fibre Layers	Vacuum Level #	Processing Temperature *
1	Type 1 UD	***0°/0°***	50	22
2	Type 1 UD	***0°/90°***	50	22
3	Type 1 UD	***90°/90°***	50	22
4	Type 1 UD	0°/0°	***100***	22
5	Type 1 UD	0°/0°	***200***	22
6	Type 1 UD	0°/0°	***500***	22
7	Type 1 UD	0°/0°	50	***25***
8	Type 1 UD	0°/0°	50	***35***
9	Type 1 UD	0°/0°	50	***45***
10	***Type 2 UD***	0°/0°	50	22
11	***Type 2 UD***	0°/90°	50	22
12	***Type 2 UD***	90°/90°	50	22
Two Composite Layers among Three Glass Plates				
Test Item	Dry Fibre Sheet Type	Composite Orientation in Each Fibre Layers	Vacuum Level #	Processing Temperature *
13	Type 2 UD	0°/0°	50	22
14	Type 2 UD	0°/90°	50	22
15	Type 2 UD	90°/90°	50	22
Single Composite Layer in between Two thin Aluminium Sheets				
Test Item	Dry Fibre Sheet Type	Composite Orientation in Each Fibre Layers	Vacuum Level #	Processing Temperature *
16	Type 2 UD	0°/0°	50	22
Two Composite Layers among Three thin Aluminium Sheets				
Test Item	Dry Fibre Sheet Type	Composite Orientation in Each Fibre Layers	Vacuum Level #	Processing Temperature*
17	Type 2 UD	0°/90°	50	22

Notes: #The vacuum level represents the vacuum pump reading value so that it is the absolute pressure inside the vacuum bag. The unit of the vacuum level is mBar. *The processing temperature represents the tooling and the environmental temperature inside of the vacuum bag during infusing, most of the tests are conducted at room temperature. Only tests 10, 11 and 12 are conducted at elevated temperature with the assistance of a heat blanket. The unit of the processing temperature is °C. In this study, the resin flow front line is not detected according to any particular specification. Test 16 and 17 are carried out by using metal sheets and fibreglass until the plates fully infused. During these two tests, the infusion time is recorded from the moment the resin starts to be infused and eventually when the resin is bleed out from the outlet tube. Due to the fact that the metal sheets are not transparent, so the resin infusion distance cannot be recorded. The infusion processing time is compared with the previous experiments which consist of glass plates. The result will show the friction difference between metal sheet and glass plate surface influencing the infusion process.

5.2. Influence of the fibre orientation the infusion process

5.2.1. Experimental results

For the infusion process, fibre orientations of the dry fibreglass layups are expected to affect the infusion speed and the saturation of the infusion resin. The experimental results of tests 1, 2, 3 and 10, 11, 12 are discussed for the influence of the fibre orientation on the processing. The experiment processing parameters are listed in Table 5.2. Even though, for the experiments in this section preforms type 1 and 2 have been used, the influence of the fibre architecture on the infusion process is not discussed in this section. Section 5.5 will discuss the influence of the fibre architecture on the infusion process. Test 1, 2 and 3 used 2 layers of Type 1 non crimp unidirectional tapes in different ply orientations for manufacturing the sample with the size of 20 cm by 50 cm. The maximum infusion distance along the

Table 5.2: Experiment results for analysing fibre orientation factor influence

Item	Ply Orientation	Other Manufacturing Parameters	Final Infusion distance Unit [cm]	Infusion time Unit [minute]
Test 1	0/0	Material: Type 1 UD fibreglass, Epoxy 04908	37	160
Test 2	0/90	Vacuum level: 50 mbar	20	160
Test 3	90/90	Infusion temperature: 22°C	15	160
Test 10	0/0	Material: Type 2 UD fibreglass, Epoxy 04908	50	20
Test 11	0/90	Vacuum level: 50 mbar	50	35
Test 12	90/90	Infusion temperature: 22°C	50	50

length direction of the dry fibre sheet is 37 cm with the ply orientation of 0°/0°. There is no test result that could achieve a full-length (50 cm) infusion of the entire fibre sheet. Test 10, 11 and 12 used Type 2 weaved unidirectional tapes in different ply orientations for manufacturing the sample with the size of 20 cm by 50 cm. All 3 test completed the infusion process for the selected sample size of 20 cm by 50 cm within 1 hour. The test result of all test mentioned above is plotted in Figure 5.1.

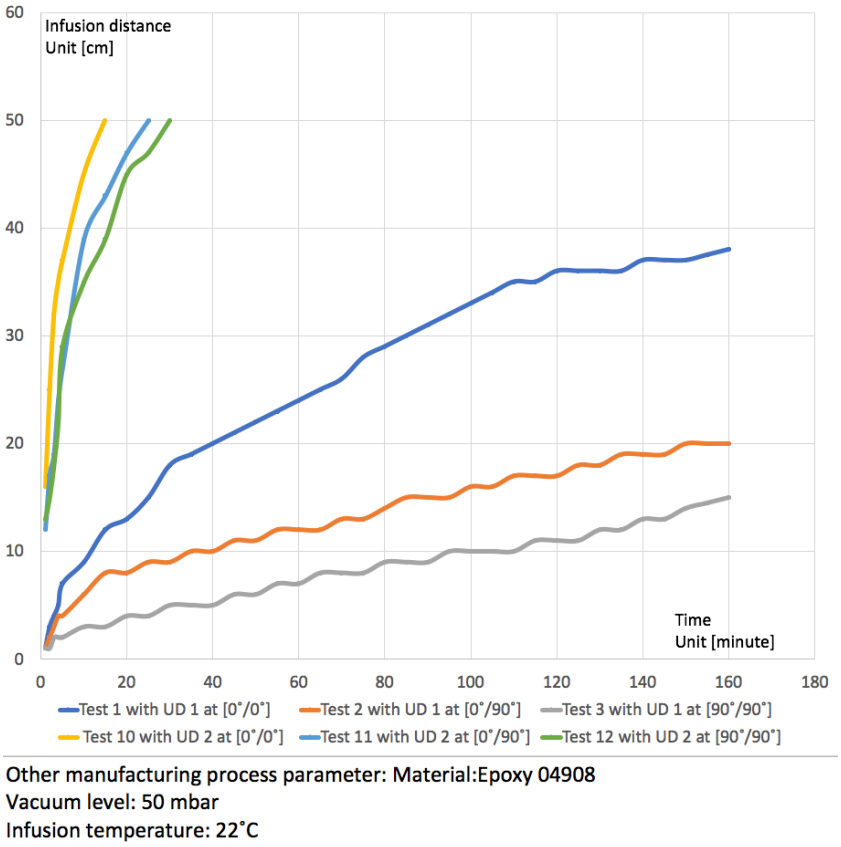


Figure 5.1: Infusion time versus infusion distance for different ply orientations, [0°/0°], [90°/90°], [0°/90°].

Figure 5.1 shows that [0°/0°] layup can be infused for the longest distance and within the pot life of the resin. The [90°/90°] layup is infused for the shortest distance with the same process time. The [0°/90°] layup has a slightly further infuse distance compared to the [90°/90°] layup. For Type 1 non crimp unidirectional tapes, the final infused distance of [0°/0°] plies layup is approximately 37 cm, which is more than twice of the corresponding [90°/90°] layup infusion distance (approximately 15cm). Additionally, Figure 5.1 demonstrates the infusion speed difference among the unidirectional and the cross ply layups. The [0°/0°] plies layup has the fastest infusion speed, [0°/90°] layup's infusion speed is following and [90°/90°] layup was infused the slowest. The infusion speeds of Type 2 weaved unidirectional tapes are about 2.5 cm/minute for [0°/0°] layup and 1.0 cm/minute for [90°/90°] layup.

The infusion speeds of Type 1 non crimp unidirectional tapes are roughly about 0.23 cm/minute for [0°/0°] layup and 0.09 cm/minute for [90°/90°] layup. As we can see from these data, the infusion speed difference between [0°/0°] and [90°/90°] layup are at least double the value.

5.2.2. Result discussion

During the VI process, the resin is flowing through the channels in between fibre bundles at the macro scale while flowing through the channels between the fibre filaments inside the fibre bundles at the micro scale at the same time. The dual flow is caused by the viscous force by the fibre bundles and the capillary force within the fibre bundles [23]. Through the visual monitoring of the experiment process, the resin flow behaviour is demonstrated for the [0°/0°] layup and the [90°/90°] layup in respectively Figure 5.2 and Figure 5.3.

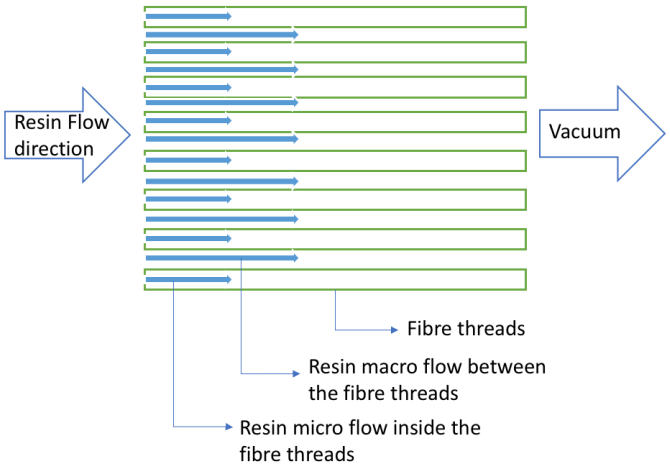


Figure 5.2: Resin flow illustration among 0 ° orientation

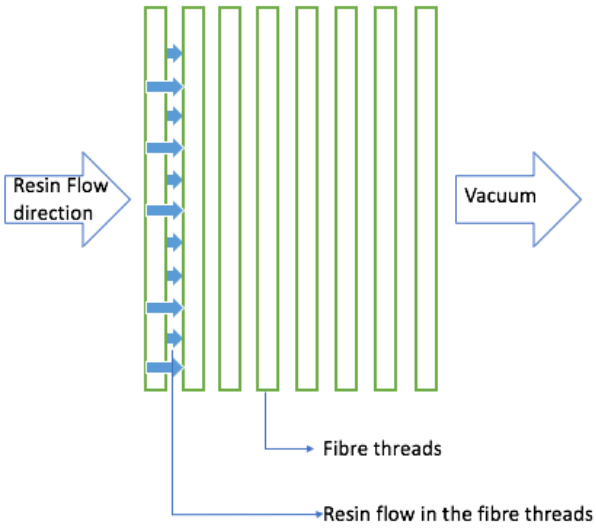


Figure 5.3: Resin flow illustration among 90 ° orientation

The test results indicate that the ply orientation of the dry fibre preform has a significant influence on both the infusion distance and the infusion speed. As we know, the resin is able to flow easily along the fibres in 0° direction, and the flow will experience more hindering by the fibres in 90° direction easily. So there is less resistance for resin flow along 0°-direction than in 90°-direction for infusion.

This explains that the [0°/0°] layup achieved the longest infusion distance. That is also the reason why the [0°/90°] layup could maintain a medium infusion speed comparing with the other two layup. As a result, the ply orientation can be used to influence the infusion speed and to improve the process. The direction from inlet to outlet direction should coincide with the 0°-direction of the fibre preform.

5.3. Influence of vacuum level on infusion process

5.3.1. Test results of Vacuum level changing influence

The vacuum level is indirectly one of the variables listed in Darcy's Law Equation 3.1. Thus it also plays an important role in the VI process. However, it was seen in Chapter 3 that most likely a change in vacuum pressure only has a small influence on the infusion speed. But this needs to be tested experimentally, which is what will be done in this section. Tests 1, 4, 5 and 6 in Table 5.3 are performed under various vacuum levels of 50 mBar, 100 mBar, 200 mBar and 500 mBar for Type 1 non crimp unidirectional tapes. The experimental parameters are listed in Table 5.3.

Table 5.3: Experiment results for analysing the vacuum level influence

Item	Vacuum level Unit [mbar]	Other Manufacturing Parameters	Final Infusion distance Unit [cm]	Infusion time Unit [minute]
Test 1	50	Material: Type 1 UD fibreglass, Epoxy 04908 Ply orientation: 0°/0° Infusion temperature: 22°C	37	160
Test 4	100		34	160
Test 5	200		34	160
Test 6	500		32	130

The infusion process has been monitored during the experiments and the infusion distance over time changing is recorded and plotted in Figure 5.4. The lay-ups of Test 1, 4, 5 and 6 did not infuse over the full length of the samples (50 cm). The infusion distance of Test 1 is 37 cm, which is the longest of all tests, although the rest of the infusion distance is maximum 5 cm shorter. Reading from Figure 5.4, the infusion speed of all tests is about 0.2 to 0.23 cm/minute.

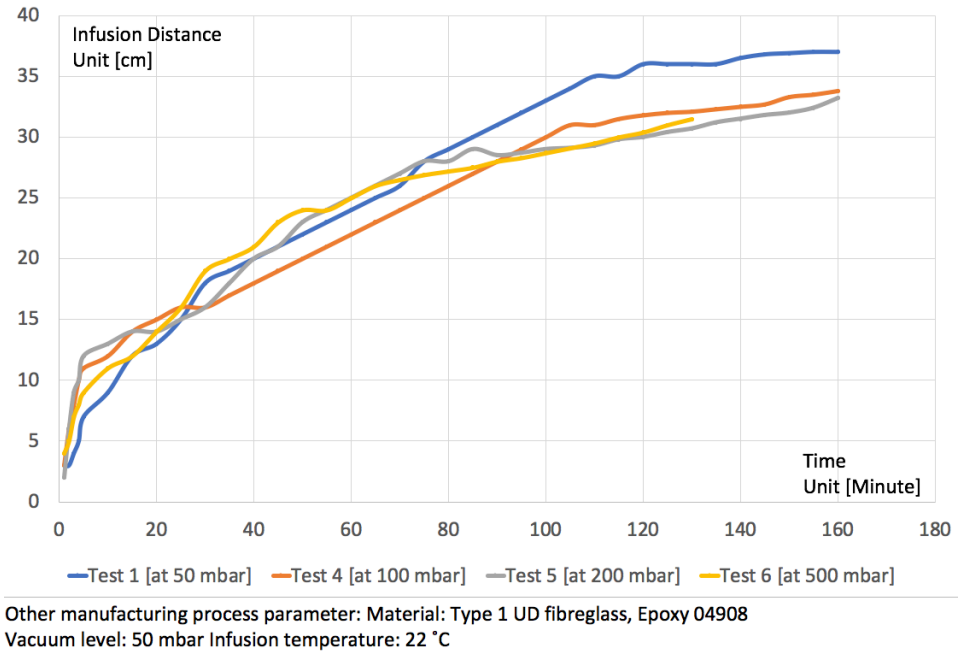


Figure 5.4: Process time comparison among various vacuum infusion pressure

5.3.2. Discussion

The test results of tests 1, 4, 5, and 6 show a slight difference on infusion distance and infusion speed with the change in vacuum level. In practice, the vacuum recording value is the reading from the vacuum gauge connected to the vacuum pump. Therefore, the relative pressure in the vacuum bag is equal to the actual atmospheric pressure minus the vacuum gauge reading pressure. This relationship is indicated in Equation 5.1. The relative pressure is the driving force for the resin to infuse the composite, which was indicated in Darcy's law equation 3.1.

$$P_{relative} = P_{atmosphere} - P_{gauge} \tag{5.1}$$

The vacuum reduces the pressure at the outlet of the fibre preform, thus the atmospheric pressure forces the resin flow through the fibre preform. The atmospheric value is recorded from the reading of the thermometer in the laboratory, which is 1019 mBar. Thus, the relative pressure value is listed in Table 5.4.

Table 5.4: Vacuum level and relative pressure value list

Item	Atmosphere Pressure Unit [mbar]	Vacuum level Unit [mbar]	Relative Pressure Unit [mbar]
Test 1	1019	50	969
Test 4	1019	100	919
Test 5	1019	200	819
Test 6	1019	500	519

It can be seen that the relative vacuum level reduces 5% for Test 4, 15 % for Test 5 and 46 % for Test 6 comparing with Test 1. During the observation of the experiments, the vacuum bag remained tight for Test 1, 4, and 5 and the vacuum bag was very loose for Test 6. It was observed that the vacuum bag for Test 6 showed larger wrinkles in the bagging film and the resin has been continuously flowing into these wrinkles. The loose vacuum bag in Test 6 resulted in an undesired resin flow path and waste. In this case, the resin was not infusing the dry fibre sheet, but vacuum bagging wrinkles were being filled with resin. In general as expected from the theoretical analysis from Chapter 3, the infusion distance and the infusion speed did not reveal a large difference on various vacuum levels. However the vacuum bag's behaviour is clearly negatively affected by the loose vacuum bag. Keeping a high value of relative pressure is needed to obtain a stable process.

5.4. Viscosity influence

5.4.1. Lowering the viscosity by increasing the processing temperature

To obtain a resin that flows easily it is important to have a low viscosity. Having a low viscosity starts with selecting a low viscosity resin. After the resin selection is fixed, it is possible to lower the viscosity even further by elevating the processing temperature of the resin [24]. However, increasing the processing temperature of the resin significantly reduces the pot life of the resin. Therefore, also the time an infusion can last is shorter. Ultimately, the reduction in pot-life might became the factor driving the maximum length of an infusion. For components that are manufactured in a production environment where timing is crucial, resin systems and infusion flow rates can often be optimised to allow near immediate gel once the component has finished infusing. This situation does require considerably stricter temperature monitoring and control. Fluctuations within the viscosity profile of the resin system can lead to components gelling before the full infusion has finished. Test 1 (reference), 7, 8 and 9 are conducted to test the influence of the viscosity change for various temperature conditions on the VI process. The processing parameters per experiment are listed in Table 5.5. The infusion distance over time changing of Test 1, 7, 8 and 9 is recorded and plotted in Figure 5.6.

Table 5.5: Experimental group for testing temperature influence

Item	Temperature Unit [°C]	Other Manufacturing Parameters	Final Infusion distance Unit [cm]	Infusion time Unit [minute]
Test 1	22	Material: Type 1 UD fibreglass, Epoxy 04908 Ply orientation: 0°/0° Vacuum level: 50 mBar	37	160
Test 7	25		38	160
Test 8	35		37	70
Test 9	45		15	35

A specially designed silicone rubber heat blanket is used for the experiments. The flexible blanket allows itself to deform, and provides uniform heat over the entire product surface. An extra weight and two layers of isolation material are used on top of the heat blanket to fix the movement of the blanket and to trap the heat that may flow through the tooling area. The experimental setup with a heat blanket is shown in Figure 5.5. To monitor the temperature changes accurately, extra thermocouples are fixed underneath the thermal blanket and at the bottom of the tooling surface during the infusion process. It can be observed from Figure 5.6 that Test 8 shows the longest distance of 38 cm at the temperature 25 °, Test 7 infused over a distance of 37 cm at 35 °C and Test 9 infused 15 cm at 45°. The infusion speed of Test 7 is the fastest with 0.53 cm/minute, Test 1 and 8 are 0.23 and 0.24 cm/minute, Test 9 is 0.43 cm/minute.

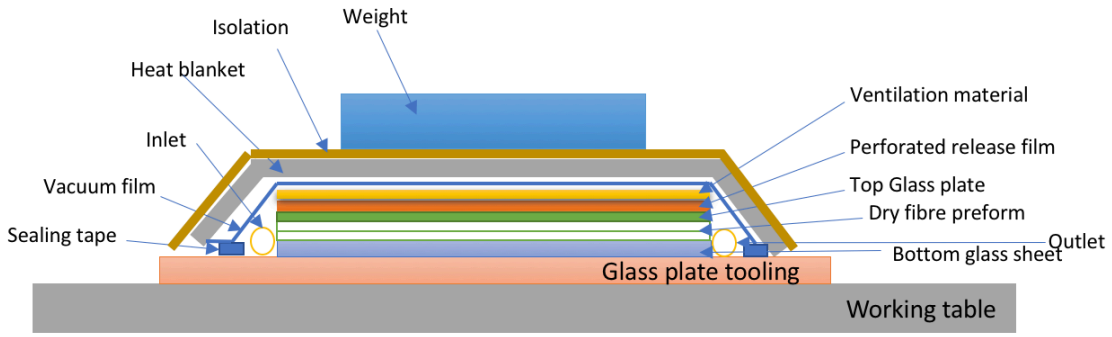


Figure 5.5: Sketch of the experimental setup with a heat blanket

5.4.2. Discussion

The test results indicate that the viscosity change with temperature has a large effect on the vacuum infusion process. The infusion speed has increased to 0.53cm/minute at 35 °C, which is more than two times of the infusion speed at 25 °C. The viscosity reduction from temperature increase is positive for improving the infusion speed. However, the final infusion distance is not improved due to the potlife reduction. Therefore, resin viscosity increased over time faster at elevated temperature which leads to similar infusion distance. The infusion is conducted within the resin's pot life. Pot life is defined as the amount of time in which the initial resin viscosity doubles [4]. Figure 5.7 illustrates the mixed epoxy viscosity change over the pot life. A linear approximation is used to simplify the relationship. As Figure 5.7 shows, the viscosity of the epoxy doubles in about 5 hours (300 ± 50 minutes from Table 4.2) at 25 °C. According to the technical sheet of the Epikote 04908, the pot life will is halved with every 10 °C elevation. So the pot life is 2.5 hours at 35 °C and 1.25 hours at 45 °C. It explains the Test 9 has the result of shortest infusion distance and relatively faster infusion speed at 45 °C. The viscosity of the resin is decreased at 45 °C which provides the infusion speed of 0.43 cm/minute, but the pot life is 1.25 hours leads to the viscosity increased rapidly to stop the infusion.

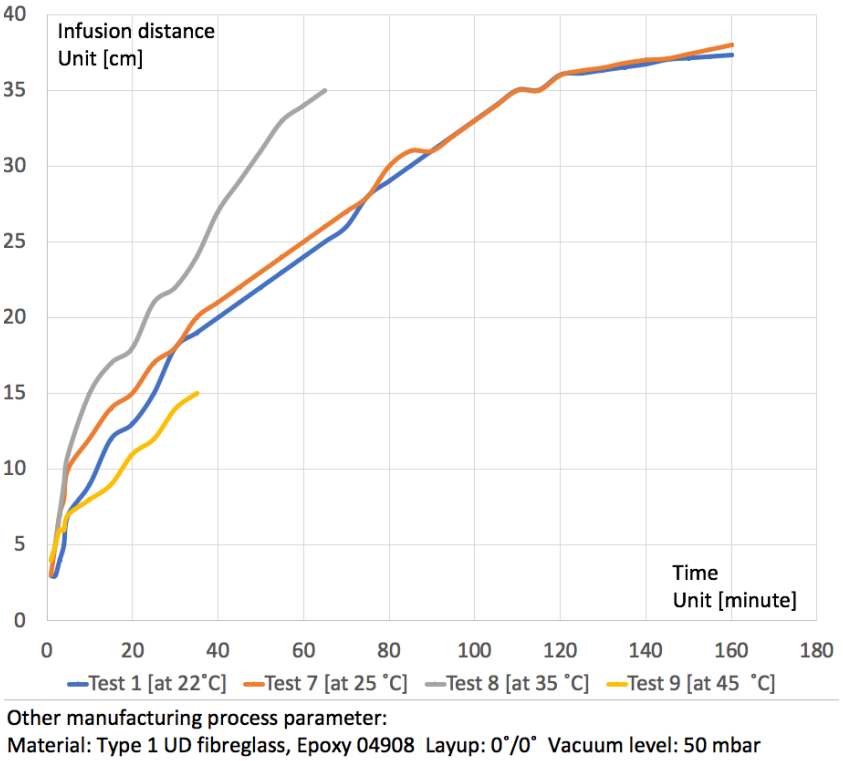


Figure 5.6: Temperature influence on the processing time

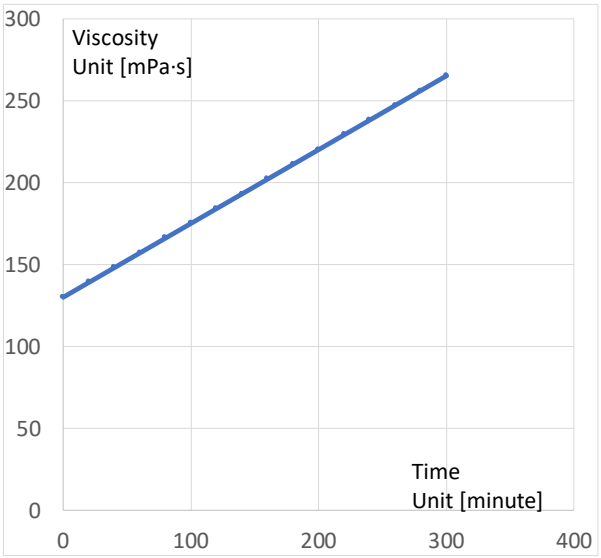


Figure 5.7: Epoxy (Epikote 04908 and Epikure 04908 mixture) viscosity changing over its potlife at 25°C

5.5. Influence of Fibre architecture permeability on VI process

5.5.1. Test Results

Among all of the variables in Darcy's law, permeability of the fibre reinforcement is one of the most important influence factors [9, 14]. This was also seen in Chapter 3. The results of Test 1 and Test 10 are compared to demonstrate the permeability difference caused by fibre architecture diversity. In this comparison, although Type 1 UD tapes and Type 2 UD tapes both aligns the fibres along one direction in the sheet, the binding pattern and method are completely different. Type 1 non crimp unidirectional tapes has distributed the fibres over the sheet width uniformly, as Figure 5.8 shows. Type 2 unidirectional tapes has the textile structure in which the major amount of the fibres align in 0° direction only while a minor amount of the fibres running in the 90° direction with the intention of maintaining the primary fibres in position.

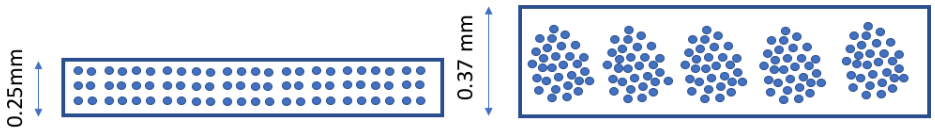


Figure 5.8: Sketch comparison of of the fibre bundles distribution in Type 1 non crimp unidirectional tape fibre architecture (left) and Type 2 weaved unidirectional tape fibre architecture(right)

Test 1 used Type 1 non crimp unidirectional tapes with the layup of [0°/0°] to infuse while Test 10 used Type 2 weaved unidirectional tapes. The experiment processing parameters are listed in Table 5.6.

Table 5.6: Experiment group for testing the fibre architecture influence on vacuum infusion process

Item	Fibreglass sheet type	Other Manufacturing Parameters	Final Infusion distance Unit [cm]	Infusion time Unit [minute]
Test 1	Type 1: Saertex 30004593 (U-V-E-228g/m²-1500mm)	Material: UD fibreglass, Epoxy 04908 Ply orientation: 0°/0° Vacuum level: 50 mbar Infusion temperature: 22 °C	37	160
Test 10	Type 2: Saertex 30003318 (U-E-397g/m²-635mm)		50	20

Figure 5.9 shows a significant difference in infusion distance between Test 1 and Test 2. Test 1 shows that the Type 1 non crimp unidirectional tapes sample is infused for 37 cm length over 2h 40m. Test 10 shows that the Type 2 unidirectional tapes sample is fully infused for 50 cm length within 20 minutes. The infusion speed of Test 1 is 0.23 cm/minute while Test 10 is 2.5 cm/minute.

5.5.2. Discussion

In this case, Type 2 UD reinforcement in Test 10 in Figure 5.9 could achieve a satisfactory infusion result where resin can flow through a component within the potlife of the resin, which means that Type 2 UD reveals a higher permeability than Type 1 UD tapes. Figure 5.10 demonstrates the fibre architecture of the VIFML sample made of Type 2 UD in cross ply layup. In Figure 5.10, the fibre bundles are clearly observed in the orange circles that each bundle is attached. Due to the weave structure of Type 2 unidirectional tapes, the fibre reinforcement does not distribute uniformly in the laminate, but individual bundles remains to be seen much individually. This is the reason why the resin could infuse Type 2 unidirectional tapes faster than Type 1 non crimp unidirectional tapes: extra macro channels that exist between the fibre bundles.

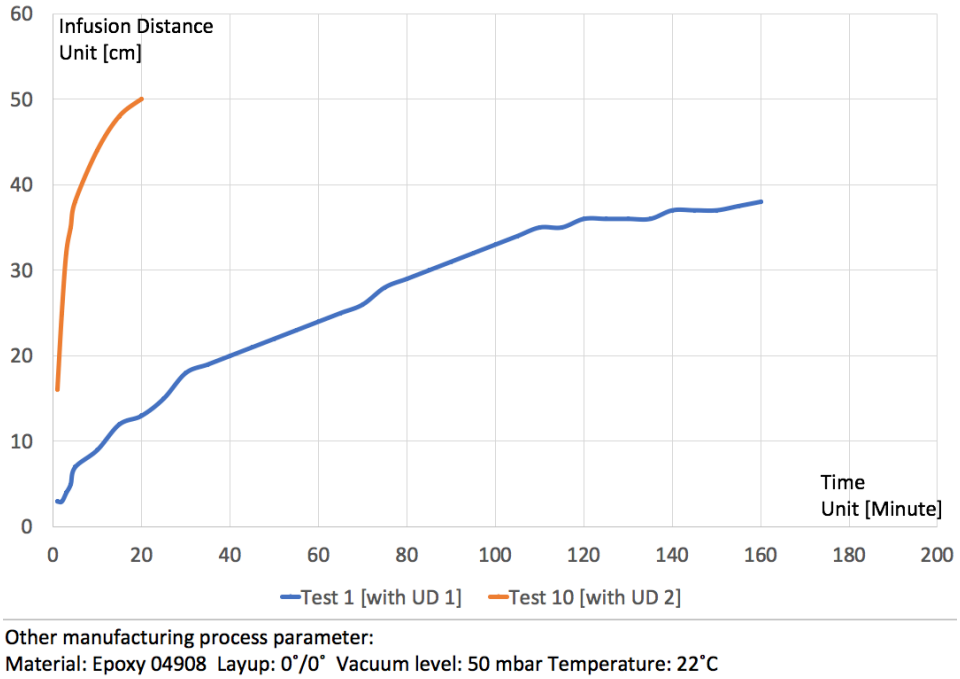


Figure 5.9: Infusion distance over time for Type 1 non crimp unidirectional tapes and Type 2 weaved unidirectional tapes

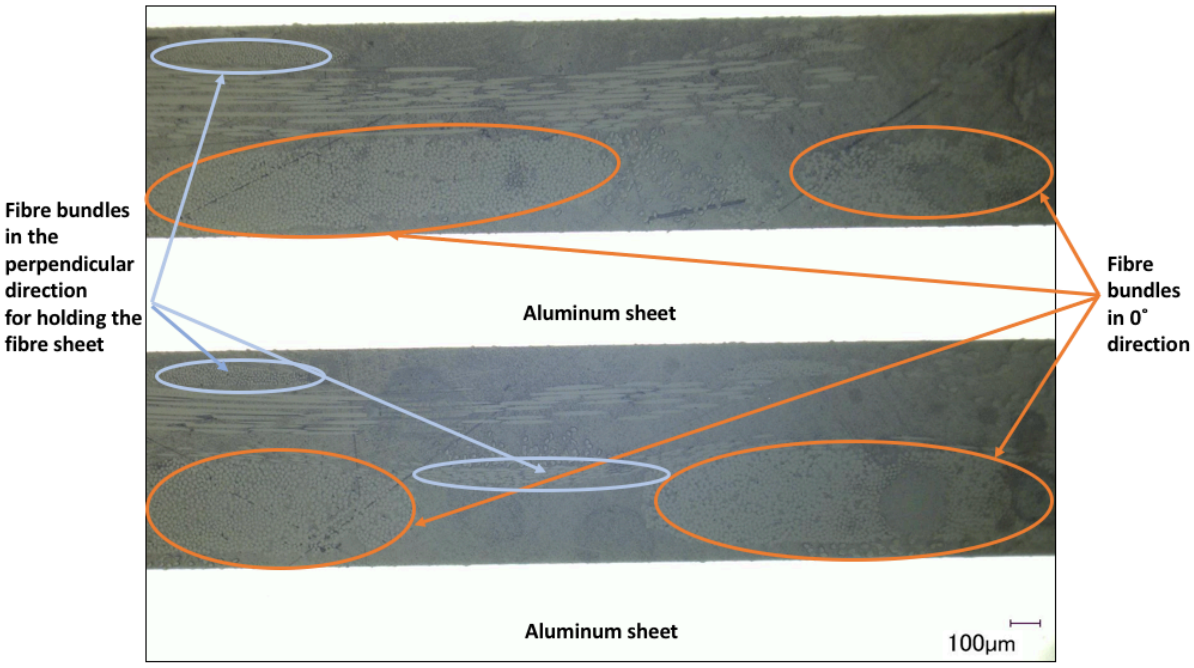


Figure 5.10: Cross-sectional micro graph of a sample made of Type 2 UD with crossply layup

5.6. Two composite layers and three glass plates infusion

Test 13, 14 and 15 are conducted to verify whether the two composite layers alternating with three glass plates could be infused simultaneously, and whether it differs from single composite layer infusion process. The result of Test 13, 14 and 15 are reported in Table 5.7 below.

Table 5.7: Two composite layers and three glass plates infusion test and result

Item	Ply Orientation in each ply	Other manufacturing Parameters	Final infusion distance Unit [cm]	Infusion time Unit [minute]
Test 13	0°/0°	Material: Type 2 UD, Epoxy 04908	50	30
Test 14	0°/90°	Vacuum level: 50 mBar	50	45
Test 15	90°/90°	Infusion temperature: 22°C	50	55

It can be observed that both the composite layers can be infused simultaneously with the current experimental setup. The infusion processing times are recorded, and shown in Figure 5.11. The infusion processing times, and speeds are similar with those of the single composite layers structure and the various layup sequence refer to Table 5.1. The friction difference between glass plates and aluminium sheets are considered for this group of experiments. As indicated from the test results, the friction differences are not significant enough to influence the processing time. Furthermore, a group of microscopy tests have been performed to check the micro-structure of the samples. Type 1 unidirectional tapes are distributed more evenly, and the cross-section area is smaller than for Type 2 unidirectional tapes. The fibre architecture should be uniformly distributed as the ideal status, however, handling this material in practice is very difficult to keep every tow in straight lines.

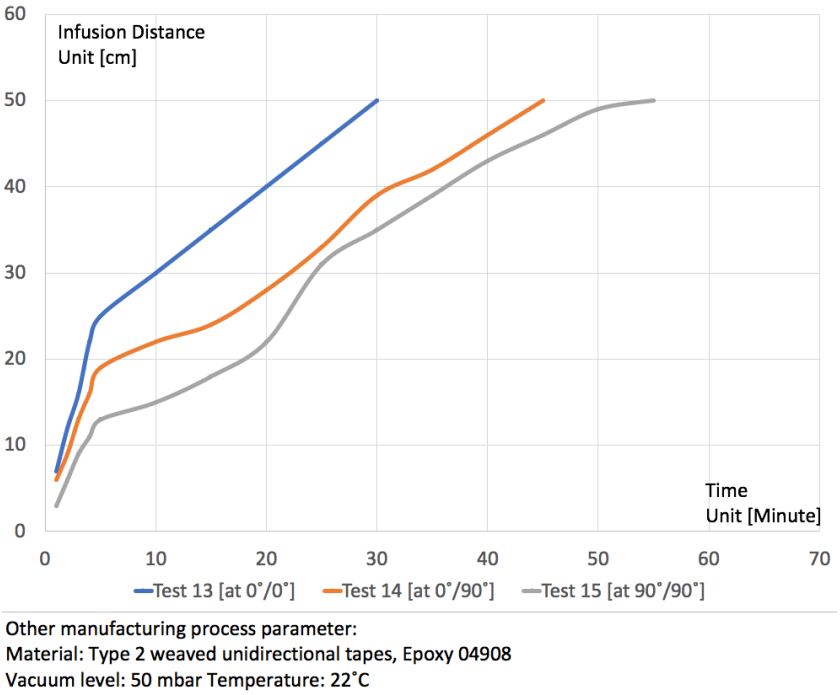


Figure 5.11: Infusion process time comparison for the structure of two composite layers among three metal sheets

5.7. Fibreglass layers between aluminium sheets infusion process

Test 16 and test 17 use the 2024 aluminium sheets for the infusion experiments. The results are listed in Table 5.8.

Table 5.8: Fibre metal laminates infusion test result

Item	Ply orientation in each ply	Other Manufacturing Parameters	Final Infusion distance Unit [cm]	Infusion time Unit [minute]
Test 10	0°/0°	Material: Type 2 UD fibreglass, Epoxy 04908 Vacuum level: 50 mBar Infusion temperature: 22 °C	50	20
Test 14	0°/90°		50	45
Test 16	0°/0°		50	25
Test 17	0°/90°		50	55

The friction difference between glass plates and aluminium sheets are considered for this group of experiments. As it indicated from the test results, the friction differences could be assumed that it is not so significant to influence the processing time. In this study, cross-sectional microscopy has been performed to check the microstructure of the samples and potential delamination in the samples.

5.8. Visual inspection results

Visual inspection is conducted on the samples after the de-moulding process. The visual inspection results demonstrates that the infused composite layers are continuous and there are not visually fibre waviness occurred. There are no obvious dents or defect on the surface of the composite layers.

5.9. Cross-sectional microscopy inspection results & discussion

Various infused plates have been inspected using cross-sectional microscopy. To prepare the cross-sectional microscopy samples, the plates were trimmed at various locations, embedded in special resin and polished using an automated Struers polishing machine. After the sample preparation, the cross-sections were analysed to inspect the interface of the resin and the aluminium sheets, the fibre volume content, and the presence of voids. Two representative cross-sectional micro-graphs of infused FML are shown in Figures 5.12 and 5.13. Two layers of fibres have been infused in between three layers of aluminium sheets. The aluminium layers and glass fibre/epoxy layers have been indicated in the Figures. The micro-graphs were captured by using a CCD camera within the Leica Qwin system. Leica Qwin is an image processing and analysis software package, that can provide the fibre volume fraction and voids content. The result of fibre volume content ranges from 54 % to 65 % and void content ranges from 0.5 % to 1.5 % during the study. Figure 5.12 shows an infused FML with two composite layers and three metal layers. It can be seen that no gaps exist between the epoxy and the metal interface. It seems that the interface is consistent over the entire cross-section. The main fibre direction is the 0° direction, which is perpendicular to the paper. The fibres in other directions are the stitching fibres used to keep the UD fibre bundles together. Some of these stitching can clearly be seen as 90° horizontal fibres going over the cross-section. Within the 0° fibre bundles no voids could be detected. However, some areas shows the presence of small voids. The voids were mainly found in between two fibre bundles, in between a fibre bundle and a stitching bundle or in between a fibre bundle and the metal sheet. These are all locations within the preform enclosed by the surroundings, most likely indicating that the resin could not fully impregnate these areas. This is potentially caused by a too high viscosity of the resin and the use of the current preform. Figure 5.13 shows one glass fibre/epoxy layer in between two aluminium sheets. This figure nicely shows the interface of the epoxy resin and the metal sheets. The metal sheets have some surface roughness, and the resin managed to follow the rough surface. In the upper right corner, a resin rich area is shown that does not contain fibres or voids. These resin rich areas might help the resin the flow through the preform. It can be seen that this figure does not contain any visible voids.

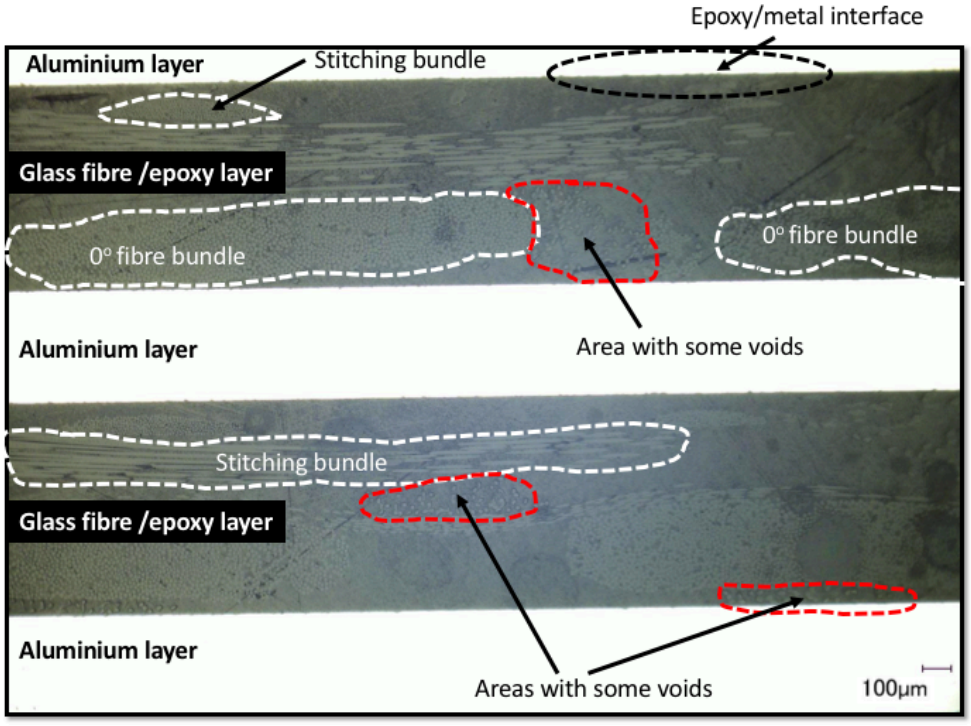


Figure 5.12: Representative cross-sectional micro-graph of vacuum infused FML with two glass fibre epoxy layers and three metal layers. Type 2 UD tapes have been infused at room temperature.

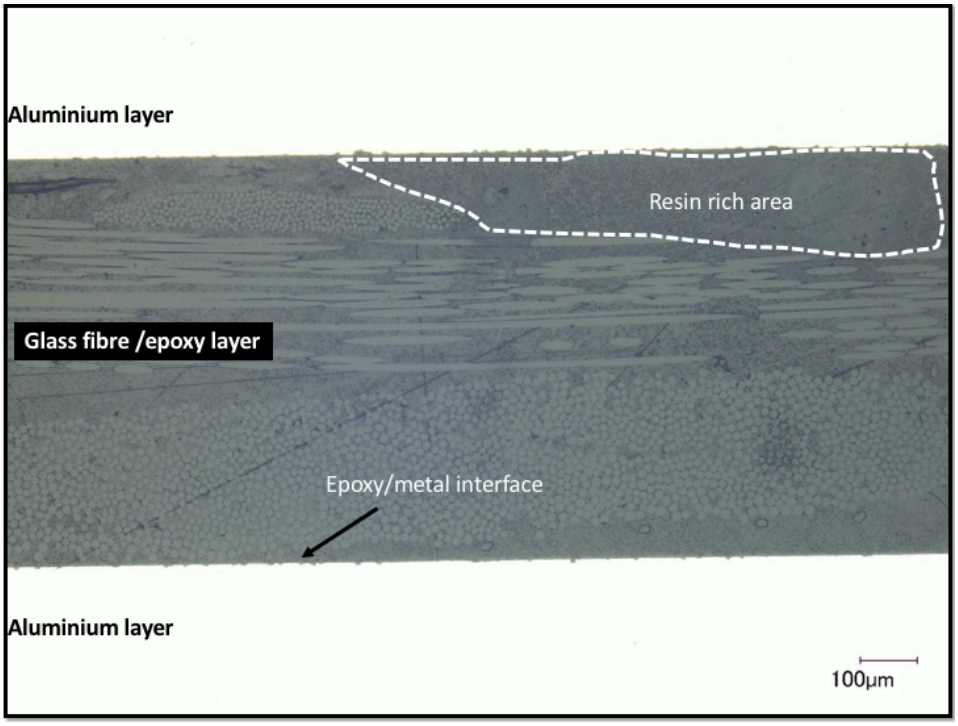


Figure 5.13: Representative cross-sectional micro-graph of vacuum infused FML. One composite layers is displayed in between two metal sheets. Type 2 UD glass fibre was infused at room temperature.

5.10. Reflection on sensitivity analysis

In Chapter 3 a sensitivity analysis was performed with respect to the parameters involved in the vacuum infusion process. It was found that the permeability and the resin viscosity have the largest impact on the achieved infusion time for an infusion length of 50 cm. The applied vacuum infusion level and the fibre volume fraction were found to have a minimum impact on the infusion process. In Section 5.5 it was found that the fibre perform has a very large influence on the infusion time. The yarn architecture is directly related to the permeability of the glass fibre layer. The experimental findings are in agreement with the findings from theoretical analysis performed in Section 3.2.1. However, for Type 1 yarn architecture the permeability seems to be much lower than the the permeability range used in the sensitivity study in Table 3.1. Section 5.2 shows that the fibre orientation also has an impact on the permeability and therefore it largely impacts the infusion time. The applied vacuum level in Section 5.3 was found to only have a small impact on the infusion time. This finding is in agreement with the sensitivity analysis performed in Chapter 3. Therefore, it can be concluded that it is not worth using lower vacuum levels in order to increase the infusion speed. According to the sensitivity analysis performed, the resin viscosity has a large impact on the infusion time. The same trend was experimentally found by elevating the resin temperature during the infusion process. However, when the temperature was elevated too much gelling of the resin occurred already very early in the infusion process, due to which the viscosity is increased again slowing down the infusion process. It is verified in this chapter that the estimated values of the infusion times found in the sensitivity analysis in Chapter 3 are correct. Experimentally it is found the fibre architecture has the largest impact on the infusion time. The fibre architecture therefor is absolutely the driving parameter that determines whether the infusion is possible or not. This must be taken into account for future applications.

6

Analysis on industrial application

The feasibility of the vacuum infusion process on FMLs is demonstrated by the experimental study on a lab scale in Chapter 5. Therefore, in this chapter, the applicability of the vacuum infusion process on FMLs for industrial applications is discussed for the size, configuration and automation possibilities. In this Chapter only the weaved UD-glass fibre Type 2 is considered, because it was found in Chapter 5 that the non crimp UD tape Type 1 could not be infused over a length of 50 cm, and it was concluded that the non crimp UD glass of Type 1 is most likely not suitable for the VI of FMLs.

6.1. Introduction

The VIFML product from the previous experiments has a fibre volume of 50 % to 60 %, which is comparable to the conventional ACFML. Additionally, the VIFML product features similar quality characteristics to the existing Glare structure: the fibres are fully impregnated in the matrix within the composite layer, the bonding between metal sheets, and the composite layers are continuous and uniform. Since the resin is infused through the edges of the laminate, it is not necessary to machine holes in the metal layers to accommodate an infusion pathway through the thickness of the materials. Therefore, the quality inspection results are satisfying.

6.2. Maximum infusion distance from VI process

Figure 6.1 shows an extrapolation of the infusion result from test 10, in which type 2 fibres where infused in the [0°/0°] direction. The extrapolation is performed by matching Equation 3.3 to the experimental data. Additionally, the figure shows the ideal estimated infusion length with the parameters from Table 3.3. This is a theoretical infusion when all infusion parameters have the ideal/optimised values for the infusion. The vertical black dashed line at 160 min indicates the maximum possible infusion time before the viscosity becomes too high to still be infused. This maximum possible infusion time is estimated in Appendix A. According to the extrapolation in Figure 6.1 it takes 80 min to infuse over distance of 100 cm. From the intersection of the extrapolation with the vertical line at 160 min infusion time, it becomes clear that the maximum possible infusion length with the current setup and materials is [0°/0°] direction is approximately 138 cm. The theoretical infusion length determined in Chapter 3 from Darcy's parameter values in Table 3.3 gives a maximum theoretical ideal infusion length of 420 cm. Fibre architecture optimisation and better resin selection and processing might make it possible to come closer to the theoretical ideal infusion time. Thus, it is expected that the process has the potential to infuse over distances larger than 138 cm, but additional research is needed. In Figure 6.2 the extrapolations of test 10 in [0°/0°] infusion direction, and test 12 in [90°/90°] infusion direction are shown. The maximum possible infusion length for the [90°/90°] case is 103 cm. It can be seen the the fibre orientation has a large influence on the infusion distance. The maximum infusion distance is reduced with approximately 34 % when infusing over the [90°/90°] direction in comparison to the [0°/0°] direction. The fibre direction largely influences the maximum possible infusion length. Therefore, it is preferred to infusion over the [0°/0°] direction to obtain the largest infusion length. The maximum infusable width would be defined by the tooling size, because it is the infusion length that limits the process. However, it is recommended to experimentally verify whether indeed a large width

can be infused.

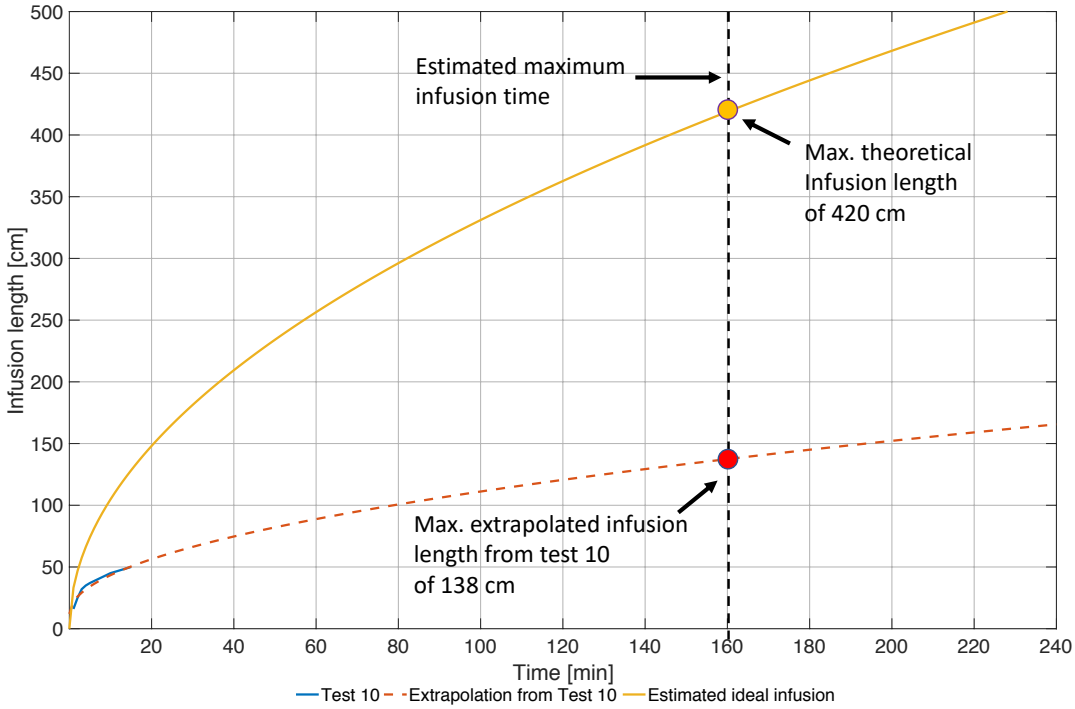


Figure 6.1: Maximum estimated infusion length extrapolated from Test 10 performed on [0°,0°] Type 2 glass preform, shown in the red dashed line. The purple line shows the ideal infusion time obtained when Equation 3.3 is used for the parameters values shown in Table 3.3. In this case the viscosity changes with time according to the relationship shown in Figure 5.7. The yellow line shows the ideal infusion time without taking the viscosity change into account.

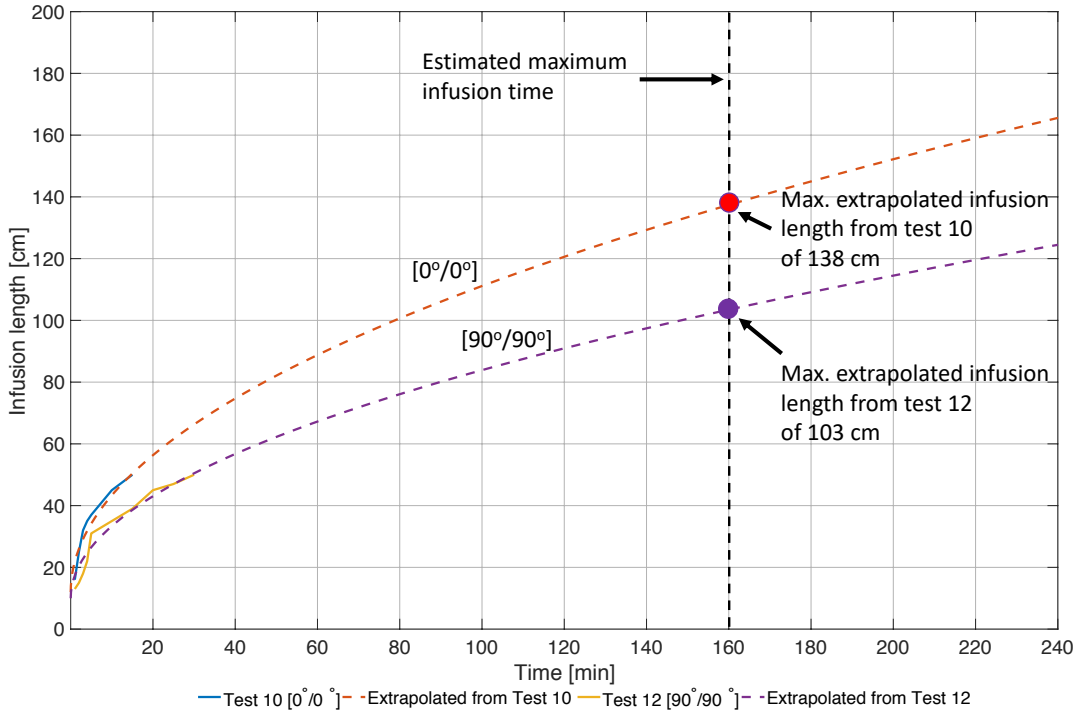


Figure 6.2: Maximum possible infusion distance extrapolated from Test 10 for [0°,0°] and Test 12 for [90°,90°] performed on [0°,0°] Type 2 glass preform.

6.3. Evaluation on infusing different types of products

- **Products with long and narrow configuration:** Glare has been applied on the leading edge of the tail of the A380 thanks to its excellent impact properties. The leading edge component is a primary structure with a long and narrow shape. As the discussion indicated in the previous paragraph, the maximum infusion distance from the VIFML method was estimated to be approximately 1.4 m. Therefore, the resin infusion orientation should always be from the narrow side of this kind of product, extending the resin feed line along the long side of the product to minimize the infusion distance.

- **Single and double curved panels:** The textile architecture of the dry fibreglass reinforcement has a large effect on the vacuum infusion manufacturing process. The unidirectional tapes of the dry fibre preform might split or overlap over complex contours. The split positions potentially cause runners during the infusion process. Therefore, curved product manufacturing demands high operational skills and experience from the technicians to prepare the dry fibres preform before the infusion process.

6.4. Influences of details like splicing, doublers and ply drops on VI process

In Glare, splices are commonly used for manufacturing large panels. Because the metal sheets in Glare have a maximum width of 1.5 m [5]. Splices are made of bridging fibre layers among aluminium sheets to connect multiple layers in Glare, as it is demonstrated in Figure 6.3. The VI process is possible to apply on FML with splices due to the continuous fibre layers in the structure. However, the splicing gap between the adjacent metal sheets is usually 1 mm wide [5]. It is possible that the gap area leads to resin runner issues during the infusion. However, based on the observation during the previous experiments for setup improvement in Chapter 4, gaps of 1 mm-width were not risky and did not cause runners. Therefore, it is unlikely that the splicing gaps would cause potential runners so that the VI process is possible to apply for manufacturing FML with splicing. This assumption needs further and dedicated experiments to be verified.

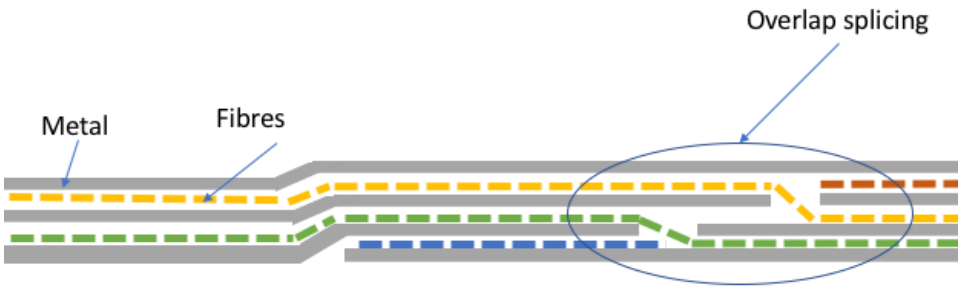


Figure 6.3: 2D sketch of overlap splicing

Additionally, adding metal sheets shown in Figure 6.4 as interlaminar doublers in FML, the laminate enhances the local material properties. In Figure 6.4, it could be observed that there is additional adhesive in the laminate at the end of the interlaminar doubler. For the VI process, this is also another potential runner at the adhesive location. It should be tested with further experiments.

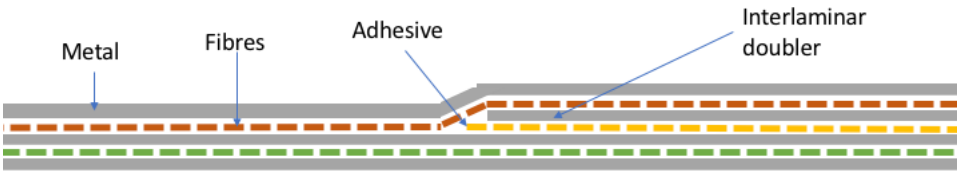


Figure 6.4: 2D sketch of the interlaminar doubler

Another specific feature of FML is the external doubler bonded on the skin of larger FML panels, see Figure 6.5. The external doubler is applied on the large FML skin to offer extra strength or stiffness. The external doubler can also be infused separately after the large FML skin panel is manufactured. The individual VI manufacturing on the external doubler is basically the same process as reported in Chapter 4. Furthermore, it might also be possible to adjust the vacuum bagging process to infuse the FML panel with external doublers simultaneously. The idea is applying extra resin feed inlet and outlet on the location of the external doublers through the vacuum bagging film covering the larger FML panels as well. The vacuum bagging structure would be adjusted for allowing.

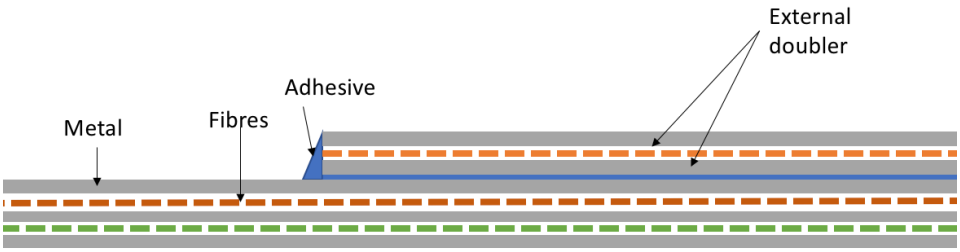


Figure 6.5: 2D sketch of external doubler

A ply drop-off doubler in FML is referring that there is an internal thickness step in the laminate and the thickness step is not visible on the outside of the laminate, see Figure 6.6. The ply drop-off doubler is manufactured similarly as the splice structure from the traditional autoclave curing method. From Figure 6.6, it can be observed that there is a larger area filled with adhesive inside the laminate for the internal ply drop-off than the splice structure. For the VI method, the adhesive filled area at the edge of the inner aluminium layer could be a potential runner location.

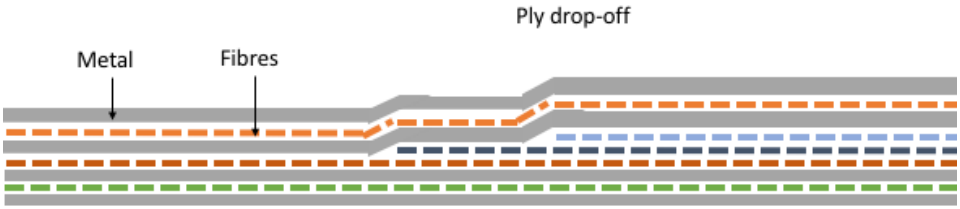


Figure 6.6: 2D sketch of the ply drop off

6.5. Recommendations on infusing large parts

During the experimental study of VIFML application, several recommendations arose for the infusability of larger and more complex products. The recommendations are listed as below.

- Resin with lower viscosity: In this study, Epoxy is chosen for the infusion process because of its excellent properties such as wetting dry fibreglass, strong bonding and low viscosity. The low viscosity property allows the epoxy to quickly infuse through the desired area well before the pot life of the resin. The viscosity and the pot life could be changed by blending different kinds and amounts of the hardener. Various hardeners for providing a lower viscosity epoxy are recommended to test in the further study. Besides the viscosity the resin must also have sufficient strength, and an appropriate stiffness. Thus, the resin selection will be a compromise of these parameters.
- Dry fibre with a different textile structure: As we observed in this study, Type 1 non-crimp unidirectional tape and Type 2 woven unidirectional tapes present significant differences in performance during the infusion process. Therefore, the unidirectional tapes with different textile patterns are recommended to be studied for their suitability in the infusion process.
- Automation recommendation: The long labour time is observed during the experimental study. Therefore, the possibility of automation is also considered for VIFML. Firstly, an automation system of resin mixing and degassing can be developed for reducing the human input involved in the mixing step and providing precise mixture ratio. The automatic resin mixing system should be a equipped with separate storage for the resin and the hardener; the resin should be mixed with a small amount at the beginning of the infusion and continuously provided throughout the entire process. The automatic resin mixing system would provide a controlled resin feeding speed and eliminate a large amount of the resin waste. Secondly, the dry fibre preform could be assembled by automated placement. The automatic fibre placement technology could offer an increased production speed to form composite layers and also provide better precision of the composite layers. Therefore, fibre distortions caused by technician operation could be eliminated.

6.6. Evaluating the VI FML

As other processes indicated, there are pros and cons of the VI process for FML manufacturing.

6.6.1. Pros

- Replace autoclave curing by oven curing or room temperature curing: Vacuum Infusion process is a low cost alternative compared to the prepreg process. The oven equipment and room curing methods are significantly cheaper than autoclave curing. In this study, the VI process successfully manufactured a FML product which is comparable on the fibre volume content and voids content to the existing structure without using an autoclave from the result of Chapter 5.
- Easy layup operation during long processing time: The dry fibre sheets are lighter and easier to adjust during the layup process compared to the prepreg. Furthermore, the dry fibre layup could be conducted for significantly longer time for room temperature layup. The limited pot life of the prepreg usually demands for an intensive labour contribution.
- Extra resin retreval during vacuum infusion is conducted by using a resin trap connected to the end outlet tube. Therefore, no excess resin is contained in the vacuum bag and it is more convenient for de-moulding. It is preferable because the extra resin is always bled out by the bleeder in a vacuum bagging process. This extra resin creates sharp edges around the product surface which is risky for the technician's safety during demoulding process. And the strategy of locating the edge bleeder on the product also relies on the technician's experience skill. It is possible to cause poor resin area due to the edge bleeder is placed at the wrong location.
- No perforated metal sheets required: The VIFML fabricated in this study is letting the resin infuse over the length direction of the product instead of the thickness direction, so there is no requirement of using perforated metal sheets to provide infusion paths comparing with the research conducted by B.J. Jensen in 2009 [10]. Therefore, the VIFML product has similar structure with the current GLARE parts with continuous metal sheets.
- Cost reduction comparing with the traditional manufacturing method: This is presented in Chapter 7 by a theoretical estimation study on the total cost for the VIFML and the ACFML products. The total cost is divided in the material cost, labour cost and equipment cost. Each type of cost is

estimated and the main cost drivers like product size, hourly wage and equipment capability are ranked by conducting a sensitivity analysis. In general, Chapter 7 give the conclusion that the overall manufacturing cost of VI process is lower than the traditional manufacturing process.

6.6.2. Cons

- Labour hours: At the current stage, the involved labour time is still quite long due to the consistent monitoring during the fabrication process. At the current experimental stage, consistent monitoring is necessary for developing the VIFML method into a reliable and repeatable process. The issue of extensive labour time could be improved by further studying automation and lean manufacturing.
- Various dry fibre structures have a large influence on the infusion result: Type 1 non crimp unidirectional tape provides a uniform distribution of the fibres over the warp dimension, while there are more threads going over and under the fibres in Type 2 unidirectional tape. However, Type 1 non-crimp tape is also more difficult to be infused. The balance between uniform fibre architecture and infusability still demands more exploration on different dry fibre textile structures.
- In the vacuum bagging process, the prepreg contains uniformly distributed resin over the entire composite layer, however, the vacuum infusion method requires the vacuum tube placement at certain locations, including the resin inlets, outlets and the relative in-bag extensions of these tubes. The vacuum tubes placements are critical and vary for different product sizes and configurations. These considerations must be evaluated before lay-up and could be optimised based on actual production performance. The placement of vacuum tubing increases the layup difficulty compared to the vacuum bagging method.
- Complicated vacuum bagging structure: Due to the importance of eliminating the potential resin runners, the vacuum bagging structure for VIFML is more complicated than for the ACFML method. The locations of all the pleats are designed to adapt to the relative product configuration. It could be expected to develop a pleats location guide for various product configurations for improving and regulating the pleats strategy on the vacuum bagging structure design.

7

Cost analysis

A theoretical cost estimation model is used in this study to compare the manufacturing costs between VI process and the traditional autoclave method for FML [25]. The cost drivers related to both the manufacturing processes of vacuum infusion and autoclave methods are interpreted regarding material, labour, tool and equipment factors [26, 27].

7.1. Cost model introduction

The cost model developed in this section is based on general steps of the manufacturing process listed in Figure 2.1. The details of the input and variables are explained below. In this study, only one sample size (20 cm-wide and 50 cm-long) is considered, so the geometry and material inputs were used to define the functional unit: a flat laminate of length (L), width (W) and thickness (h) made from the raw materials of dry fibreglass sheet and resin. Geometric complexity was not considered in this study. The labour activities provided data for the calculation of the working hours. The equipment inputs included purchase cost, maintenance and the work shift data. These are used to calculate equipment costs. The detailed computations associated with all inputs are described below. In this study, the total manufacturing costs are expressed on a per-part basis as monetary value (Euros), the manufacturing costs are divided into labour cost, materials cost and equipment cost, as is indicated in Equation 7.1

$$C_{total} = C_{labour} + C_{materials} + C_{equipment} \tag{7.1}$$

A flowchart indicating the VI FML manufacturing process is shown in Figure 7.1. On the left in Figure 7.1, the process steps during manufacturing are illustrated in various icons with an explanation. The rhombus icons represent the manufacturing cost items influenced by material selection and the product dimension. The rectangular icons represent the steps highly influenced by human activities, which for example is the labour time of the technicians. The arrows indicate the process flow. On the right part, the factors influencing the cost analysis are summarised and clearly listed. Figure 7.1 provides a straightforward illustration to guide the cost estimation as follows in this chapter.

7.2. Materials cost

The material cost is a sum of the different types of the raw materials and consumables used during the manufacturing process. When raw materials are cut, waste of materials cannot be avoided. So the waste of the raw materials should be included. The prices of materials used in the traditional autoclave method and the VI process are listed in Table 7.1. The material usage ratio chart can be found in Table 7.2.

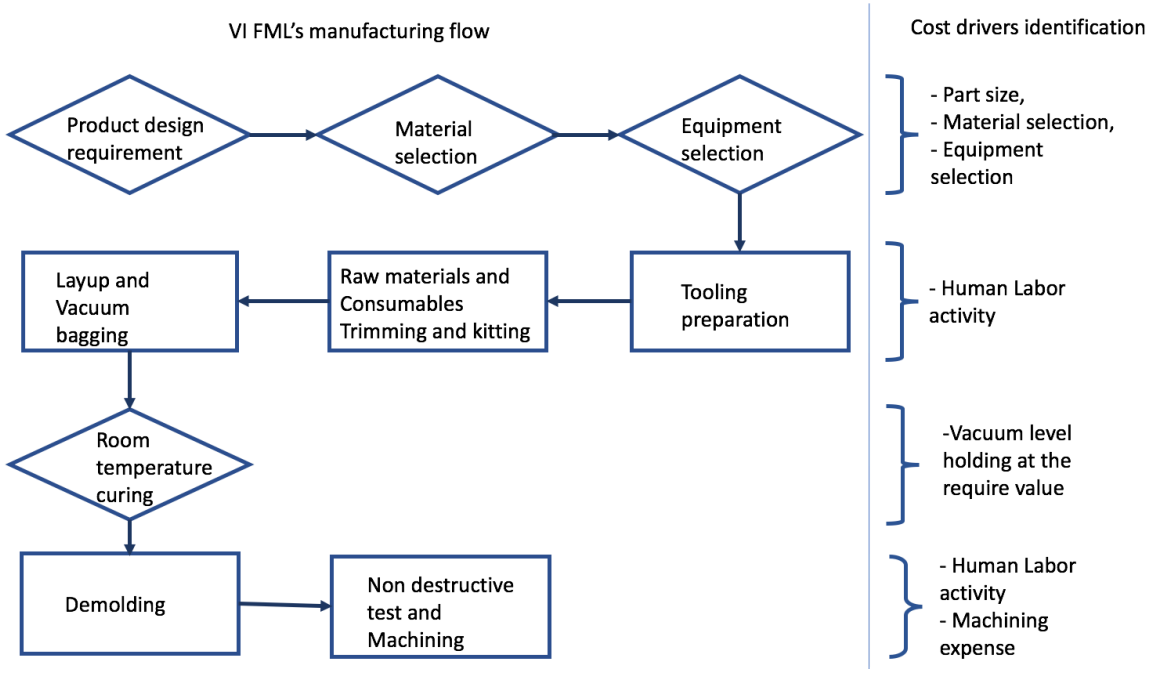


Figure 7.1: A flowchart demonstrating VI FML manufacturing process and major cost influencing factors.

Table 7.1: Materials price list. Note: ^{a} value are obtained from www.fibreglast.com

Materials	**Unit**	**Unit Price Unit [Euro]**
Fibreglass^a	Square Metre [m^2]	4.5
Epoxy^a	Kilograms [kg]	18
Prepreg^a	Square Metre [m^2]	52
Vacuum foil^a	Square metre [m^2]	0.17
Tacky tapes^a	Roll	7
Pressure sensitive tape^a	Roll	7
Ventilation materials^a	Square metre [m^2]	2
Release agent^a	Litre [litre]	80
Flow mesh^a	Square metre [m^2]	3
Markers^a	NA	1
PVC vacuum tube^a	Metre [m]	1.2
Mixing sticks^a	25 per pack	3
Cleaning solution^a	Litre [litre]	40

Table 7.2: Material use ratio (Net/gross Ratio) list.

Item	**Autoclave method**	**Resin infusion method**
Prepreg use ratio	0.7	-
Dry fibreglass use ratio	-	0.7
Epoxy use ratio	-	0.3
Vacuum bagging film overhang value [mm]	Length: 300 mm Width: 300 mm	Length: 600 mm Width: 600 mm
Ventilation material overhang value [mm]	Length: 125 mm Width: 125 mm	Length: 125 mm Width: 125 mm
Other consumable use ratio	0.7	0.7

The material cost is divided into raw materials cost and the consumable cost. For each sample the

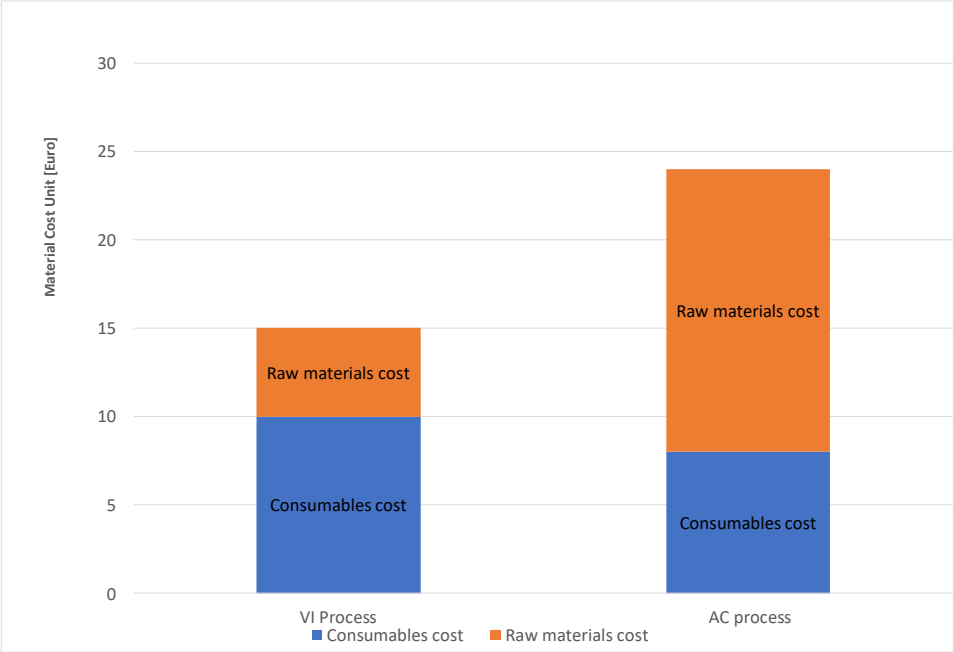


Figure 7.2: Materials cost comparison between VI process and AC process for the manufacturing of FML (Sample size of 20 cm by 50 cm with 2 metal sheets and 1 composite layer)

material cost is calculated using Equation 7.2.

$$C_{material} = \sum \left\{ \frac{MaterialActualUsage}{MaterialUsageRatio} \cdot UnitPrice \right\} \tag{7.2}$$

As the result calculated by Equation 7.2 with Table 7.1 and Table 7.2, the material cost for one VIFML sample is 15 euros and for one ACFML sample is 24 euros. The sample size used for cost estimation is 20 cm by 50 cm.
In this study, the raw material cost for vacuum infusion process is approximately 31 % of the materials cost of the traditional FML manufacturing method. The consumables for vacuum infusion process are slightly higher for the traditional method.

7.3. Labour Cost

The labour cost per manufacturing sample in this study is estimated by multiplying the total labour hours by the hourly wage, as it can be seen in Equation 7.3.

$$C_{labour} = (HourlyWage) \times (TotalLabourTime) \tag{7.3}$$

Taking one composite layer with Type 2 UD embedded in resin between two thin metal sheets as an example, the required labour time is listed in Table 7.3. In Table 7.3, a generic series of discrete tasks for the processing is listed. The steps include raw materials and consumable cutting, tool cleaning and de-greasing, release agent application, dry fibreglass layup, vacuum bag building and leak test, resin mixing and de-gassing, infusion, curing and de-moulding. These are the steps where labour is involved. For simplicity, a single operator was assumed to work exclusively on a single part throughout the steps outlined above. The required time for a given activity was defined according to the experimental process result. It should be noted that the required labour time listed here is shorter than the processing time in each step, e.g. the release agent application process does not need a technician to wait for the release agent to dry, but only to apply the release agent on the tooling. The individual processing time is compared between the VI process and the AC process in Figure 7.3 below. Most steps during both processes are similar, but there are extra manual steps for VI process such like resin mixing, degassing and infusion steps. Additionally, due to the runner elimination consideration, the vacuum bagging of vacuum infusion process is more complicated for the same structure and size of the product. The

labour time for each manual operation step and the total labour time are listed in Table 7.3.

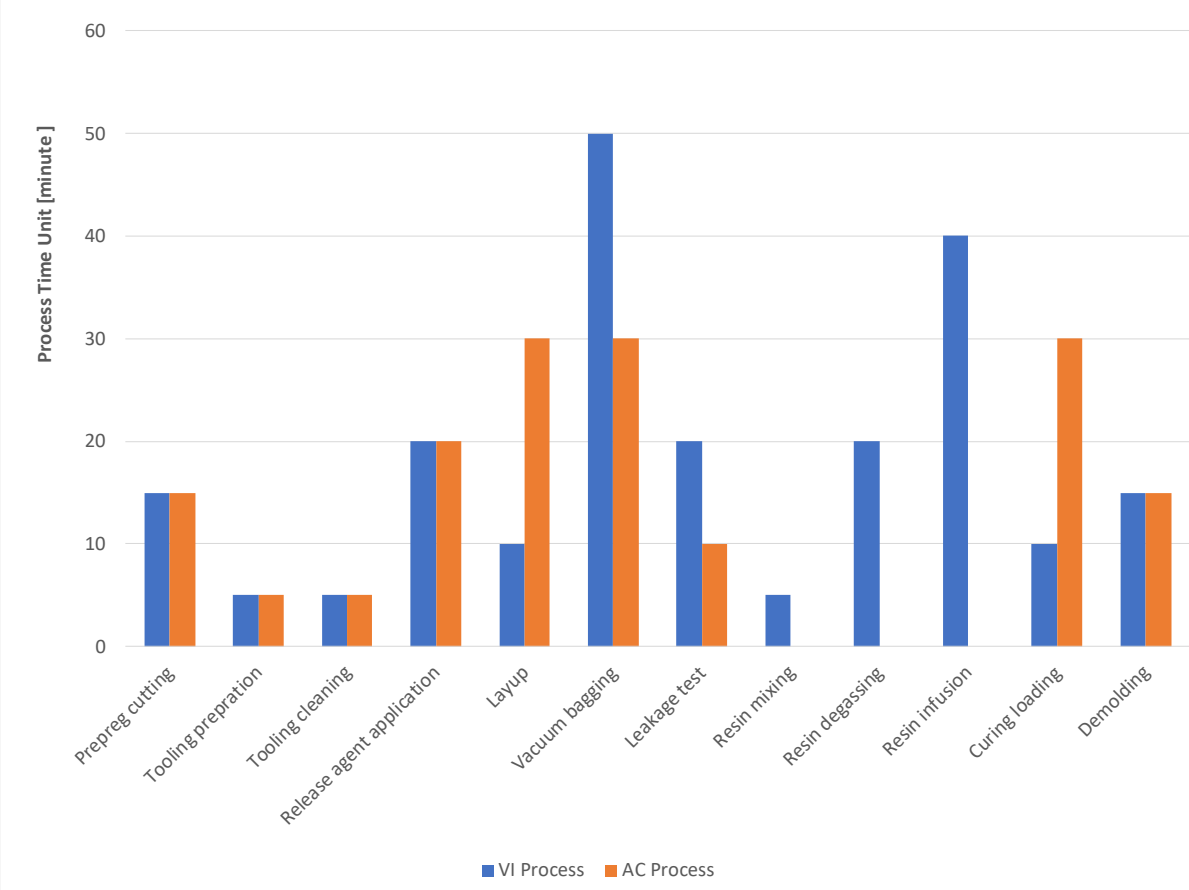


Figure 7.3: Labour time comparison between VIFML and ACFML manufacturing(Sample size of 20 cm by 50 cm with 2 metal sheets and 1 composite layer)

Table 7.3: Labour Cost Estimation List for VI and AC method. Note: ^{b} value are obtained from the experiment record in this study. ^{c} value is estimated on the average wage in the Netherlands in 2017.

Item	**Unit**	**Time consumed on Autoclave method**	**Time consumed on Vacuum Infusion method**
Prepreg cutting^{b}	minute	15	15
Tooling preparation^{b}	minute	5	5
Tooling cleaning^{b}	minute	5	5
Release agent application^{b}	minute	20	20
Layup^{b}	minute	30	10
Vacuum bagging^{b}	minute	30	50
Leakage test^{b}	minute	10	20
Resin mixing^{b}	minute	-	5
Resin de-gassing^{b}	minute	-	20
Resin infusion^{b}	minute	-	40
Loading autoclave/oven^{b}	minute	30	10
Demoulding^{b}	minute	15	15
Total	minute	**160**	**215**
Hourly wage : 30 euros/h^{c}			
Labor cost	**euro**	**80**	**107.5**

As it is calculated by using Equation 7.3 and Table 7.3, the labour cost for AC process is estimated to be

80 euros per panel and the labour cost of the vacuum infusion process is estimated to be 107.5 euros per panel. This shows that the required labour increased nearly 35 % for the vacuum infusion process in comparison to the AC method.

7.4. Equipment cost

The traditional FML's manufacturing method uses an autoclave while the VI process uses an conventional oven instead. Equipment cost includes the interest, the depreciation cost and the maintenance cost, as it is demonstrated in Equation 7.4.

$$C_{equipment} = C_{depreciation} + C_{interest} + C_{maintenance} \tag{7.4}$$

In this study, the cost items are estimated by breaking down to one sample fabrication cost to compare with each other. It is assumed that there are 250 working days per year and two shifts per working day for both autoclave and oven equipment. It is also assumed that 2 panels are manufactured each oven shift and 4 panels are manufactured per autoclave shift. The last assumption is that both an oven and an autoclave would be used for 10 years after purchase, which means that the intended life time of the equipment is 10 years. The depreciation cost per year can be estimated by using a straight line method with Equation 7.5.

$$C_{depreciation/year} = \frac{C_{purchase}}{10 years} \tag{7.5}$$

The total equipment cost is the sum of the purchase cost, the bank interest and the maintenance cost. It is listed in Table 7.4.

Table 7.4: Equipment cost list. Note: ^{d} value is estimated assumed value.

Item	Unit	Unit Price
Bank interest^{d}	percentage	5
Autoclave purchase cost ^{d}	euro	2,000,000
Autoclave annual maintenance cost^{d}	euro/year	50,000
Oven Purchase cost^{d}	euro	200,000
Oven annual maintenance cost^{d}	euro/year	5,000

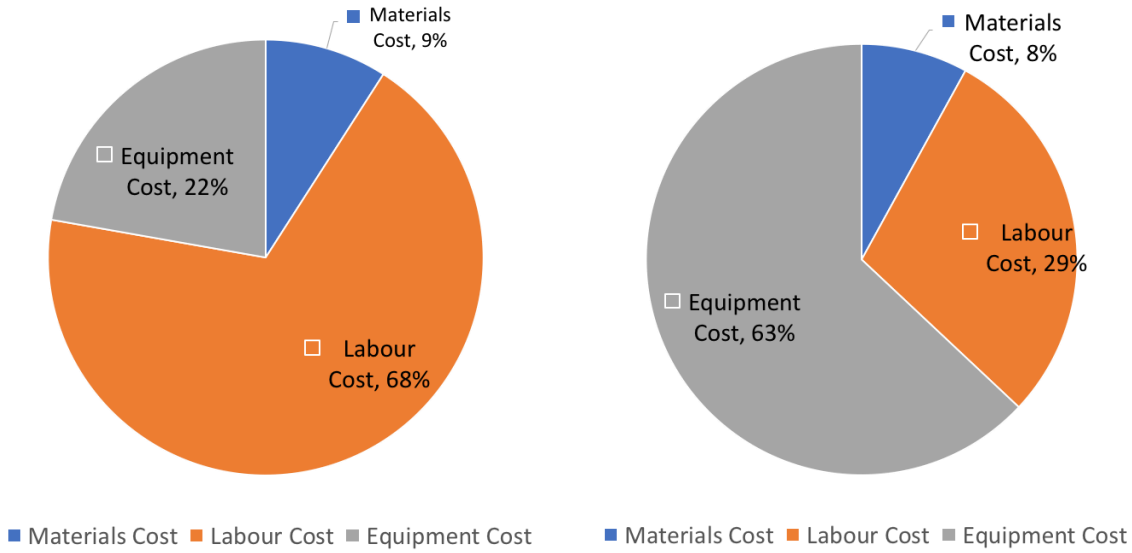
Combined with the values listed in Table 7.4 and the production schedule assumptions, the equipment cost can be calculated per panel manufactured by autoclave and oven by applying Equation 7.4. The equipment cost for a panel manufactured by VI process using an oven curing is 35 euros and the equipment cost for a panel manufacture by an autoclave curing is 175 euros. As a result, the equipment cost for VI process is significantly lower than AC process, which is a 80 % reduction.

7.5. Cost comparison between the Vacuum Infusion process and Autoclave curing process for FML manufacturing

The total cost comparison is conducted between the traditional autoclave manufacturing steps, and the new developed VIFML process. Firstly, the cost estimation is conducted on a sample with the size of 20 cm by 50 cm, layup with 2 metal sheets and 1 composite layer for both manufacturing methods. From the result of the previous sections, the result of the cost estimation is listed in Table 7.5 and illustrated in Figure 7.4. The equipment cost and materials cost are also decreased during the Vacuum infusion process. The labour time is 35 % higher for the VI process than for the AC method. However, the higher labour cost associated with vacuum infusion process is easily compensated for by the savings on materials, and especially the equipment cost. In general, the total cost from the VI process is still significantly lower than the AC method.

Table 7.5: Cost Estimation for FML 2A-1/2-0.4mm(Sample size of 20 cm by 50 cm)

Item	FML 2A-2/1-0.4mm by VI process	FML 2A-2/1-0.4mm by AC process
Material Cost [Euro]	15	24
Labour Cost [Euro]	108	80
Equipment Cost [Euro]	35	175
Total Cost [Euros]	158	279



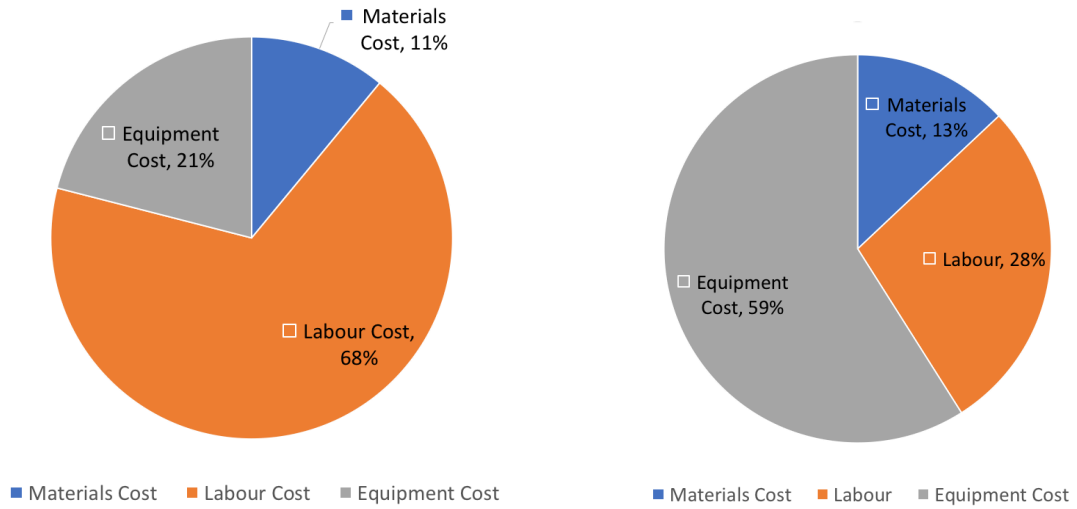
(a) VI process (b) AC process

Figure 7.4: (a) Cost distribution of FML 2a-2/1-0.4MM sample (20cm by 50 cm) manufactured by VI process. (b) Cost distribution of FML 2a-2/1-0.4MM sample (20cm by 50 cm) manufactured by AC process

Secondly, another cost estimation is conducted on another kind of sample with the size of 20 cm by 50 cm, layup with 3 metal sheets and 2 composite layers. The material cost increases due to the additional metallic and composite layers. The labour cost also increased due to the increased layup operation (assumed that laying up one ply is 5 minutes operation). It should be noted that since the sample area size is not changing, the other processes, except for the layup process, are not influenced by the sample's thickness increase. Therefore, the equipment cost is not changing for this case. The cost estimation is conducted using the method in the previous sections. The cost distribution for the fabrication of samples with two composite layers and three metal sheets for both VI and AC processes is listed in Table 7.6 and illustrated in Figure 7.5. It can be observed that the labour cost in the VI process is still taking the largest part in the total cost.

Table 7.6: Cost Estimation for FML 2A-3/2-0.4mm(Sample size of 20 cm by 50 cm)

Item	FML 2A-3/2-0.4mm	FML 2A-3/2-0.4mm
Material Cost [Euro]	18	39
Labour Cost [Euro]	113	85
Equipment Cost [Euro]	35	175
Total Cost [Euro]	166	299



(a) VI process (b) AC process

Figure 7.5: (a) Cost distribution of FML 2A-3/2-0.4MM sample (20cm by 50 cm) manufactured by VI process. (b) Cost distribution of FML 2A-3/2-0.4MM sample (20cm by 50 cm) manufactured by AC process

In general, the total manufacturing cost of the VI process is lower than the total manufacturing cost of the AC process for the same product. However, the labour cost for manufacturing a single product is significantly higher in the VI process. The labour cost is taking more than half of the total cost for VI process, therefore, decreasing the labour cost is highly recommended to be studied in the future.

7.6. Cost sensitivity analysis

In this section, a brief sensitivity analysis is performed on how changes of the input cost parameters affects the change of the total cost output. The cost drivers are ranked according to their sensitivity with respect to the manufacturing process. The total cost output is broken down into labour cost, material cost and equipment cost. The result from the previous cost estimation is used as the base estimation value of each variable. Therefore, the cost would vary against the base estimation as a change in percentage. To study the effect of the cost drivers, Equation 7.6 for the sensitivity index is applied to describe relationship on how these individual cost drivers influence the total cost. In this equation $\Delta\%$ is the percentage change of respectively the total cost and the cost driver.

$$SensitivityIndex = \frac{\Delta\%_{TotalCost}}{\Delta\%_{CostDriver}} \tag{7.6}$$

The base values of the reference sample are listed in Table 7.7 for the sensitivity analysis. The base value includes the product details, relevant cost values and the main cost drivers, which will be discussed in the following sections.

Table 7.7: Base Value for Sensitivity Analysis

Item	Value
Sample details	Flat panel of 20 cm width by 50 cm length, FML 2A-2/1-0.4mm, 2 layers of aluminium and 1 layer of fibre, each metal layer is 0.4 mm
Hourly Wage	30 Euros/hour
Processing time	215 minutes
Material Cost	15 Euros
Equipment Cost	35 Euros
Labour Cost	108 Euros
Total Cost	158 Euros

7.6.1. Labour cost sensitivity analysis

The hourly wage is an important cost driver influencing the labour cost in the manufacturing process. For instance, the hourly wage could vary significantly for different countries or for people with different working experience. Assumed the manufactured sample size is 20 cm by 50 cm with 2 metal sheets and 1 composites layer structure. In this case, the hourly wage range is assumed to vary from 10 Euros/hour to 60 Euros/hour. The corresponding sensitivity index is calculated and listed in Table 7.8.

Table 7.8: Hourly Wage factor sensitivity analysis for VI process

Item	Base Value of Hourly Wage of 30 Euros/hour	Minimum Value with Hourly Wage of 10 Euros/hour	Maximum Value with Hourly Wage of 60 Euros/hour
Estimated Labour Cost per each sample	108 Euros	36 Euros (-67%)	215 Euros (99%)
Total Cost	158 Euros	86 Euros (-46%)	265 Euros (68%)
Sensitivity Index	-	0.69	0.69

7.6.2. Equipment cost sensitivity analysis

During the industrial application, it is common that several products are cured together in the same cure cycle to meet the high speed production rate. To study the sensitivity of the batch curing factor, there are some assumptions made below:

- The current oven is capable to cure maximum 8 panels per cure cycle.
- There are 250 working days per year.
- There are 2 shifts per work day.
- The useful equipment time is assumed as 10 years.

The depreciation cost is estimated by Equation 7.5. Therefore, a sensitivity analysis regarding to the number of panels cured per batch is studied and the result is listed in Table 7.9. It could be observed that the amount of products cured in the same cycle is very important for the equipment cost reduction during a high speed production.

Table 7.9: Sensitivity Index for Batch curing influence for VI process

Item	Base Value of 2 samples per cure cycle	Minimum Value of 1 sample per cure cycle	Maximum Value of 8 samples per cure cycle
Estimated Equipment Cost per each sample	35 Euros	70 Euros (100%)	8.75 Euros (-75%)
Total Cost	158 Euros	193 Euros (22%)	131.75 Euros (-17%)
Sensitivity Index	-	0.22	0.23

7.6.3. Materials cost sensitivity analysis

As we know, the price of the material change influences the total material cost during manufacturing. The material cost consists of the raw material cost and the consumables cost. To simplify the study, the consumable price is considered as fixed, while the raw material price changes for the sensitivity analysis. The corresponding sensitivity index is calculated and listed in Table 7.10.

Table 7.10: Sensitivity Index for raw material price changes for VI process

Item	Base Value	MinimumValue of raw material cost	Maximum Value of raw material cost
Estimated Raw Material Cost per each sample	5 Euros	2.5 Euros (-50%)	20 Euros (300%)
Estimated Consumable Cost per each sample	10 Euros	10 Euros	10 Euros
Total Cost	158 Euros	155.5 Euros (-1.5%)	173 Euros (9%)
Sensitivity Index	-	0.03	0.03

Additionally, the change in product surface area or thickness influences the material cost and the total cost during the manufacturing process. Therefore, the materials cost sensitivity analysis is also conducted on changing the sample's thickness and the sample's surface area individually.
Firstly, the sensitivity analysis about the product thickness change is discussed. Assumed that the sample area size is 20 cm by 50 cm. The raw materials remain the same type, but the number of the layers changes from 2(metal)/1(glass fibre) to 5/4 to 9/8. Therefore, the material cost changes linearly based on the method in Section 7.2. The processing time also changed due to the additional plies, as it is mentioned in Section 7.5, each extra plies layup takes 5 minutes. The equipment cost stays the same for this case. The result of the cost estimation on the various thicknesses on manufacturing of the sample is listed in Table 7.11 and the sensitivity index is calculated accordingly.
Secondly, the sensitivity analysis about the product surface area change is discussed. Assumed that the sample layup remains at 2 metal sheets and 1 composite layer. The estimated minimum size of the sample is chosen as 10 cm by 10 cm. Based on the estimation for the maximum infusion area of VIFML product, the maximum infusion distance is 1.4 m. Therefore, the dimension of the estimated maximum infusion part is assumed as 1.4 m by 1.4 m. The material cost is calculated as the method

Table 7.11: Sensitivity Index of Material thickness changing

Item	Base Value of lay up of of FML 2A-2/1-0.4mm	Minimum Value of layup of FML 2A-5/4-0.4mm	MaximumValue of layup of FML 2A-9/8-0.4mm
Estimated Thickness	1.4mm	4.8 mm (243%)	8.4 mm (500%)
Estimated Material Cost per each sample	15 Euros	24 Euros (60%)	36 Euros (140%)
Estimated Labour Cost per each sample	108 Euros	123 Euros (13%)	143 Euros (32%)
Total Cost	158 Euros	182 Euros (15%)	214 Euros (35%)
Sensitivity Index	-	0.06	0.07

in Section 7.2. Due to the change in area of the sample, the tooling size and the vacuum bagging size need to change accordingly. Thus, a new model of the process estimation is developed for this case. The process time is estimated according to Table 7.12 below. The equipment cost is estimated without change. Therefore, the cost estimation is conducted and the result is listed in Table 7.13.

Table 7.12: Process Estimation for Product with various Surface area

Item	Base value Unit [minute]	Minimum Value Unit [minute] (For product with surface area < 0.1 m^2)	Maximum Value Unit [minute] (For product with surface area > 0.1 m^2)
Prepreg cutting	15	$15 - \frac{Base\ Area\ Size}{Estimated\ Area\ size}$	$15 + \frac{Base\ Area\ Size}{Estimated\ Area\ Size}$
Tooling preparation	5	$5 - 0.2\times\frac{Base\ Area\ Size}{Estimated\ Area\ Size}$	$5 + \frac{Base\ Area\ Size}{Estimated\ Area\ Size}$
Tooling cleaning	5	$5 - 0.2\times\frac{Base\ Area\ Size}{Estimated\ Area\ Size}$	$5 + \frac{Base\ Area\ Size}{Estimated\ Area\ Size}$
Release agent application	20	$20 - 0.5\times\frac{Base\ Area\ Size}{Estimated\ Area\ Size}$	$20 + \frac{Base\ Area\ Size}{Estimated\ Area\ Size}$
Layup	10	$10 - 0.1\times\frac{Base\ Area\ Size}{Estimated\ Area\ Size}$	$10 + 5\times\frac{Base\ Area\ Size}{Estimated\ Area\ Size}$
Vacuum bagging	60	$60 - 3\times\frac{Base\ Area\ Size}{Estimated\ Area\ Size}$	$60 + 3\times\frac{Base\ Area\ Size}{Estimated\ Area\ Size}$
Leakage test	20	20	20
Resin Mixing	5	5	5
De-gassing	20	20	20
Infusion	40	*Refer to the extrapolation result in Figure 6.2*	
Demoulding	15	$15 - 0.2\times\frac{Base\ Area\ Size}{Estimated\ Area\ Size}$	$15 + \frac{Base\ Area\ Size}{Estimated\ Area\ Size}$

Table 7.13: Sensitivity Index Analysis on various sample surface area with the same layup

Item	Base Value of sample size of 0.2m by 0.5m	MinimumValue of sample size of 0.1m by 0.1m	Maximum Value of sample size of 1.4m by 1.4m
Estimated product surface size	0.1 sqm	0.01 sqm (-90%)	1.96 sqm (1860%)
Estimated Material Cost per each sample	15 Euros	1.5 Euros (-90%)	294 Euros (1860%)
Estimated Labour Cost per each sample	108 Euros	61.5 Euros (-43%)	280 Euros (160%)
Total Cost	158 Euros	98 Euros (-38%)	609 Euros (285%)
Sensitivity Index	-	0.42	0.15

7.6.4. Ranking of Sensitivity influence

Using the information of the sensitivity index analysis above, the cost driver of hourly wage changing is influencing the total cost most with the sensitivity index of 0.69. The equipment cost influences the total cost least with the sensitivity index from 0.22 to 0.23 on the condition of high-speed production required. The raw material price influences the total manufacturing cost with the sensitivity index of 0.03. And the material thickness and the product size demonstrate the different influence on the total cost with the sensitivity index from 0.06 to 0.42. Hence, the cost driver of hourly wage value is identified to influence the total manufacturing cost most while the material price has the least influence. Therefore, several recommendations to reduce the production cost are made as follows:

- Outsourcing the production to the area with a lower hourly wage to reduce the labour cost, however, other costs such like management cost, tax and transportation cost etc. should also be considered for the final decision;
- Apply Lean manufacturing on the process to reduce the waste and reduce the labour hours. Therefore, the total cost could be minimised;
- Develop curing racks or another curing tooling to allow more pieces of the production cured at the same curing cycle. The improvement of the oven curing efficiency would lower the total cost.

7.7. Concluding remarks

The materials, size of the sample, the layup process and the cure cycle conditions for these two different composite manufacturing methods were illustrated. The cost breakdown for the composite production process was analysed and identified according the cost estimation model developed by Gotowski [25]. The results of the experiments and analysis conclude that using OoA gives the lowest total production cost with a reduction of 43 % in comparison to the autoclave process for the thinner sample and 44 % reduction for the thicker sample.

8

Conclusion and Recommendations

8.1. Conclusions

An alternative manufacturing method for Fibre Metal Laminates was studied and presented in this report to provide an economical technique with acceptable product quality. The proposed technique is vacuum infusion of the dry fibres in between the aluminium sheets. This technique was found to be feasible by infusion dry glass fibre sheets in between glass plates. The glass plates made it possible to visually monitor and inspect the infusion process. When a stable infusion process was established, FML with 3 metal layers and 2 glass fibre layers were successfully infused. The resulting FMLs were analysed using cross-sectional microscopy for their fibre and void content. Special attention was needed for the preparation of the vacuum bag to avoid runners: edge dams of tacky tape and pleats were needed. The main observations are the following:

- The dry fibre preform has a large impact on the infusion distance and duration. The uniform non-crimp unidirectional tape infused infused slower than the weaved unidirectional tape, in which the fibre bundles are stitched together. The non-crimp unidirectional tape could not be infused fully over 50 cm.
- The infusion distance and speed depends on the fibre orientation. Infusion in 0° direction results in the fastest infusion.
- The applied vacuum did not influence the infusion distance and speed to a large extent. A too low vacuum pressure (500 mbar) did result in loose bag structure and an unsuccessful infusion.
- The viscosity of the resin was altered by heating up the resin during the infusion with a heat blanket. At too high resin temperatures (e.g. 45°C) the resin started curing before a full infusion was established. Heating the resin to 35°C was found to halve the duration of the infusion compared to room temperature. But a slightly shorter infusion distance was reached, most likely because of the earlier curing of the resin.
- The weaved unidirectional tape was used to produce actual FML with three sheets of aluminium and two layers of glass fibre at room temperature. These infusions were found to be successful with a void content of 1.5 % and a fibre volume fraction of at least 54 %. The thickness was slightly larger compared to the traditional manufacturing approach because the glass layers had a larger thickness. The cost analysis showed a 44 % cost reduction for the vacuum infusion process compared to the traditional autoclave manufacturing process of FML. The main cost driver for the traditional approach was found to be the equipment cost, which could be reduced by using the vacuum infusion approach.
- By extrapolating the experimental infusion curves, it was estimated that under the current conditions a maximum infusion length of 1.4 m most likely is possible when infused over the 0° direction, and a maximum infusion length of 1.0 m is expected to be possible when infused over the 90° direction. However, the theoretical estimation showed that potentially an infusion distance of 4.2 m might be reached when resin and preform selection are optimised.

- For industrial applications special attention will be required when splicings, (external) doublers and ply drop-offs existing in the product because open spaces created in these cases might act as resin runner, which might result in dry-spots and voids.

All in all it can be concluded that manufacturing FMLs by using vacuum infusion is feasible, and cost effective in comparison to the traditional prepreg plus autoclave method. This study opens the doors for additional research to make vacuum infusion of FMLs possible in an industrial setting.

8.2. Recommendations

The main recommendations are listed:

- The textile structure of the dry fibre unidirectional tapes are significantly influencing the infusion results, therefore, more exploration and trials on other textile structure of dry fibreglass tapes should be conducted. For example, the new renovation of the textile structure Spread tow fabric could be considered as a new candidate to build a new FML structure.
- The labour time did not reduce in this study. Thus it is recommended to study lowering the labour time. Automated layup is an excellent choice for manual operation reduction, especially for the large structure component layup.
- Glare materials aim at carrying loads of tensile, shear and bending. Therefore, the mechanical tests such like tension tests, three-points bending tests and fatigue tests are recommended.
- Glare is also well known for its excellent fatigue resistance and impact resistance properties, so the fatigue test and impact test can be conducted on VIFML materials to compare with the current Glare materials.
- It is recommended to study new resin types that have a low viscosity during a long period of time. Making it possible to infuse longer parts.

A

Estimated maximum infusion time

Figures A.1, A.2 and A.3 show the estimated viscosity change over time for the resin used in this study. The figures show that the pot life is halved for every increase of $10°C$ with respect to the room temperature of 25 $°C$[16]. In Chapter 5 infusions where performed under these temperature conditions in respectively tests, 1, 8 and 9. The time at which the infusions stopped is indicated in the figures with the blue dot. An estimation of the corresponding viscosity is made. It can be seen that at room temperature the resin stopped flowing after 160 min, for the $35°C$ is stopped at 70 min and for $45°C$ it stopped at 35 min. This corresponds roughly to an estimated viscosity of $190 - 198$ mPas. The maximum infusion time is taken from Figure A.1 because this is the room temperature case, which has been used for most experiments and is most favourable to be used in industry. Figures A.2 and A.3 support maximum infusible viscosity with their values of around 190 mPas. Therefore, the maximum infusible time is estimated to be 160 min.

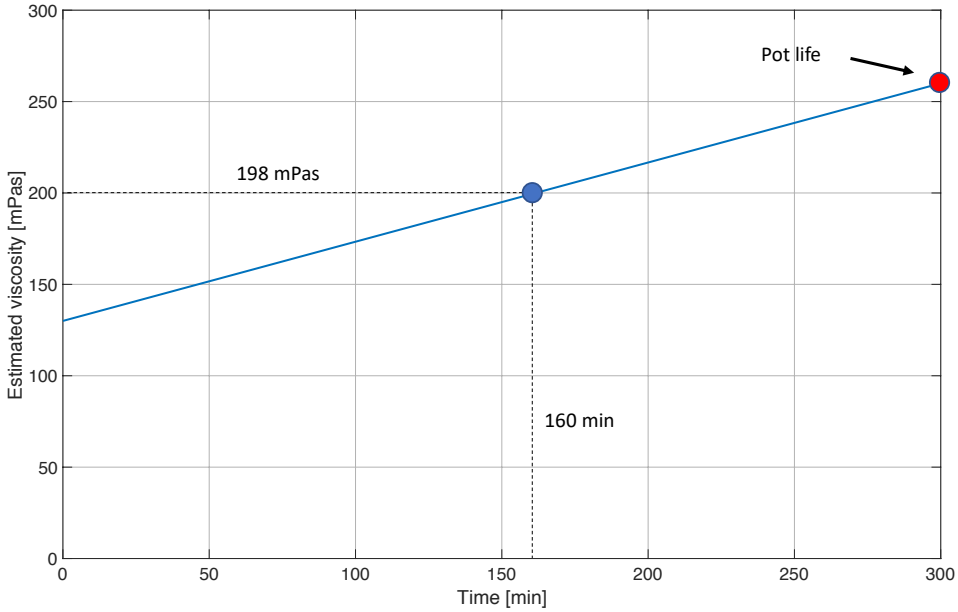


Figure A.1: Estimated viscosity change over time at room temperature [16]. The moment when the infusion stopped is indicated by the blue dot. Type 1 glass fibre.

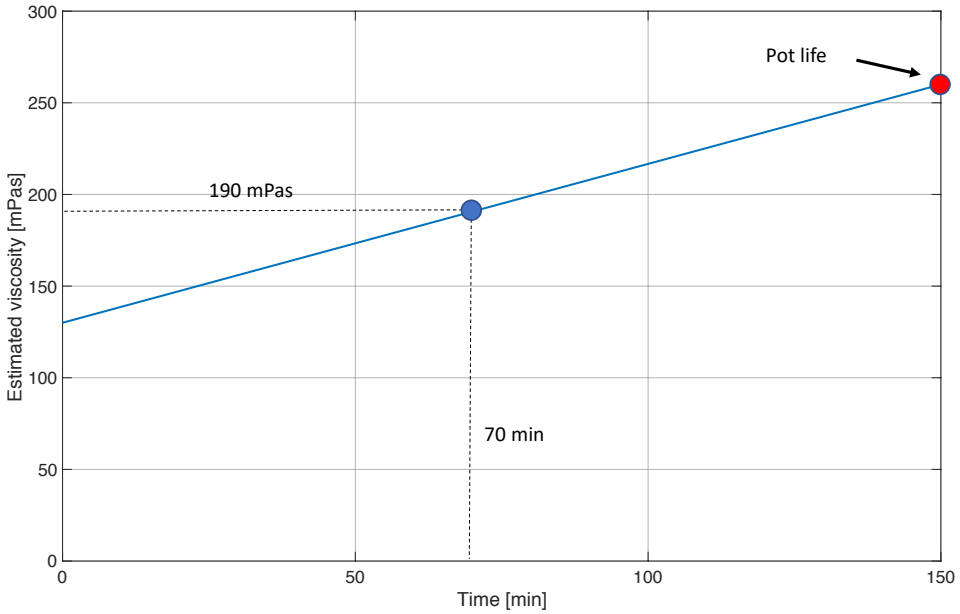


Figure A.2: Estimated viscosity change over time at $35°C$ [16]. Type 1 glass fibre.

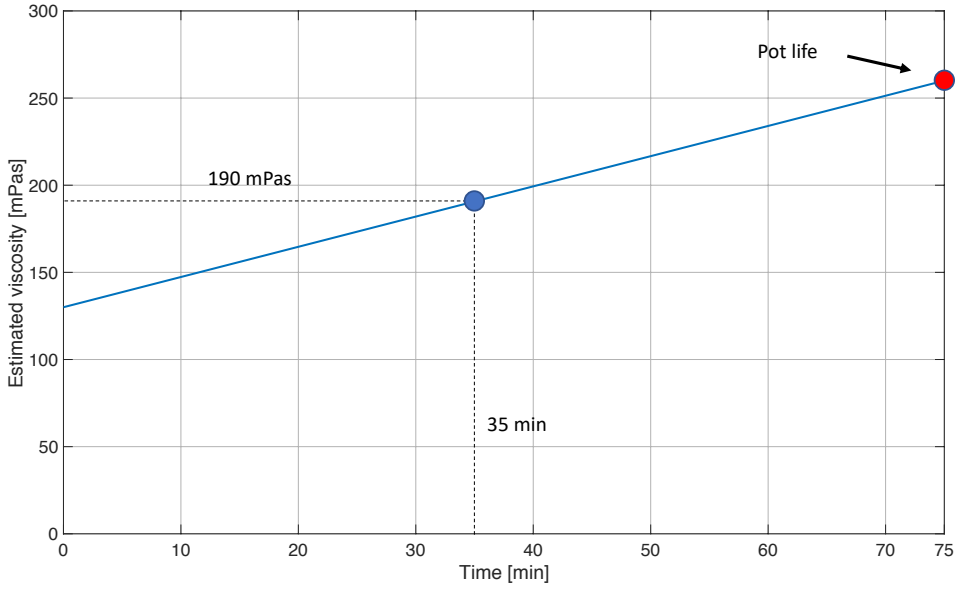


Figure A.3: Estimated viscosity change over time at $45°C$ [16]. Type 1 glass fibre.

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