DEVELOPMENT, MODELLING AND ANALYSIS OF VACUUM ASSISTED MULTIPoint MouldING FOR MANUFACTURING FIBRE-REINFORCED PLASTIC COMPOSITES

by

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A thesis submitted to the University of Plymouth in partial fulfilment for the degree of

DOCTOR OF PHILOSOPHY

School of Engineering

[In collaboration with Munich University of Applied Sciences]

May 2019
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It is a capital mistake to theorize before one has data. Insensibily one begins to twist facts to suit theories, instead of theories to suit facts.

(Sherlock Holmes, 1892)\textsuperscript{1}

\textsuperscript{1} in *A Scandal in Bohemia* (1891) by Sir Arthur Conan Doyle, discovered on a bronze plaque embedded in the sidewalk of Durnford Street, Plymouth (UK)
Acknowledgements

I wrote this thesis during my employment at the Munich University of Applied Sciences as part of the research project Flex4CFK. For their financial support to both the project and to my student fees, I want to thank Fa. Huber Kunststoff und Technik GmbH. In addition, I am deeply grateful for the support of Fa Putzin Maschinenbau GmbH and Mr. Jens-Hendrik Schmidt. They manufactured all the mechanical components for the multipoint tool test bench and the prototype and gave valuable input in the design process. My gratitude also goes to SGL Carbon SE for supporting me with carbon fibre material for testing.

I want to thank my supervisors Prof. Christoph Maurer and Prof. Dr. Frank Abraham for their support and supervision during this endeavour. My gratitude goes to my colleagues and especially to Georg Lößl, our lab foreman, who always offered a helping hand and kept me awake and sharp with a gazillion cups of coffee.

Thank you to all the students that supported me in my work as student aids in the course of their final theses. The huge amount of work that went into this book would not have been possible without them.

I thank my parents for their unconditional support throughout all my academic endeavours. However, the biggest THANK YOU goes to my best friend, the love of my life and future wife. Bettina, without you, I would never have finished this enormous project. You supported me whenever I was close to giving up. You kept me going and built me back up when I was down. I deeply hope to be able to repay you one day.
Author's Declaration

At no time during the registration for the degree of Doctor of Philosophy have I been registered for any other University award without prior agreement of the Doctoral College Quality Sub-Committee. Work submitted for this research degree at the University of Plymouth has not formed part of any other degree either at the University of Plymouth or at another establishment.

Parts of this study were carried out in collaboration with SGL Carbon SE, Putzin Maschinenbau GmbH, Airbus Helicopters and Huber Kunststoff & Technik GmbH, and University of Applied Sciences Nuremberg. All content of this thesis represents my individual contribution if not indicated otherwise. All contributions of other sources are referenced in the text.

Publications:


Presentations at conferences:


Word count of main body of thesis: 79.493

Signed
Date 04 November 2019
Abstract

Matthias Wimmer

Development, modelling and analysis of Vacuum Assisted Multipoint Moulding for manufacturing fibre-reinforced plastic composites

Multipoint tooling is a mould making technology that enables the rapid reconfiguration of a mould to create individual components. It replaces the commonly used, elaborately designed, and costly manufactured solid die, with an array of individually adjustable pins. These pins can be set to represent a large variety of freeform surfaces. An elastic interpolation layer (IPL) is used to smoothen the pin array and forms the actual tooling surface. This technology is well established in sheet metal forming and other areas of manufacturing. However, only little research has been conducted in the area of fibre-reinforced plastic composites.

In this thesis, a novel multipoint tooling technology is introduced, that is specifically designed for fibre-reinforced plastic (FRP) manufacturing. Different to existing solutions, this Vacuum Assisted Multipoint Moulding (VAMM) is capable of creating concave and convex geometries on a single sided mould. This enables the use of established FRP manufacturing processes without further adaptation. Two iterations of this technology are developed: A manually adjusted small-scale test bench is used to validate the VAMM concept and conduct experiments on, and a fully automated full-scale manufacturing prototype then is used to demonstrate the feasibility of the technology for an industrial application.

The elasticity of the IPL introduces two system immanent dimensional defects: the overall shape deviates due to the deformation of the IPL and the punctual support of the interpolation layer leads to a golf-ball-like surface effect. A process model was created to predict behaviour of the VAMM tool and the interpolation layer, and estimate the expected part quality. An iterative shape control algorithm was implemented, to improve the dimensional accuracy of the manufacturing process, by readjusting individual pins in the tool. On this model, a sensitivity analysis was conducted to quantify the influence of the process and pin array parameters on the dimpling of the tool surface. The most important parameters were identified and used in a Metamodel of Optimal Prognosis (MOP). This MOP enables the rapid estimation of the system behaviour. It was used to optimise the VAMM process and the interpolation layer in order to maximise the geometric part quality. With this method two IPL designs, one with a single, and one with two separate layers of silicone rubber, were evaluated. It turned out that the dual layer configuration can handle a 24 % higher process pressure, while using a 9 % thinner interpolation layer, to produce parts similar to the single layer configuration.
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List of Abbreviations

A/F   Across Flats
AABB  Axis Aligned Bounding Boxes
ALHS  advanced Latin Hypercube Sampling
AVAB  average absolute
CAD   computer aided design
CFRP  carbon fibre-reinforced plastics
CMM   coordinate measuring machine
CNC   computer numeric control
CoD   coefficient of determination
CoP   coefficient of prognosis
DATAFORM  Digitally Adjustable Tooling for Manufacturing Aircraft Panels Using Multipoint Forming
DDF   Digitized Die Forming
DoE   Design of Experiment
DOF   degrees of freedom
DTF   Deformation Transfer Function
EA    evolutionary algorithm
FDS   Flexible Die System
FE    finite element
FEA   finite element analysis
FRP   fibre-reinforced plastics
FST   Flexible Surface Tooling
GD&T  geometric dimensioning and tolerancing
GFRP  glass fibre-reinforced plastics
HA    hydraulically actuated pin concept
HMI   human-machine interface
IFCD-MPF  Individually Force Controlled Displacement MPF
IPL   interpolation layer
LAN   local area network
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>LHS</td>
<td>Latin Hypercube Sampling</td>
</tr>
<tr>
<td>MCR</td>
<td>Monte Carlo Simulation</td>
</tr>
<tr>
<td>MDD</td>
<td>Multipoint Deep Drawing</td>
</tr>
<tr>
<td>MOP</td>
<td>Metamodel of Optimal Prognosis</td>
</tr>
<tr>
<td>MPF</td>
<td>Multipoint Forming</td>
</tr>
<tr>
<td>MPFS</td>
<td>Multipoint Sandwich Forming</td>
</tr>
<tr>
<td>MPST</td>
<td>multipoint stretch forming tool</td>
</tr>
<tr>
<td>MPT</td>
<td>multipoint tooling</td>
</tr>
<tr>
<td>NC</td>
<td>numeric control</td>
</tr>
<tr>
<td>NPQL</td>
<td>Non-linear Programming by Quadratic Lagrangian</td>
</tr>
<tr>
<td>PDO</td>
<td>process data object</td>
</tr>
<tr>
<td>PLC</td>
<td>programmable logic controller</td>
</tr>
<tr>
<td>PMMA</td>
<td>Polymethyl methacrylate</td>
</tr>
<tr>
<td>R²</td>
<td>coefficient of determination</td>
</tr>
<tr>
<td>RMS</td>
<td>root mean square</td>
</tr>
<tr>
<td>RTFF</td>
<td>Reconfigurable Tooling for Flexible Fabrication</td>
</tr>
<tr>
<td>RTM</td>
<td>resin transfer moulding</td>
</tr>
<tr>
<td>SA</td>
<td>sensitivity analysis</td>
</tr>
<tr>
<td>SDL</td>
<td>shaft driven leadscrew pin concept</td>
</tr>
<tr>
<td>SDO</td>
<td>service data object</td>
</tr>
<tr>
<td>SMPF</td>
<td>Sectional Multipoint Forming</td>
</tr>
<tr>
<td>SPS</td>
<td>semi parallel [pin actuation] setup</td>
</tr>
<tr>
<td>SSU</td>
<td>sequential setup pin concept</td>
</tr>
<tr>
<td>UD</td>
<td>unidirectional (e.g. fabrics)</td>
</tr>
<tr>
<td>VAMM</td>
<td>Vacuum Assisted Multipoint Moulding</td>
</tr>
<tr>
<td>VARTM</td>
<td>vacuum assisted resin transfer moulding</td>
</tr>
<tr>
<td>VGM</td>
<td>Variable Geometry Mould</td>
</tr>
<tr>
<td>VI</td>
<td>vacuum injection</td>
</tr>
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</table>
List of Symbols

In this work, vectors are generally written in **bold** small letters as $\mathbf{x} = \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix}$, and matrices are written in **bold** capital letters as $\mathbf{X} = \begin{pmatrix} x_{1,1} & x_{1,2} & \cdots & x_{1,n} \\ x_{2,1} & x_{2,2} & \cdots & x_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m,1} & x_{m,2} & \cdots & x_{m,n} \end{pmatrix}$.

The following symbols are used within the thesis:

- $\bar{I}_1$ first deviatoric principal invariant
- $\bar{I}_2$ second deviatoric principal invariant
- $A^*_i$ projected area
- $C_{10}, C_{01}, C_{11}$ phenomenological material constants
- $D_i$ dimpling parameter (unspecified)
- $D_{min}$ minimal dimpling
- $D_{orth}$ orthotropic (normal) dimpling
- $D_{vert}$ vertical dimpling
- $D_{vol}$ volumetric dimpling
- $E_{AVAB}$ average absolute error
- $E_{rr}$ global shape error or average shape error
- $N_i$ number of pins in a row
- $N_w$ number of pins in a line
- $V_i$ volume between two faces in a geometries
- $e_{AM}$ absolute maximum shape error
- $e_{RMS}$ root mean square shape error
- $e_{zi}$ local shape error
- $l^*$ actual length of the pin array
- $r_i$ inner circumradius of the pin
\( r_o \) outer circumradius of the pin
\( s_c \) coupling success rate
\( t_{IPL} \) total thickness of the IPL
\( t_{IPL1} \) thickness of the top layer of the dual layer IPL
\( t_{IPL2} \) thickness of the bottom layer of the dual layer IPL
\( w' \) actual width of the pin array
\( z_{ai} \) \( z \) coordinate of the \( i \)-th sampling point on the actual part
\( z_a \) \( z \) coordinates of all sampling points on the actual part
\( z_{ti} \) \( z \) coordinate of the \( i \)-th sampling point on the target part
\( z_t \) \( z \) coordinate of all sampling points on the target part
\( G_p \) transfer function of a forming process
\( N_f \) Nodes of the surface \( S_f \)
\( S_c \) compensated surface (target surface \( S_t \) with effects of manufacturing process compensated)
\( S_f \) simulated (formed) surface
\( S_m \) measured surface (physical)
\( S_p \) part surface (surface of the desired component)
\( \rho_f \) density of the fibres in a composite
\( \rho_m \) density of the matrix in a composite
\( \Delta z_i \) distinct shape error value for each pin
\( \Delta z_- \) distance between actual and target geometry in negative \( z \) direction
\( \Delta z_+ \) distance between actual and target geometry in positive \( z \) direction
\( \Delta z_A \) areal shape error between the actual and target geometry
\( \Delta z \) shape error value vector for a tool
\( h \) characteristic dimension of a finite element
\( \Delta t^{\text{crit}} \)  critical time step
\( \Psi \)  strain energy potential
\( K \)  initial bulk modulus
\( N \)  number of pins in a pin array
\( RMSE \)  root mean square error
\( SS_E \)  unexplained variance
\( SS_E^p \)  sum of squared prediction errors
\( SS_R \)  variance of an output due to regression
\( SS_T \)  total variance of an output
\( V \)  volume between two geometries
\( a \)  pin size
\( c \)  speed of sound
\( d \)  incompressibility parameters
\( e \)  global shape error
\( l \)  nominal length of the pin array
\( n \)  normal vector
\( w \)  nominal width of the pin array
\( C \)  correction coefficient matrix
\( S \)  target surface
\( p \)  point vector
\( \Delta p \)  process pressure (difference between ambient pressure and pressure in the VAMM vacuum chamber)
\( \Delta d \)  shape error (node based)
\( \alpha \)  significance level
\( \beta \)  maximum gradient between pin and interpolation layer
\( \mu \)  initial shear modulus
\( \varphi \)  fibre volume fraction

\( \psi \)  fibre mass fraction
List of Publications

During the work on this thesis, the following research papers where published by the author:


In addition, talks were given at international and national scientific conferences:


List of Supervised Work

During the work on this thesis, the author supervised the following Bachelor, Master and Diploma thesis at the Munich University of Applied Science:


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Moulds and dies are expensive and contribute significantly to a product's price. This is increasingly true if the total number of products is small. In single item production, like in prototyping, the tooling cost is a main driver of product prices. This together with the ongoing transformation in production, from large quantities towards mass customisation, and the advancing digitalization, require new types of tooling and moulds to be cost efficient. Multipoint tooling (MPT) is a reconfigurable mould making technology, for manufacturing panels, that can supersede the need to fabricate dedicated moulds or dies for a new product. Instead, the adaptive tool is reconfigured for the new part and manufacturing can start immediately [Li et al. 2014]. The technology therefore meets the demand for more product variants with lower production volumes and even mass customisation.

Fibre-reinforced plastic (FRP) composites have become more and more important in all kinds of engineering applications due to their high strength at low weight and are considered a key trend of the future [Witten et al. 2014]. However, only little research in the manufacturing of FRP components on multipoint tools has been conducted [Walczyk et al. 2003; Munro et al. 2004; Wang 2009] and no adaptation to practice is yet known. This thesis will introduce Vacuum Assisted Multipoint Moulding (VAMM), a novel multipoint tooling technology for the manufacturing of fibre-reinforced plastics, which tries to overcome the limitations of previous installations, and prevent dimpling and shape error, two system immanent defects in multipoint tooling. State of the art virtualisation and optimisation methods will be used in the virtual development of the tool in order to achieve this.
1.1 Multipoint Tooling for Manufacturing of Individual Parts

Multipoint tooling is a die making technology that enables the rapid manufacturing of individual freeform panels. It replaces the commonly used, elaborately designed and manufactured solid die with an array of individually adjustable pins. These pins can be set to represent a large variety of freeform surfaces. The discrete representation of the target surface however, is not directly viable as a mould. To smoothen the surface, some sort of interpolation layer is placed on top of the pins, as shown in figure 1-1. The created smooth surface can subsequently be used as a mould for a large variety of forming and moulding operations.

![Figure 1-1 - Solid die and flexible die created by a pin array, with an interpolation layer creating a smooth tooling surface](image)

The technology of multipoint tooling can initially be traced back over 150 years to Cochrane [1862] who invented an adjustable press for naval applications. From there however, it took over 100 years for multipoint tooling to first be mentioned in scientific literature by Nakajima [1969]. He designed the first numerically controlled (NC) multipoint tool and tested it successfully in a number of manufacturing operations. In the 1990s, extensive research was conducted at the Michigan Institute of Technology (MIT), in an attempt to create a cost efficient and rapid manufacturing system for aircraft panels [Walczyk et al. 1998]. In this project, first attempts have been made to compensate errors, introduced by the elastic interpolation layer [Valjavec 1999; Valjavec and Hardt 1999]. Later numerical methods were introduced, to improve this error compensation [Socrate and Boyce 2001].

Since then, the technology has been adapted to a variety of manufacturing processes and materials, ranging from stretch forming [Valjavec and Hardt 1999] and hydroforming [Paunoiu et al. 2015a] of sheet metal to thermoforming of plastic sheets [Su et al. 2012; Simon et al. 2013] and moulding of concrete [Pedersen and Lenau 2010; Henrikson et al. 2015]. It has also been demonstrated in a number of industrial applications, ranging from aviation [Walczyk et al. 1998], to medicine [Tan et al. 2007] and the automotive industry [Simon et al. 2013]. Lately it was also used in manufacturing of fibre-reinforced plastics, where carbon composites were made on a multipoint tool, using single diaphragm forming [Walczyk et al. 2003] and double diaphragm forming [Munro et al. 2004].
1.2 Research Project FlexForCFK

The work leading to this thesis was in part conducted within the research project *FlexForCFK*\(^2\) initiated by Prof. Christoph Maurer at the Munich University of Applied Science. The goal of the project was to develop an industrialisable multipoint tooling technology for the manufacturing of fibre-reinforced plastic composites. The focus of the development was set on using established manual manufacturing processes, like wet lay-up, vacuum bagging, resin infusion and prepreg moulding, which are considered standard in the industry for single item and prototype production. In addition, the new technology should not lead to any new restrictions in the production process or the produced parts. Within the project, a prototype of a novel production ready multipoint moulding technology was developed. This Vacuum Assisted Multipoint Mould introduces vacuum to force the interpolation layer onto an adjustable pin array enabling the production of concave and convex parts in a single sided multipoint mould. The pins in this tool are closely packed with a hexagonal cross section and the interpolation layer itself has multiple functional layers to improve the part quality.

The project started in January 2014 with a scheduled runtime of three years. The project consortium, led by the Munich University of Applied Sciences, included industrial partners covering the entire value chain of German carbon fibre-reinforced plastic (CFRP) composite manufacturing: SGL Carbon SE is a manufacturer of carbon fibres and carbon fibre pre-products. Putzin Maschinenbau GmbH is a small to medium enterprise (SME) manufacturer of moulds and machine parts for production machines. In the consortium, they act as a potential manufacturer and distributor of the VAMM system. Airbus Helicopters and Huber Kunststoff & Technik GmbH are two companies manufacturing FRP composite products and components, and are considered potential users of the developed technology. The consortium is completed by the University of Applied Science Nuremberg as an additional academic partner.

All the industrial partners supported the research project financially. The additional individual contributions of the project partners were as follows:

- **SGL Carbon SE** supplied carbon fibre prepreg material for the tests conducted on the tools as described in chapter 5. They also supported the student projects of Schweiger [2015], Ertl [2016] and Gruber [2017] with know-how on curing cycles and heat treatment of their prepreg materials. This input helped develop and optimise the heating system introduced in chapter 4.4.4.

- **Putzin Maschinenbau GmbH** manufactured all the individual metal components for the VAMM test bench as well as the VAMM full-scale prototype. In the course of the development of the VAMM system (see chapter 4.3 to 4.6),

\(^2\) The project *FlexForCFK* was funded by the German Federal Ministry of Education and Research under the funding scheme FHPprofunt (funding number 03FH041PA3)
they gave regular feedback regarding the feasibility of designs for the production process.

- **Airbus Helicopters** analysed their parts portfolio for components that could be produced on VAMM\(^3\) and supplied the project with proprietary reference geometries that could potentially be manufactured on VAMM in the future. In this context, they were also involved in the definition of the requirements for the VAMM system for an industrial application and a student project by Hellmer [2015], developing a method for measuring and evaluating the surface of the VAMM tools (as used in chapter 6.4.3). For the researchers in the project, they also offered training in the production of fibre reinforced composites in their internal laboratories.

- **Huber Kunststoff & Technik GmbH** supported the project with know-how about composite manufacturing and mould making for prototype applications. They also acted in an advisory capacity in the development of plastic components for the VAMM system and manufactured components for prototypes and the VAMM test bench (see chapter 4.5). Additionally, they were involved in the definition of requirements for the VAMM system from an SMEs point of view.

- **The University of Applied Sciences Nuremberg** was responsible for the exploitation of the VAMM technology. Therefore, together with the author they developed a framework for implementing the VAMM technology in an industrial environment [Lušić et al. 2015] and developed a system of 3D printed micro attachments in order to eliminate the inherent limitations of multipoint tooling to only ever manufacture mildly curved parts [Lušić et al. 2016a]. Therefore, they developed fixation systems for the damage-free fitting of attachments on the IPL and optimised filler structures for the 3D printed parts in order to withstand the loads during FRP manufacturing [Lušić et al. 2016c]. They also developed an alternative system for compensating shape error (alternative to the one introduced in this theses in chapter 6.6) based on 3D surface scanning [Lušić et al. 2016b].

The project was finished after three and a half years in July 2017. The delay of six months resulted from the temporary insolvency of the partner Putzin Maschinenbau GmbH. This made it necessary to allocate the remaining tasks to the academic partners. With this additional time, it was still possible to finish the project successfully. A fully automated prototype of the VAMM manufacturing system was developed and validated. This prototype in the future can be used to test the feasibility of the VAMM technology for a wide range of FRP composite applications. Possible applications of this technology range from sports equipment over automotive

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\(^3\) In the course of this analysis, the parts portfolio of the company was searched for components with only mild curvatures (means radius \(>100\) mm at any point; see \(^7\), page 12) and which could be produced on the VAMM prototypes due to their size. Some 20 parts were identified to meet these requirements.
applications in prototyping, racing and customisation to aerospace, repairs and retrofitting, as well as all areas where small quantities of varying panels are needed.
1.3 Definition of Problems

The concept of Vacuum Assisted Multipoint Moulding is an advancement of the established MPT, aimed specifically at the manufacturing of fibre-reinforced composites in an industrial environment. In contrast to existing MPT tools, VAMM should be able to be used in established manufacturing processes without the need for further modification. This means, that the specific characteristics of established FRP manufacturing technologies have to be identified and taken into account in the development of the technology.

Multipoint tooling in general offers a great increase in flexibility compared to traditional die making. However, the elastic interpolation layer necessary to create smooth surfaces also increases the complexity of the manufacturing process. The workpiece is no longer supported by a solid die over the entire surface. Instead, the elastic tooling surface only has point contact to the pins underneath. This can reduce the surface quality of the part\(^4\), and can lead to visible dimples on the parts surface, as shown in figure 1-2. Research showed that dimpling could be reduced, by increasing the thickness of the interpolation layer [Eigen 1992; Walczyk and Hardt 1998; Cai et al. 2009]. This however introduces a global deviation of the actual, to the target shape of the part [Liu et al. 2010a]. This so-called shape error and the aforementioned dimpling are considered the two system immanent defects in multipoint tooling. Figure 1-3 schematically shows the difference between the two.

It can be seen, that dimpling is a local effect limited to the area surrounding an individual pin, whereas the shape error is a global deviation of the actual geometry, of a manufactured part, to the target geometry. This in turn means that due to the adjustability of the tool, shape error can be compensated by readjusting the pins in the array accordingly.

\(^4\) In this work the terms part quality and surface quality always refer to the system immanent effects of dimpling and shape error, unless stated otherwise. The smaller these effects are, the higher the part quality is considered.
For the Vacuum Assisted Multipoint Moulding system, it is of utmost importance that the produced components are dimensionally accurate and without defects, such as dimpling. Otherwise, the technology cannot be a suitable alternative for existing solid tools. This results in a number of specific research questions as stated in chapter 2. Within the project, this means that the shape error needs to be measured and compensated and dimpling needs to be measured and minimised as far as possible. The dimensional accuracy, on one hand, can be evaluated by measuring the distance between the target shape and the actual shape for each individual pin. A shape control algorithm that reliably compensates shape error by readjusting the pins needs to be developed. A process model can be used to accelerate the convergence of this shape controller [Anagnostou and Papazian 2004]. Dimpling on the other hand could be prevented by designing the interpolation layer adequately. For a well-founded design however, a profound understanding of the behaviour of the IPL is required. This means the parameters influencing dimpling have to be identified, and the magnitude of their influence needs to be quantified. In order to do that successfully however, dimpling has to be measured first. This, in turn, is only possible, if the measured deviation, between an actual shape and a target shape, is ensured to actually be dimpling and not shape error or a combination of the two. By compensating the shape error in advance, the dimpling defect for a given tool configuration could be separated. From the remaining deviation between the target shape and the actual shape, the dimpling could then be evaluated. Different ways of doing so would need to be analysed and benchmarked. With this virtual manufacturing process and evaluation tool chain, the influence of individual parameters on dimpling can be identified. Additionally, it can be used to find an optimal interpolation layer and an optimal configuration of process parameters for the VAMM. Only then, dimple-free parts can be ensured. In addition to the geometric quality of the parts, their mechanical properties have to be taken into account as well.

Fibre-reinforced plastics are created through curing during the manufacturing process. That is why the tooling can play a significant role in the quality of the manufactured components. This in turn means that the effects of the elastic tooling surface on the mechanical properties of parts have to be evaluated and benchmarked against parts made using conventional tooling. Only if both, the dimensional and mechanical properties of VAMM manufactured components, are comparable to parts made with conventional tools, then the VAMM technology can potentially be used in an industrial environment.
1.4 Justification of Research

Multipoint tooling (MPT) has already been known for nearly 150 years as a possible solution for cost efficient single item production. Yet, it is still neither commercially available nor successful, and remains a niche technology. This raises the question, why research in MPT should even be relevant.

Still, recent developments and specific needs in the FRP composite industry can be identified that justified the research in this area: On one side, the production of fibre-reinforced plastic composite, in the next couple of years, is expected to grow significantly. On the other side, with Industry 4.0, there is an ongoing paradigm shift in industrial production, towards individualization and mass customisation. It will be shown, that these developments make the MPT technology industrially attractive and research, focusing on understanding the process and its individual components, meaningful.

In recent years, well publicised flagship projects in the transport and aviation sectors led machinery manufacturers to identify fibre-reinforced plastic composites in general, and carbon fibre-reinforced plastic composites in particular, as a key trend of the future [Witten et al. 2014]. Its high strength and low specific weight make it the ideal material for panel structures in lightweight applications. This is also the reason, why FRP composites have already been widely adapted in areas like defence and aerospace for many years [US Department of Energy 2014] and also made their way into wind turbines, compressed gas storage tanks, as well as luxury and, more recently, even mainstream automobiles and sports equipment. In addition, the material in its uncured form can easily be draped making it very interesting in areas like single item production, prototyping, and design, due to resulting low tooling cost. It can also be used in areas where metal forming, due to the machinery needed, is not cost efficient. Market analysis shows that these advantageous properties lead to an increase in demand for CFRP composites. In 2013, global CFRP production had a volume of 46 kilotons with 49% being processed on open moulds. Additionally, a significant increase in demand for such technologies can be expected since the global CRP market volume has nearly doubled between 2009 and 2015 and is supposed to triple until 2020. In glass fibre-reinforced plastics (GFRP), the production volume in Europe alone reaches 1,043 kilotons in 2014. From that, 138 kilotons of fibre were processed in open moulds. This is 13% of the total market volume in Europe. [Witten et al. 2014] It can be concluded that manual manufacturing processes in open moulds play an important role in FRP production and represent a huge market. More so, it is even expected to grow significantly in the future making FRP composites a real key trend of the future.

Like most forming processes, FRP manufacturing requires dies and moulds as tooling equipment. In low volume and single item production, these tools however are a critical cost factor. Tools for double curved and freeform surfaces are particularly challenging to produce. According to Nagahanumaiah et al. [2005] moulds for 3D freeform surfaces can cost up to ten times more than 1D moulds and up three times
more than 2D moulds. Therefore companies are constantly seeking for ways to reduce the cost and lead time of tooling development and manufacturing for their product fabrication [Altan et al. 2001]. In traditional production processes for each dedicated part, there is a dedicated die or mould. Looking at the aerospace industry for example, the total production numbers for many aircraft models is below 1000 planes for a twenty-year production life. The part count for such an aircraft however may exceed 3 million [Walczyk et al. 2003], many of which are being made from FRP composites. For these parts, moulds are needed but are rarely used during their product life. In such low volume production, it is estimated that 70 % of the “total production time” of a die or mould consists of storage time, when no value is created. Moreover, due to declining prices and profit margins for products, the demand for building moulds in far less time, and globalization that leads to increased foreign competition, the acceptance of “new technologies” is considered high in the mould making industry. [Altan et al. 2001]

According to the US Department of Energy [2014] reducing cost in production of FRP composite components is one mayor challenge in the FRP technology and will require more effective and predictable manufacturing processes that reduce cycle times without diminishing performance characteristics.

Additionally, in many industries, there is a shift in the production paradigm from high volumes to high variant diversity\(^5\) and even mass customisation of products [Götz and Simon 2014]. This change is enabled by the growing digitisation of production and driven by the customers demand for personalised products [Tseng and Piller 2003b]. When mass customisation is no longer limited to changing the components in an assembly, but actually enables the customer to change form and function of individual components, the manufacturing process can no longer be handled by established production lines [Tseng and Jiao 2007]. At the same time, this increase in variants should neither increasing cost nor the time effort in producing such products. Tooling cost for dedicated parts however make this virtually impossible [Koren et al. 1999]. Reconfigurable manufacturing systems, like MPT, which can produce more variants than traditional manufacturing systems at low and fluctuating volumes with short lead-times at a low price, can resolve this discrepancy [Bi et al. 2008]. Table 1-1 compiles the four levels of mass customisation, defined by Tseng and Piller [2003a], and corresponding characteristics of multipoint tooling. It shows that the characteristics of MPT already fulfil three of these levels (differentiation, cost efficiency and relationship). Only the solution space cannot be addressed since it is an organisational criterion and not related to tooling [Tseng and Piller 2003a].

---

\(^5\) According to ROLAND BERGER STRATEGY CONSULTANTS [2012] since 1997 the product variety in the automotive, chemical, machinery, fast moving consumer goods, and pharmaceutical industry has increased by over 150 % while the average product life decreased by 70 %
Table 1-1 - Comparing demands of mass customisation and multipoint tooling characteristics based on Lušić et al. [2015]

<table>
<thead>
<tr>
<th>level of mass customisation&lt;sup&gt;6&lt;/sup&gt;</th>
<th>enabling multipoint tooling characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>differentiation based on customised products</td>
<td>Adjusting shapes of products to customers’ needs can be achieved quickly by adjusting pins. Similar to additive manufacturing tools, the promptly reconfigurable die is independent from the panel. Thus, the engineering and production effort for customised design is minimised significantly.</td>
</tr>
<tr>
<td>cost efficiency similar to mass production</td>
<td>Deterministic correlation between mould and part is eliminated. This allows allocating tool cost to a high number of products resulting in low tool cost per unit. In addition, manufacturing at least one rigid die for each geometry is not necessary. This improves the following:</td>
</tr>
<tr>
<td></td>
<td>• material, energy and time consumption for producing rigid dies,</td>
</tr>
<tr>
<td></td>
<td>• the need for storing and delivering of unused dies and</td>
</tr>
<tr>
<td></td>
<td>• expenses for scrapping no longer needed dies.</td>
</tr>
<tr>
<td>relationship to increase customer loyalty</td>
<td>Following both characteristics mentioned above, customer’s demands are easier to fulfil with little additional effort by using multipoint tooling. Thus, the customer proximity intensifies and (brand) loyalty increases.</td>
</tr>
<tr>
<td>solution space</td>
<td>Not the multipoint tool itself, but the engineering process needs to enable the solution space, since the product quality depends on the process quality behind it. Thus, engineering processes need to be modified to meet the requirements of mass customisation</td>
</tr>
</tbody>
</table>

According to Pedersen and Lenau [2010], there are at least 143 possible areas of application for multipoint tooling, based on criteria such as the need for individual geometry and the acceptability of less perfect surface quality. However, in the past attempts at commercialisation were only focused on the aerospace industry, where

<sup>6</sup> according to Tseng and Piller [2003a].
consolidation efforts and cost cutting has resulted in a very limited commercial market for this type of product [Munro and Walczyk 2007]. This leaves a multitude of untapped potential applications.

It can be assumed that in today’s manufacturing environment, and more specifically in the FRP composite manufacturing environment, the demand for a reconfigurable mould is greater than ever. Previous research has focused primarily on hardware development, with a focus on new pin actuation concepts and process adaptation. However, these solutions never gained commercial acceptance. In order to overcome this step from academic research into the industry, a new MPT technology has to adopt existing processes, and not adapt them, to minimise the impact on existing manufacturing lines. Additionally, a high component quality and process reliability have to be ensured. For this purpose, the system immanent errors, mainly dimpling and shape errors, must be solved holistically. The VAMM technology proposed in this thesis addresses these aspects. Additionally, the virtual model of the VAMM manufacturing process enhances the prediction quality of the process and reduces uncertainties associated with manufacturing on a soft surface which in turn will increase the acceptance of VAMM as a potential manufacturing technology for commercial use. This, together with the enormous potentials of the MPT technology for mass customisation and digitisation, justifies further research in multipoint tooling. The interest of the industrial partners in the publicly funded research project FlexForCFK, associated with this thesis, further emphasises that a commercial exploitation of the technology is within reach.
1.5 Contribution of this Thesis

In this thesis, the Vacuum Assisted Multipoint Moulding technology is introduced. VAMM is a novel multipoint tooling technology specifically tailored to (C)FRP manufacturing. This technology enables the rapid and cost-efficient manufacturing of mildly curved 7 single items, customised products, prototypes and small lot production of fibre-reinforced plastic parts and components.

In contrast to existing MPT technologies, VAMM is able to reproduce geometries with concave as well as convex areas and inflection points in an open mould configuration without the use of an upper mould. This is achieved by the use of a vacuum between the pin array and the interpolation layer to deform the IPL as desired, enhancing the geometric capabilities compared to previous installations of MPT. Additionally, FRP manufacturing specific requirements are considered in the design of VAMM. This enables the use of established manufacturing processes for fibre-reinforced plastic composites including wet lay-up, vacuum bagging, resin injection moulding and prepreg vacuum bagging without any adaptations. The feasibility of this concept is demonstrated through experiments on the purpose built VAMM test bench and the full-scale prototype.

As in all multipoint tooling technologies, the system immanent dimpling and shape error also occur in VAMM. Even though, dimpling is well described in existing literature, no clear definition has ever been given. In this thesis, four possible definitions are introduced and benchmarked against each other. From these benchmark experiments, conversion formulas for the four dimpling parameters are derived. This enables reliable comparison between different dimpling measurement.

In order to evaluate dimpling reliably, however, it must be ensured that the measured deviation between an actual tool geometry and the target geometry is not a global deviation, the so-called shape error. In order to separate the dimpling from the shape error, a shape control algorithm is implemented in the VAMM system. It repositions individual pins in an iterative process in order to minimise shape error to a point where it does no longer influence the dimpling evaluation. This enables the separation of dimpling and shape error and consequentially also a reliable dimpling evaluation. Extensive virtual tests prove the reliable function of this algorithm.

Additionally, the thesis contributes to a deeper understanding of interpolation in multipoint moulding and insight into the design of optimised interpolation layers. Therefore, a comprehensive computer model of the manufacturing process is introduced and verified, that enables the prediction of the estimated surface quality of

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7 In this work curvatures are assumed to be mild as long as the radius is not less than 100 mm at any point on the component. This is an arbitrary definition specified by the project consortium of the FlexForCFK project.
the manufacturing operation, and hence reduces uncertainty in the manufacturing process.

This virtual manufacturing model is capable of emulating all steps in the creation of a part using VAMM. This includes the part creation, pre-processing of the pin coordinates, the forming process on the tool, as well as quality control and dimpling evaluation. Within the model, a numeric finite element model predicts the IPL behaviour in the forming process, depending on geometric, material and process parameters.

With the help of this model, the interpolation layer an manufacturing process are analysed. The interpolation layer is known to be the machine component, most significantly influencing part quality. When designed properly, an interpolation layer can prevent dimpling sufficiently, but it also influences the possible forming resolution and limits of the tool. However, research in this component has been neither conclusive nor comprehensive. Since the vacuum underneath the interpolation layer increases dimpling in VAMM, additional effort has to be invested in designing it. In order to gain a deeper understanding of the VAMM process and the design parameters influencing dimpling, parameter studies and sensitivity analysis are conducted. This way, the critical parameters influencing dimpling are identified, increasing the understanding of the VAMM process in particular and the MPT process in general. This has two effects:

- First, based on the results ideal interpolation layer are designed using optimisation methods to increase the capabilities of the tool while not compromising the part quality.
- Second, this knowledge can be transferred to any future VAMM installation in order to develop an equally optimal IPL.

At the end, these efforts result in a production ready VAMM system, including all the necessary hardware, control software and accompanying IT processes needed to operate it, which can be implemented in an industrial production setting. The process is sufficiently understood and all parameters influencing the manufacturing results are known and their influence is quantified.

The tool and process are capable of manufacturing all sorts of mildly curved FRP components. This could include ship hull segments, automotive panels, satellite dishes and antennas, snowboards, surfboards, and kitesurf boards. Additionally, the tool could enable the on-demand manufacturing of replacement parts on site e.g. in aviation applications.
1.6 Thesis Outline

The research presented in this thesis is organised in eight chapters. The thesis outline is illustrated in figure 1-4. In particular,

**Chapter 1** introduces the novel Vacuum Assisted Multipoint Moulding technology (VAMM) and the general topic of multipoint tooling. It discusses the problems with existing solutions and the resulting research questions to be answered in this thesis, and clarifies the contribution of this thesis to the body of knowledge.

**Chapter 2** gives a brief introduction in fibre-reinforced plastic composite manufacturing, emphasising small lot and single item production. The history, recent developments and the state of the art in multipoint tooling is presented, and the system immanent defects dimpling and shape error are introduced. Subsequently, solutions to tackle each of these defects are discussed. From there, the research gap is derived and the research questions are proposed.
Chapter 3 discusses the aim of this thesis and introduces in detail the research methodology to answer the previously stated research questions. It gives a brief overview over methods to develop a manufacturing system and finite element analysis for simulating forming processes. Sensitivity analysis and surrogate modelling, as well as multi objective optimisation are subsequently introduced. At the end, the established methods for evaluating mechanical properties of fibre-reinforced plastics are presented.

Chapter 4 discusses the development of the VAMM system in detail. It introduces the architecture and the design considerations for the critical components and describes the intended operation of the system. Subsequently, two variants of the tool are designed and their configurations are described in detail: The VAMM test bench is intended for validation, variation research and trial and error studies that can be conducted on a small scale. The full-scale VAMM prototype on the other hand is intended for production of components close to the industrial reality. On this tool, components for mechanical testing and performance evaluation are manufactured.

In Chapter 5, the machine concepts and manufacturing operations proposed chapter four are validated. Additionally, the quality of the resulting parts made on the VAMM tool is evaluated experimentally. The geometric quality of components is tested on the VAMM test bench. On the VAMM full-scale prototype, samples are manufactured to evaluate the influence of VAMM on the mechanical properties of composites.

In Chapter 6, a virtual model of the VAMM manufacturing system is developed. The architecture and workflow of the model is introduced and the individual components are described. The model can work with real components’ 3D CAD data, as well as create parts based on geometric primitives. For these parts, an initial pin configuration is derived and a finite element model of the VAMM tool, developed in chapter 4, is used to predict the system behaviour. Subsequently, a method for evaluating shape error is introduced. This shape error is then compensated with a shape control algorithm. In order to evaluate the final part quality, dimpling evaluation methods are introduced and compared.

In Chapter 7, the VAMM system is optimised. Therefore, experiments are conducted on the virtual VAMM manufacturing model, introduced in chapter five, using Design of Experiment. Parameter boundaries for these virtual experiments are defined, based on physical experiments described in chapter 7. The results are then used to conduct a sensitivity analysis and identify the system parameters critically influencing dimpling. A metamodel is then created in order to describe the system behaviour based on these critical parameters. On this metamodel, optimisation algorithms are applied to find an optimal process configuration and interpolation layer for the VAMM tool. The optimised interpolation layer is then used in the physical VAMM system developed in chapter 4.
Chapter 8 summarises the main contributions of this research work and gives conclusions. Additionally, some suggestions and recommendations are put forward for future research on the VAMM tool and technology.
Chapter 2  Background

The development of a manufacturing process is a multidisciplinary process. To adapt multipoint tooling proficiently to the production of FRP composites, the material itself, as well as the established manufacturing methods must be understood first. The first part of this chapter gives a brief introduction into fibre-reinforced plastic composites. There, specific parameters are discussed and established, as well as advanced mould making technologies are presented.

The second part of this chapter describes the history and previous developments in multipoint tooling and areas of application to give an overview over the state of the art. Critical design parameters are introduced, existing solutions for each individual parameter are discussed, and real-world applications are presented.

Dimpling and shape deviation are the two most prominent system immanent defects in multipoint tooling. Both these defects are introduced in the third and fourth part of this chapter. Definitions are introduced and ways for measuring them are discussed. Subsequently, surface interpolation methods for handling the dimpling phenomenon are discussed and shortcomings in recent approaches are identified. Shape control algorithms are introduced for compensating the shape error by readjusting the pins in the tool. Established shape control algorithms are discussed and their performance is evaluated.

The chapter concludes with the resulting need for action, in order to adapt multipoint tooling to the manufacturing of FRP composites.

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8 In this review, only publications in German and English language are considered. In the timeframe from 2001 to 2017, 28 publications in Chinese were discovered which are not part of this review.
2.1 Fibre-reinforced Plastic Composites for Individual Components

This chapter gives a brief overview of the basic principles of fibre-reinforced plastics, specific nomenclature, commonly used materials, and established manufacturing processes for single item production later used in this thesis. Further information on FRP composites can be found in dedicated textbooks e.g. by Hull [1995] or Grove [2018].

2.1.1 Basic Principles of fibre-reinforced Plastic Composites

Composites are a combination of at least two components, each with distinct functions. A homogeneous matrix material is bonded with one or more other materials, with different material properties, resulting in a combination of material properties. Fibre-reinforced plastic composites (FRP) are structural engineering materials that use fibres (see yellow layers in figure 2-1) to enhance the mechanical properties of a plastic matrix. By combining these two components, each with different material properties, a final product with specifically designed material and mechanical properties can be created. Commonly used reinforcement fibres are made from glass, carbon or aramid. The matrix materials used are either thermosetting resins like epoxy, vinyl ester and phenol formaldehyde resins or thermoplastic polymers like polyester and polypropylene.

![Schematics of a fibre composites with fibres (yellow) in two orthogonal directions, a core (blue) and the matrix indicated as a layer covering the fibres (gray)](Image published on Wikimedia under Public Domain by user PerOX, 2009)

It is critical to understand, that unlike other structural materials, the actual FRP composite does not exist at the beginning of a manufacturing process. Instead, it is created during the process, by combining the components in a specific way and curing them afterwards. At the beginning of the process, the fibre material is flexible and behaves more like a fabric than a structural material. This ability, to drape the textile easily, also makes FRP composites highly attractive for prototyping, individual parts, and one-off components. This is mainly because no special tooling equipment is needed for forcefully deforming the material. The matrix material by contrast can be anything from a liquid to a viscous state. Only through curing, the resin hardens and
Background

gives the material its final shape and properties. These properties are influenced by the reinforcement fibres, the matrix, the fibre orientation, as well as the fibre lay-up.

**Properties of FRP Composites**

Fibre-plastic composites in general exhibit high specific stiffness and strength. This makes them suitable materials for lightweight construction applications. The mechanical and thermal properties of fibre-plastic composites can thereby be adjusted in many ways. The mechanical properties of most reinforcing fibres are considerably better than those of un-reinforced resin systems. Hence, the mechanical properties of the composite are dominated by the fibre. Thereby, the following four main parameters govern the properties of the composite:

- fibres mechanical properties,
- interface between fibre and resin,
- quantity of fibres in the composite or fibre volume fraction and
- orientation of the fibres in the composite.

Additionally, the fibre-matrix combination, as well as the layer sequence can be varied. This way, components with tailored anisotropic properties can be created depending on the orientation of the fibre reinforcement.

The mechanical properties of the fibres, as well as the interface to the resin are dependent on the specific materials used. The orientations, as well as the placement of the fibres, depend on the design of the component. The fibre volume fraction however is largely depending on the manufacturing process used and varies depending on its quality: It is the ratio of the volume of the fibres to the total volume of the laminate. It can be used as a measure for the quality of that laminate, since higher fibre volume contents in general produces a proportionally stiffer and stronger laminate [Grove 2018]. The maximal possible ratio with closely packed fibres is 78.5 % due to the circular cross section of the fibres. In real world applications, a fibre volume content value of around 60 % - 70 % is targeted. A higher value increases the risk that there could be not enough resin in the laminate to fill all cavities reliably. The laminate then is considered to be too “dry”.

**Reinforcement Fibres**

The properties of a fibre composite are significantly influenced by the utilised fibres. They are supposed to transfer the tensional loads within the component. In the field of high-performance applications, glass and carbon fibres are well established. They are particularly suitable due to their high specific stiffness and strength, which are several times higher in unidirectionally oriented composites compared to steel. Moreover, even in quasiisotropic laminate constructions, the specific characteristics can still be significantly superior to those of metallic materials. The fibre materials can be used in
different areas of engineering depending on their individual properties. Glass fibres for example are best suited for less stressed components with high surface requirements. Due to their very high specific strength and stiffness, carbon fibres on the other hand, are preferably used in highly loaded structural components. In addition to glass and carbon fibres, there is also a variety of alternatives available, which includes aramide fibres, mineral fibres such as asbestos, or natural fibres such as sisal, flax or ramie.

**Reinforcement Forms**

Since individual continuous fibre filaments are difficult to handle, they are generally combined into semi-finished fibre products. These are usually strands, flat structures or three-dimensional structures. The most common semi-finished products in the production of individual parts are rovings, woven fabrics and unidirectional (UD) non-crimp fabrics.

As a first step in the production of each semi-finished products, fibres are combined into yarns, referred to as rovings. These are fibre bundles with a defined number of fibres running almost parallel [Grove 2018]. Typically, this number is between 1,000 (1 k) and 24,000 (24 k), but can also be more than 50 k. Rovings with higher fibre counts are referred to as heavy tows.

Woven fabrics consist of warp and perpendicular weft threads [DIN Deutsches Institut für Normung e. V. 1969]. The type of linkage, also known as binding, largely determines the properties of the fabric. Especially the drapability and sliding resistance (in dry condition) are influenced by the weave [Grove 2018]. Frequently occurring weaving types are the plain weave, in which the weft threads cross after each warp thread, the twill weave, in which one warp thread is skipped at a time, and the atlas weave, in which there is interlacing after four warp threads at a time. This binding of the yarns creates a wavy yarn course. This leads to a reduction in the mechanical properties of the fabric compared to a corresponding UD fabric. The modulus of elasticity and strength, for example, can be up to 40 % lower in the worst case. [Park 2018]

UD non-crimp fabrics on the other hand, according to EN 13473-1 [DIN Deutsches Institut für Normung e. V. 2001], are textiles, which consist of one or several unidirectional layers of unwoven fibres. These layers consist of parallel, straight reinforcing fibres that are glued or stitched together to improve handling. The layers can be produced in different orientations and fineness. [Mathes and Witten 2014] The straight form of the reinforcing fibres makes the mechanical properties superior to those of woven fabrics [Bergmann 1992].

One or multiple layers of these pre-products can be combined in a component to create a material with tailored mechanical properties. Such a collection of laminated layers shaped into a mould, as shown in figure 2-1, is called a lay-up. One or multiple layers of fibres oriented in a single direction are called a lamina.
loads from different directions, multiple lamina with different fibre orientations can be stacked to create a laminate. The lay-up of such a laminate is defined by the lamina angles and can be written as shown in figure 2-2. For example, a unidirectional laminate with 8 plies oriented along the main axis of a part (i.e. in a 0° angle) is written as \([0^\circ]^8\). For non-specifically loaded composites, a quasi-isotropic laminate whose elastic properties in the laminate plane are invariant with respect to the rotation about the laminate normal can be designed using a simple cross-plied, quasi isotropic lay-up like \([0^\circ\ 90^\circ\ +45^\circ\ -45^\circ\ -45^\circ\ -45^\circ\ +45^\circ\ 90^\circ\ 0^\circ]\) as shown in figure 2-2 b.

![Figure 2-2 - Laminates with different lay-ups: (a) unidirectional laminate with \([0^\circ]^8\) plies and (b) cross-plied quasi isotropic lay-up with \([0^\circ\ 90^\circ\ +45^\circ\ -45^\circ\ -45^\circ\ -45^\circ\ +45^\circ\ 90^\circ\ 0^\circ]\) plies](image)

**Matrix Systems**

The fibres in a composite structure have to be bonded and held into place by a matrix in order to have a defined form. This matrix is the medium, which transfers load from the external environment into the reinforcement fibres and between fibres. In FRP composites, two matrix systems are well established. Thermoplastic matrix systems use a fusible thermoplastic that is applied to the fibres in its hot, liquid form, and solidifies while cooling. Thermosetting systems on the other hand are (multi component) resins, which chemically crosslink when combined with a hardener.

The most commonly used reaction resins in structural components are epoxy resins (EP resins) which crosslink by addition polymerisation with a hardener (amines or anhydrides) to a thermosetting moulding material. This reaction is initiated by mixing the resin components with the hardener, using additional reaction accelerators if necessary. Adherence to the stoichiometric ratios of resin and hardener is of utmost importance for the properties of the moulding material. When working with polyamines, it should be noted that special precautions must be taken as these compounds have a corrosive, toxic and sensitising effect and thus pose an increased health hazard.

The cycle time of resin preparations with polyamine hardeners is usually less than 30 minutes at room temperature. Resins prepared with carboxylic acid hybrids can be processed between three hours and up to several days. By adding reaction accelerators or inhibitors or by changing the curing temperature, however, the cycle time can be drastically reduced or increased depending on demand.
2.1.2 Common Manufacturing Processes for FRP

There are numerous ways of manufacturing FRP composite components. Some are well suited for low volume production; others are best suited for mass production. However, typically they involve the following four steps, but not necessarily in the same order [Mazumdar 2002]:

- **Impregnation:** The fibres are combined with the resin to form a lamina. This can be done either in or outside of the mould. It is important for each fibre to be completely covered in resin in order to achieve good mechanical properties.

- **Lay-up:** In this step, the fibres are placed in the mould at the appropriate places and at desired angles in order to achieve a fibre architecture as dictated by the predefined design. The performance of a composite structure is highly dependent on the fibre orientation and lay-up sequence.

- **Consolidation:** Good resin-to-fibre contact is required in the laminate in order to achieve optimum mechanical properties. Dry spots and voids in the laminate can be prevented in this step by bringing the lamina into close contact using pressure and/or a vacuum.

- **Solidification:** In this step, the component receives its final hardened form. Depending on the resin used, this is achieved at room temperature or by applying temperatures of up to 180°C to the laminate. This process can take a couple of seconds for thermoplastics and up to multiple hours for some thermoset resins.

Single sided open moulds or two-sided closed mould are used to form the laminate into the desired shape. It is common practice to refer to one side of the tool as a lower mould and the other side as the upper mould [Mazumdar 2002]. This nomenclature is independent of the moulds configuration in space. A single sided tool, in this convention has a lower but no upper mould.

For the manufacturing of freeform panels in small quantities, manufacturing processes using single sided or open moulds are common. Wet lay-up, vacuum bagging and resin infusion are three well-established processes used in various industries from naval, automotive to aerospace for components with different demands in quality. [Cripps et al. 2006]

**Wet Lay-up**

The wet lay-up process, as shown in figure 2-3, is the simplest and most established process for FRP composite manufacturing. Nowadays it is used mainly for large parts with mediocre structural requirements like boat hulls and associated parts.

As for all traditional manufacturing processes, a rigid mould is used to give the laminate its final shape. Whenever a high-quality surface is required, in a first optional step, a pigmented gel coat is sprayed or brushed onto the mould. After surface drying
the gel coat, the reinforcement fibres are placed on the mould and the resin is poured, brushed, or sprayed on. Subsequently, manual rolling the lay-up thoroughly wets the reinforcement fibres with the resin, removes entrapped air and consolidates the FRP composite. Afterwards additional layers of fabric and resin are added similarly to create the desired lay-up. The catalyst or accelerator in the resin initiates curing, thereby hardening the composite. Depending on the resin-catalyst system, no external heating is needed. The curing times can range from several hours up to several days.

![Wet lay-up schematic](image)

The requirements on the mould in this process are very low. There is no external pressure and only little to no thermal load. This enables the use of cheap moulding materials like wood and polyurethane, making tool changes relatively cheap and simple.

The lack of consolidation pressure in this process leads to relatively low fibre-volume contents ranging from 40% to 50%. This, in turn, leads to mediocre structural properties and a variable thickness distribution.

**Vacuum Bagging**

For high performance parts, like sporting goods (e.g. tennis racquets and skis) aircraft structural components (e.g. wings and tail sections) and racing car components, vacuum bagging can lead to a substantial increase in composite quality. In this process, the lay-up is consolidated by using a vacuum bag to create up to 1 bar of consolidation pressure.

In order to apply a vacuum to the fibre lay-up, the air and resin flow has to be guided during the manufacturing process. Therefore, an additional vacuum built-up is placed on the mould, as shown in figure 2-4. On top of the fibre lay-up, a peel ply ensures the clean separation of the part and the auxiliary. Additionally, it creates a uniform surface finish on the part after removal. A perforated release film with a defined pore spacing defines the resin flow out of the laminate. This controls how much excess resin is removed from the laminate. An absorbent fabric allows unhindered airflow and
absorbs the excess resin. The build-up is sealed at the top with a polymer vacuum film and sealing tape.

Additional to combining dry fibres and resin in the mould, so-called prepregs can also be utilised. These fabrics are pre-impregnated with a pre-catalysed resin in an industrial process. The resins are stabilised making them nearly unreactive at ambient temperatures. This results in a shelf life of several weeks up to months at room temperature and even longer when stored frozen. The resin content in these fabrics is typically between 30% and 40%. It is nearly solid at room temperature and exhibits a sticky surface or ‘tack’. The prepregs are laid up onto the mould and heated to temperatures typically ranging from 80°C to 180°C. This causes it to reflow, eventually crosslink, and harden.

The process features relatively low cost and high component quality. The fibre volume content is typically between 50% and 60% with a low void content of 2% – 3% [Grove 2018]. Health and safety problems are reduced, especially when prepregs are used. However, the setup of the vacuum build-up is not trivial and special care must be taken to ensure impermeability. Furthermore, many consumables are required, which have a negative impact on both the sustainability and the cost of a component.

**Resin Infusion**

Resin infusion is a general term for a number of manufacturing processes like resin transfer moulding (RTM), vacuum assisted resin transfer moulding (VARTM) or vacuum injection (VI). It is adopted as a low cost alternative to autoclave moulding [Grove 2018] e.g. in the manufacturing of boat hulls and aerospace components as it produces high quality parts with good dimensional tolerances on both surfaces, combined with minimal health hazards (particularly styrene emissions). The basic principal of the process is shown in figure 2-5. The dry laminate is placed in a mould. It thereby is either laminated and draped inside the mould or laminated outside the mould, preformed and then placed in the mould. The tooling cavity is sealed similar to the vacuum bagging process, using the same auxiliary material. However, there can be multiple vacuum bagging outlets and there is at least one additional inlet to the sealed cavity, connected to a resin tank. The liquid resin is introduced to the fibre lay-up either via
positive pressure on the resin side or “sucked” into the laminate via negative pressure on the outlet side. The pressure or vacuum is maintained until the component is completely impregnated with resin. Then the resin inlet is closed off and the vacuum is either maintained or applied until the resin is hardened. The flow of resin and the thorough saturation of the fibres require special consideration. “Race tracking” is a common problem, where the resin follows the path of least resistance and leaves unsaturated dry areas in the laminate. This can however be prevented by strategically placing inlets and outlets.

Other Processes

Other processes include diaphragm forming [Bersee et al. 2007] and double diaphragm forming [Chen et al. 2017]. There, the fibre lay-up is laminated and impregnated outside of the mould. The laminate is then placed under or between two diaphragms and consolidated by applying a vacuum. The diaphragms are then placed above the mould and the area between the lower diaphragm. Then, the mould is evacuated. Thereby the laminate is vacuum formed onto the mould where it subsequently hardens.

2.1.3 Moulds for FRP Composites Production

Mould making is a critical step in the creation of a fibre-reinforced plastic composite. The mould shapes the fibre laminate into a desired form. The previously discussed manufacturing processes are utilising single sided moulds for this purpose. In the design of such moulds, the following criteria have to be taken into account [Mazumdar 2002]:

- **Shrinkage:** During the curing process, resins show shrinkage to varying degrees. This must be taken into account when designing tools in order to obtain a dimensionally accurate component.
- **Thermal expansion:** The moulds, as well as the laminate are subject to thermal expansion during the manufacturing process and the corresponding
introduction of heat. In order to minimise residual stresses and dimensional inaccuracies in the composite, the thermal expansion of mould and laminate should closely match.

- **Stiffness**: During part fabrication, the mould experiences significant pressure. This should not lead to significant deformations since these cause distortions in the part.

- **Surface quality**: The surface finish of the product is directly related to the surface finish quality of the tool. A high surface quality of the mould is therefore desirable.

Moulds can be manufactured in a variety of ways and from a variety of materials. In small lot production, specifically in open mould processes, there are two established methods of mould making: moulds machined form a solid block and fibre-reinforced plastic moulds built on a positive of the desired component. [Campbell 2004]

Machined tooling from material like steel or aluminium are commonly used for small to medium sized parts [Mazumdar 2002]. From a solid block of material, the tool is manufactured by CNC milling and (if needed) finished by lapping, form grinding, manual grinding or electrical discharge machining. Individual components and prototypes are often manufactured using moulds made from simple to mill materials like wood or polyurethane foams like Ureol (a highly filled polyurethane). Table 2-1 compiles the cost of moulds made from these materials for a generic free-form component. As expected, the wood tool is the cheapest, with the polyurethane tool being ~15 % and the aluminium tool being ~110 % more expensive.

<table>
<thead>
<tr>
<th>mould material</th>
<th>wood</th>
<th>polyurethane foam</th>
<th>aluminium</th>
</tr>
</thead>
<tbody>
<tr>
<td>cost</td>
<td>1,064 €</td>
<td>1,208 €</td>
<td>2,258 €</td>
</tr>
</tbody>
</table>

In cases where a simple mould from wood or plastic is not sufficient, but a hard mould from metal is not yet needed or when thermal expansion is critical, tools can also be laminated from CFRP. Therefore, in a first step a master pattern is created. This can either be an existing part or a part being milled e.g. from Styrofoam. On this master, first a release agent is applied to ensure separation of the mould. Subsequently, a gel coat is applied creating a glossy, shiny surface finish. On this gel coat, the actual tool is laminated using one of the manufacturing processes discussed in chapter 2.1.2. Large tools can be reinforced using inlets, creating a sandwich structure, or by using an external support structure [Mazumdar 2002].

Beside these two established technologies, there are other, less common ways of rapid tool making. Laminated tooling is a tool making technology that uses thin layers of material that are contoured and then laminated together. This results in a pre-tool with a stepped surface that is finished in a milling operation. Compared to moulds
machined from block material, this results in reduced lead times at reduced cost. [Wimpenny et al. 2003]

Alternatively, in netsize casting in a first step a Styrofoam mould is produced by CNC milling. It is then siliconised and filled with a resin material. After hardening this resin, the form block has nearly the shape of desired mould. In a finishing step, it is then milled to form. For large moulds, this also reduces the lead-time due to the reduced milling effort. [Buchholz 2007]
2.2 Multipoint Tooling

Multipoint tooling is a technology used in reconfigurable dies and moulds. The commonly used rigid tool is replaced with an array of individually adjustable pins that can create a discrete representation of a large variety of freeform surfaces. On top of this discrete surface, an interpolation layer is applied to create a smooth surface. This smooth surface is then used as tooling surface for forming or moulding operations. In recent years, various multipoint tools for different applications and manufacturing processes have been introduced. This chapter describes the technology in general, starting from the early beginnings to recent developments. Key technologies are discussed and categorised in terms of their intended use. Two basic categories will be distinguished:

- **forming technologies**, that are used to change the shape of a rigid pre-form. This includes stamping, deep-drawing, hydroforming and other forming operations and
- **moulding technologies**, that are used to shape liquid or pliable raw material.

Subsequently design parameters and principle considerations for designing multipoint tools will be discussed. Finally, examples from academic research and some real-world applications are presented.

2.2.1 History and State of the Art in Multipoint Tooling

The idea of using reconfigurable pins instead of solid blocks is not new. In 1862 John Cochrane [1862] invented a “[…new and useful machine or press for bending metallic plates into the various forms of mould required in naval construction and for other purposes[…]]”. His machine consists of two opposite arrays of individually adjustable screws with movable head plates between which steel panels can be formed. This reconfigurable press technology is nowadays known as multipoint tooling. He intended this machine to be used for forming ship hulls though there is no documented case of it being actually used. Since then, many variations of such reconfigurable tools have been developed. Yet, they are all based on this basic principle of individual pins creating a discrete representation of a freeform surface.

The first academic research into multipoint tooling was conducted by Nakajima [1969]. In his tool for “Reconfigurable Manufacturing by Wire”, he uses freely moving, thin wires with round cross sections packed in a square retainer. These wires are adjusted using a NC controlled ultrasonic vibrating stylus that is swept back and forth across the tools surface, pushing the pins into position where they are then clamped into position. To protect the workpiece from scratching a thin elastic membrane was introduced on top of the pins. This tool was successfully used as a die in press working of steel metal, as well as compression moulding, vacuum forming of plastics and die-casting.
The first flexible moulding and casting tool was developed by Wolak et al. [1973]. Their “infinitely reconfigurable surface generator” uses an array of individually adjusted uniformly spaced threaded rods in a base plate. On these pins, a rubber layer, the so-called interpolation layer, is placed to create a smooth surface. Rigidax® casting material was used to cast forming dies for stretch forming of aluminium parts for the aircraft industry, in the created mould. However, according to Munro and Walczyk [2007], no actual stretch forming over the cast tool was ever reported.

In the 1980 Hardt and Gossard [1980] developed a “Flexible Die System” (FDS) at the Laboratory for Manufacturing and Productivity at Massachusetts Institute of Technology and tested it in a number of manufacturing processes for sheet metal forming. They used rubber forming in order to simulate hydroforming, as well as press and stretch forming [Hardt et al. 1981]. To improve the shape fidelity of the produced parts they developed proportional [Hardt et al. 1982] and more complex spatial frequency based control algorithms [Hardt et al. 1985] that proved feasible for simple 2D geometries.

Finckenstein and Kleiner [1991] combined the concepts of Nakajima [1969] and Wolak et al. [1973] in their “system for flexible fabrication” (see figure 2-6). Their machine consists of three modules: the flexible die, the setup module, and the press. The flexible die consists of an array of pins and a holding frame similar to the one proposed by Nakajima [1969]. For adjustment this pin array is placed in a setup apparatus on top of an array of screws mounted in a baseplate, similar to the one developed by Wolak et al. [1973]. Theses screws are adjusted with a 4-axis NC controlled screwdriver. The target position for each screw is derived from a CAD model of the intended forming surface. The flexible die is set by placing it over the adjusted
array of screws and releasing the clamping mechanism. The loose pins drop onto the screws, thereby copying the adjusted geometry. There, they are locked into place creating a rigid die. The array can subsequently be used for deep drawing operations in a standard deep drawing machine. [Finckenstein and Kleiner 1991]

With these three basic components, a software to derive pin coordinates from CAD models, a reconfigurable pin array and numerically controlled tool adjustment, all at their disposal, many researchers built their own reconfigurable multipoint tools. Munro and Walczyk [2007] published a conclusive review of the development in multipoint tooling, or pin-type tooling as they call it, covering mainly American and European research. They found that the technology is constantly progressing since its initial invention and that the same basic design features suggested by Cochrane [1862] keep reappearing in later patents such as close packing of the pin matrix, leadscrew positioning of pins, square pin shape, and hemispherical pin tips. They also state that the most significant improvement over the Cochrane design is powered actuation of individual pins as suggested by Pinson [1979] and the introduction of the interpolation layer to prevent dimpling by Wolak et al. [1973].

Intensive research in multipoint tooling started in the late 1990s. Together with Boing and others, a research group at Michigan Institute of Technology around Hardt, Boyce, Walczyk and Papazian designed a “Reconfigurable Tooling for Flexible Fabrication” (RTFF) for stretch forming sheet metal. Unlike previous installations of the technology, they implemented the individual adjustment proposed by Pinson [1979] and implemented closed loop shape control algorithms to compensate for shape errors, springback, and other production variables [Hardt et al. op. 1991; Hardt et al. 1993; Walczyk and Hardt 1998; Papazian et al. 1999].

At the end of that project, research in „Multipoint Forming“ (MPF) of sheet metal was started at Jinlin University in China [Li et al. 1999; Cai and Li 2002; Li et al. 2002]. There, a variety of MPF tools in different scales have been developed over the years [Li et al. 2014]. Their sizes range for microscopic applications [Liu et al. 2012] over medium sized applications e.g. for panels for high speed trains and ship hulls [Yuan 2014] to large scale applications like structural components for the Beijing Olympic stadium [Li et al. 2014]. Jilin University was also involved in the European project “Digitally Adjustable Tooling for Manufacturing Aircraft Panels Using Multipoint Forming” (DATAFORM), where airplane body panels were shaped using press and stretch forming. [Liu et al. 2009]

Later variations of the same multipoint tooling technology, all focused on stretch forming and press forming of sheet metal, were introduced under names like „Digitized Die Forming“ (DDF) [Cai et al. 2006] or „Reconfigurable Multipoint Forming“ (RMPF) [Paunoiu and Teodor 2009; Su et al. 2012] (see figure 2-9). Jia and Wang [2017a] developed “individually force-controlled displacement for MPF” (ICFD-MPF) to reduce springback in sheet metal forming.
In order to reduce cost and complexity of MPF tools Yuan et al. [2004] tried to replace one side off the adjustable tool with a self-adjusting elastic one. In their “Multipoint Sandwich Forming” (MPSF) an array of uniformly spaced pins form the lower die while the upper die is a multilayer elastic sheet made from polyurethane (see figure 2-7). Interpolation between the pins is done via a steel sheet with a rigidity low enough to be deformed according to the pin positions but high enough to prevent dimpling. On top of the steel IPL, a polyurethane sheet ensures part quality throughout the forming process. According to Wang et al. [2005], this setup leads to drastically reduced tooling cost, setup time and increased part quality due to the more uniform support of the sheet metal. However, it also decreases the resolution (pins per area) and therefore the possible geometric complexity that can be produced.

Dedicated multipoint tools for hydroforming were also developed [Paunoiu et al. 2015b; Liu et al. 2016; Selmi and Belhadjsalah 2017]. Here, the upper die is replaced by a pressure chamber. The material is forced on the pin array by applying pressure to the liquid in this chamber.

Chen et al. [2005] increased the manufacturing capabilities of their MPF technology by sectional forming panels multiple times larger than the actual tool. For this “Sectional Multipoint Forming” (SMPF) Cui et al. [2018] analysed the transition regions between forming sections.

Composites where processed on MPTs using a single diaphragm, incremental forming process (see figure 2-8 (left)) for the manufacture of curved, multi-axial, multi-ply composite parts. Here, undimpled and wrinkle-free composite parts can be formed in an incremental fashion using vacuum pressure to form both the composite and the interpolator to the mould and choosing a diaphragm and interpolator that are stiff enough. The process also demonstrates that double diaphragm encapsulation of the composite is not necessary in the case of incremental forming with a reconfigurable tool. Instead, forming can be accomplished using a single diaphragm to create a vacuum seal in the forming chamber. [Walczyk et al. 2003]
The tool was later upgraded to enable double diaphragm forming [Munro et al. 2004] as shown in figure 2-8 (right) and equipped with active control over the tool shape, as well as the temperature gradients of the composite. Active shape control improves the formability of composites in hemi-ellipsoid shape part in all cases. The forming rate and shape change sequence showed to be the forming parameters most influential on the overall part quality. [Walczyk and Munro 2009]
2.2.2 Design of Multipoint Tools

When analysing existing multipoint tools and technologies certain commonalities can be identified. These can be considered the basic design parameters. As compiled in Wimmer et al. [2016] the most important design parameters for a MPT are the density of the pin array, their cross section, design, actuation and adjustment of the individual pins, as well as the method of interpolation, to smoothen the tooling surface.

Pin Density

Pin density describes the number of pin per area and their arrangement. The pins can be arranged irregularly spaced, uniformly spaced or closely packed. Irregular arrangements (figure 2-9 (a)) are rather uncommon and most suitable in tools, which either have pins that can be rearranged for every other shape created [Hundt et al. 2014] or tools designed for a specific group of parts that all have similar characteristics in the same areas.

Uniformly spaced pin arrays (figure 2-9 (b)) can be used to reduce the number of pins needed for a given tooling area and subsequently the cost of the tool [Zhang et al. 2008]. However, this reduces the resolution of the tool (pins per area in $1/m^2$), as well as the possible complexity of parts to be created. In a closed packed array (figure 2-9 (c)-(f)), the pins are in direct contact with their neighbours. This way they can support each other against loads diagonal to the pin axis and guide each other linearly in cases where a torsional moment is applied to the pin axis during adjustment (compare pin actuation on page 36ff).
**Pin Design**

In order to keep manufacturing cost for the tool low the use of standard parts and serial parts is essential. This is particularly true for the pins since these are the most repetitively used parts in a multipoint tool. A regular tiling with repeating pins is desirable [Li et al. 2014]. Nakajima [1969] used steel wire with circular cross section in a close packed array. In this arrangement, gaps are created between the pin. These gaps do not support the interpolation layer, which can lead to larger dimples on the tooling surface. Most tools use a square cross-section for their pins. There are however three possible tessellations, as shown in figure 2-9 (d)-(f), called regular tiling, to fully cover a plane with equal regular tiles without gaps: triangular, square and hexagonal tiling [Grünbaum and Shephard 1977]. Square tiling is the most commonly used in multipoint tooling. According to Walczyk and Hardt [1998] this is due to two main reasons. First, square material is commercially available for reasonable prices compared to other, more complex profiles. Second, square pins support each other best against external loads and, if required, distribute clamping forces best through the pin array. Kirby and Stauffer [2007] also identified the capability to reproduce straight lines, as well as the resolution of a tiling as additional parameters to be taken into account in pin design and found hexagonal cross sections to be superior in these categories.

For the pin tips, different concepts have been examined. Simon et al. [2013; 2014b] evaluated a round and a squared pin tip design numerically and experimentally (see figure 2-10). They found that the squared design produced the best surface quality in a thermoforming process.

![Figure 2-10 - Round and square pin tip variant [Simon et al. 2013]](image)

Munro and Walczyk [2007] however postulate that pin tips have to be spherical to enable a tangential contact to the elastic interpolation layer. This is necessary to prevent excessive stress peaks and thus damage in the IPL. Additionally, this geometry creates a defined contact, which remains calculable in the subsequent process.

**Pin Actuation Method**

One of the questions in designing a multipoint tool is how to set the pins to their desired height. Over the years various solutions for this problem have been developed. In the first computer-controlled tool, Nakajima [1969] used robotic manipulation in form of a ultrasonic vibrating stylus attached to a NC milling machine to sweep the loose pins in place.
The aforementioned RTFF project used direct driven pin actuation, as shown figure 2-11, to adjust their discrete die. They grouped four pins to a unit with an individual controller. These pins could all be adjusted simultaneously, but need to be clamped together for a forming operation. This configuration was found to be the best compromise in positioning accuracy and repeatability, setting speed, suitability for a production environment, fabrication cost, manufacturability and maintainability, as well as maximum forming load. [Munro and Walczyk 2007]

Walczyk et al. [1998] introduced a hydraulic pin actuation setup in which the pins are pressed against a closed-loop controlled setting plate that moves away from the pin base. Each pin is then locked in position when the setting plate passes the desired height. With this method, they achieved reasonable positioning accuracy [Walczyk and Im 2000]. Boas [1997] proposed a sequential leadscrew driven method in which a servomotor can move underneath the pin array and couple to each pin to set it to the target height. Beside this rotational setup methods, linear motion was proposed to set the pins by Simon et al. [2014a]. They used a push plate to first elevate all pins to their maximum height. Then the plate lowers and each pin is fixed at its target height, with
an individual clamping mechanism. Summarising, the actuation concept contributes significantly to set up time of the whole pin array, as well as the total cost of the tool.

Im et al. [2000] compared technical properties of the three pin actuation methods shown in figure 2-12. They found the Sequential Set-Up (SSU) concept [Boas 1997] to have the best pin-positioning accuracy and repeatability, as well as the least-complex control wiring and circuitry leading to the lowest manufacturing cost of the three concepts. However, they also found technical problems concerning backlash, setup time and problems in detecting engagement of the pin leadscrew during setting.

![Image of pin actuation methods](image)

**Figure 2-12 - Different pin actuation methods: (a) Sequential Set-up (SSU) Concept (image by Im et al. [2000]), (b) Hydraulically Actuated (HA) Concept [Walezyk et al. 1998], (c) Shaft-Driven Leadscrew (SDL) Concept [Haas et al. 2002]**

**Pin Adjustment Method**

For open moulds, there are two possibilities to adjust the pins: They can either be relatively fixed, meaning that the positions of the pins are adjusted prior to the manufacturing process or they can be actively controlled and be moved during the forming process. This for example allows incremental forming of parts [Munro et al. 2004].

**Interpolation Method**

Since the discrete surface generated by the pins is not directly viable as a mould, an interpolation layer is introduced, that smoothens out the steps created by the pins. This layer can be made from a hardening material or from a (more or less) elastic sheet material. This elastic sheet can then be loosely placed on top of the pin array. The deformation of the IPL is then caused by gravity for mildly curved geometries or by an upper die pressing it in shape. Alternatively, it can be fixed to the pins, e.g. mechanically or magnetically, such enabling the pins to also pull the IPL down and
force it in the target position. Chapter 2.5 gives a more detailed discussion of these interpolation methods.

All the MPT implementations, described in the previous chapter, use some combination of these design parameters. Table 2-2 summarises the parameters and their respective potential characteristics.

Table 2-2 - Principal design parameters for multipoint tools

<table>
<thead>
<tr>
<th>pin density</th>
<th>irregularly spaced</th>
<th>uniformly spaced</th>
<th>closely packed</th>
</tr>
</thead>
<tbody>
<tr>
<td>cross section</td>
<td>cyclic</td>
<td>triangular</td>
<td>square</td>
</tr>
<tr>
<td>pin actuation method</td>
<td>robotic manipulation</td>
<td>hydraulic</td>
<td>mechanical rotational</td>
</tr>
<tr>
<td>pin adjustment method</td>
<td>relatively fixed</td>
<td>actively adjusted</td>
<td></td>
</tr>
<tr>
<td>interpolation method</td>
<td>hardening material</td>
<td>elastic sheet loose</td>
<td>elastic sheet fixed</td>
</tr>
</tbody>
</table>
2.2.3 Real World Applications

Multipoint tools have been successfully applied to a number of applications most of which are purely academic. Academic research in the last decades focused on areas like aviation, where aircraft outer skin panels were stretch formed [Walczyk et al. 1998], medicine, where individually fitted cranial implants were made from titanium [Tan et al. 2007] and transportation, where windowpanes were manufactured from polycarbonate [Zitzlsberger 2016] and Plexiglas® (PMMA) [Simon et al. 2013] for use in automotive prototypes. In civil engineering experiments with multipoint tooling as formwork for casting concrete were conducted in order to produce freeform thin walled façade elements [Pedersen and Lenau 2010; Henriksen et al. 2015, 2016].

The only well-known real world applications are from the area of civil engineering. For the Beijing Olympic stadium multipoint forming was first used in an architectural setting. The so called “Bird’s Nest” (figure 2-13, left), designed by architects Jacques Herzog and Pierre de Meuron, contains twenty-four trussed columns, each one weighing 1,000 tons (figure 2-13, bottom right), encasing the inner bowl of the stadium and supporting the roof. The purpose built MPF system SM150 (figure 2-13, top right), developed by Jilin University of China, has been used to press form parts of these trusses. In order to manufacture the large components needed, incremental sequential forming, with optimised forming path, was used. [Li et al. 2014]

In 2012, the Dongdaemun Design Park in Seoul, Korea (see figure 2-14, right), designed by Zaha Hadid, was the most irregularly shaped building in the world. Compared to other buildings incorporating freeform architecture, it has an unusually high percentage of double-curved façade panels. Among the total of 45,000 panels, approximately 22,000 panels are double curved. A specifically designed multipoint stretch-forming tool (MPSF) was applied to manufacture these panels (see figure 2-14,
left) cost and time efficient. With this tool, cost for the panels were reduced to US $ 260 per square meter compared to US $ 7,000 per square meter when using die-casting or US $ 3,000 per square meter when using hydroforming, while also reducing the average fabrication time per panel from several hours to 15 min per panel. In total 48 % of all façade panels of the building where built using MPSF. [Lee and Kim 2012]

*Figure 2-14 - Mock-up tests (top left) and panels under installation (bottom left) [Lee and Kim 2012] and finished Dongdaemun Design Park with MPSF formed façade elements (right) (Photo by Warren Whyte, 2014)*


2.3 System Immanent Defects

In multipoint tooling, the tooling surface is created by an elastic layer smoothing the discrete representation of the desired surface. This elastic layer introduces new effects to the manufacturing process. The die or mould can no longer be considered rigid. Process loads, temperature changes and other factors can lead to a deformation of the surface. This leads to a global shape deviation in the final part. Additionally, the workpiece is not supported uniformly, due to the discrete characteristic of the pin array, leading to local dimpling. In their early works Hardt et al. [1981] defined three distinct factors influencing the part quality in multipoint tooling:

**Overall fidelity of the part:** form deviation due to the elastic moulding surface

**Dimpling:** compression of the workpiece over the pin tips

**Cupping:** deformation in the unsupported area

The last definition however was never adopted in the literature and similar effects were subsequently also called dimpling. This leads to the following two distinct system immanent errors:

**Shape error,** a dimensional deviation between actual and desired part shape, caused by elastic deformation of the IPL.

**Dimpling,** the golf ball like indentations on the part created by the pins pressing through the interpolation layer.

The two phenomena are subsequently defined, in detail.

2.3.1 Shape Error in Multipoint Tooling

The introduction of an elastic interpolation layer induces a deviation between the target shape and the actual shape of the part. This shape error can be described either locally in a set of specific points of the part or globally, as a parameter describing the severity of the deviation between the desired and the actual shape. With local shape error descriptions however, it is essential to distinguish dimpling.

Wang et al. [2010] defined the local shape error $e_z$ as the difference between the z-coordinate of the shape of the formed part $a$ and the desired part $t$, at points $i$

$$e_z = z_a - z_t$$  \hfill (1)

where $z_a(i)$ and $z_t(i)$ are the z-coordinates at the $i$-th sampling point on the actual part and the target shape, respectively. Alternatively, it can be defined as

$$z_{error} = z_t - z_a$$  \hfill (2)
resulting in an inverted sign [Cai et al. 2009; Zhang et al. 2013; Jia and Wang 2017b]. These local errors can be used to calculate an error value for each pin in the array [Liu et al. 2016].

The global shape error or average error $E_{rr}$ is defined as the root mean square (RMS) of the sum of $z$-coordinate deviations at all support points. It can be written as

$$E_{rr} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (z_{ai} - z_{ti})^2}$$

where $n$ is the number of the support points, $z_{ai}$ and $z_{ti}$ are the $z$-coordinates at the $i$th sampling point on the actual shape and the target shape respectively [Wang et al. 2010; Jia and Wang 2017b].

Additional to the RMS, the average absolute (AVAB) error

$$E_{AVAB} = \frac{1}{n} \sum_{i=1}^{n} |z_{ai} - z_{ti}|$$

between the desired and the actual shape [Rao and Dhande 2002] can be considered as a measure for the shape error. Even though the evaluation of the surface quality via a global RMS and AVAB is possible, it is not very significant. It does not take into account that there are two distinctive errors, dimpling and shape error, that have to be considered separately. Global RMS and AVAB can only give a combined picture of the errors [Rao and Dhande 2002].

### 2.3.2 Dimpling in Multipoint Tooling

In multipoint tooling, the geometry of a desired part is approximated using an array of pins. Due to the nature of the tool, the geometry created by these pins is a discrete representation of the original. This means, that each pin merely contacts the target surface at a single point and that the rest of the pins surface inevitably deviates from it. This local defect is directly created by each individual pin and the area surrounding it and is called dimpling. The pattern created is similar to the surface of a golf ball.

**Definition of Dimpling**

As previously discussed, a large variety of multipoint tooling technologies has been developed. These technologies rely on different physical effects in their manufacturing process. The observable dimpling defect looks equal in all technologies. However, the reasons for this phenomenon are different and depending on the kind of manufacturing process. The definition of dimpling in the literature seems unclear. The definition varies, depending on whether forming or moulding technologies are applied.
**Forming** processes in general need a two-sided tool configuration to deform a workpiece. The upper side can itself be a multipoint tool but other variants like elastic cushion and hydroforming also exist (see chapter 2.2). This upper side pushes down on the lower side of the tool, deforming the workpiece in the process. When fully closed, the forces from the upper die are transmitted through the workpiece to the lower die. The discontinuous contact between the workpiece and the pin array creates a large force gradient between supported areas directly above the pins and unsupported areas between the pins [Hardt and Gossard 1980]. These high and concentrated loads in the IPL lead to material flowing away to the less supported areas around the pin tips. This creates an uneven thickness distribution in the workpiece and indentations on the surface. The resulting unevenness of the workpiece can be considered dimpling [Eigen 1992; Socrate and Boyce 2001; Alfaidi et al. 2010; Wang et al. 2010; Li et al. 2014]. In forming tools with a continuous upper die, as in Multipoint Sandwich Forming (elastic cushion), and in Multipoint Hydroforming an alternative definition of dimpling was adapted: Here dimpling is defined as a variation in the amplitude of the normal strain distribution, which is caused by the pins. It occurs on the contact region between the pins and the workpiece [Liu et al. 2010b]. Similarly, the normal stress distribution can be used for the evaluation as shown in figure 2-15 [Liu et al. 2016].

![Figure 2-15 - Dimpling evaluation using normal stress distribution of half-ellipsoid shell with different cover sheet thicknesses](source)

In moulding processes on the other hand, the workpiece is not loaded by an upper die. Therefore, a deformation or compression of the workpiece between two sets of pins is not possible. The interpolation layer however can deform into the unsupported areas between the pins creating a similar surface appearance. When the interpolation layer is loaded with a soft or even liquid material as in casting or when vacuum bagging is used (e.g. for fibre-reinforced plastics) to apply an evenly distributed load to the surface of the workpiece, this can cause sagging between the support points. This is schematically shown in figure 2-16. Hardt et al. [1981] called this phenomenon of deformation in the unsupported areas cupping. However, all publications afterwards referred to this phenomenon as dimpling as well. This definition will therefore also be used in this work.
Measurement Methods

Measuring dimpling is critical when trying to prevent it methodically. In early works of Ousterhout [1991] and Eigen [1992], dimpling of sheet metal was determined by visual inspection on a pass/fail basis. Based on the forming limit diagram used to predict failure in sheet metal forming, Ousterhout [1991] then developed a dimpling criterion to predict global failure in multipoint forming, using the geometry of the part and the properties of the sheet metal. Eigen [1992] later found, that such a criterion should also include interpolator properties to determine the likelihood of dimpling occurring at a given location on the part.

In order to quantify dimpling, Schwarz et al. [2002] used the shadow moiré method\(^9\) to evaluate dimple depth. They compared the method to a Browne & Sharpe Coordinate Measuring Machine (CMM) that was used to scan along the line of maximum dimple amplitude and found that CMM takes much longer than the optical moiré method, while producing similarly accurate results.

Liu et al. [2012] defined a dimpling parameter based on the root mean square error (RMSE) of the deviation between the real surfaces and the target surface:

\[
RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \Delta z_i^2}
\]  

(5)

where \(\Delta z_i\) is the distance between a point \(i\) on the actual surface and the target surface in vertical direction (compare figure 2-17). They use this parameter to evaluate the part quality in multipoint forming.

---

\(^9\) The shadow moiré method is a non-contact optical method to evaluate warp. A shadow moiré grille is used to project a fringe pattern resulting from the geometric interference between a flat reference grille and the projected shadow of the grille on a warped test object.
Zhang et al. [2008] on the other hand measure dimpling independent to the orientation of a global coordinate system. Instead, their measure is depending on the local orientation of the tooling surface. They use the distance between peaks over the pins and valleys in between (see figure 2-18) to describe the severity of dimpling.

Pedersen and Lenau [2010] extend this definition in the third dimension and define different dimpling measures for straight and diagonally neighbouring pins, as shown in figure 2-19. Both definitions however, do not take into account the actual geometry of the target geometry. Instead, they linearly interpolate between the support points.
2.4 Shape Error Compensation

In forming operations in general, the overall goal is to produce a part that is accurate to size. However, shape errors can appear for a variety of reasons. In multipoint tooling, the forming process is conducted on an elastic surface rather than a rigid tool. As stated in the previous chapter, this promotes the appearance of shape error. The flexible and rapidly reconfigurable nature of the tooling technology however, allows the compensation of this error by readjusting the pins accordingly.

In metal forming, spring-back is the main driver of shape error [Zhang et al. 2008]. After the forming load is removed, the elasticity of the metal deforms the part in a self-equilibrating residual stress state. The resulting shape error is caused by the non-uniform stress distribution through the thickness of the metal sheet.

In moulding however, this effect is not present due to the soft or liquid nature of the raw materials. Influences on the shape error can therefore be reduced to the interpolation layer, process and part parameters. Mainly the layer thickness [Liu et al. 2016] and the forming force [Jia and Wang 2017b] cause the average shape error.

The reconfigurable nature of multipoint tools allows the readjustment of individual pins, to compensate the shape error. Hence, the shape error in MPT can be considered as a control problem that can be solved iteratively. There are two possible ways to achieve sufficiently precise part shapes: either the shape error can be evaluated in line with the manufacturing process, by iteratively making and measuring parts and readjusting the tool, or it can be evaluated before the manufacturing process, using numeric simulation to predict the shape error and compensate accordingly.

In order to compensate shape errors in their stretch forming process for sheet metal, Hardt et al. [1982] proposed an iterative, closed-loop shape control methodology, able to compensate for springback effects and interpolation layer elasticity in one dimensionally and two dimensionally bent geometries [Hardt et al. 1985]. Webb and Hardt [1991] introduced a “Deformation Transfer Function” (DTF) algorithm for matched die forming of axisymmetric parts that was adapted by Ousterhout [1991] and Hardt et al. [1992] to be used in multipoint press forming and stretch forming [Valjavec 1999] of general three dimensional parts. The DTF algorithm described geometries as a spatial-frequency content and the metal forming process as a discrete transfer.
function. Figure 2-20 shows the shape control algorithm. For an actual part shape \( p \) an optimised die shape \( d \) is computed based on the shape error \( e \) of previous forming trials. The transfer function of the multipoint forming process \( G_p \) is defined in the spatial-frequency domain of the parts, by transforming all dimensional data from Cartesian to Fourier space using discrete Fourier transformation. It is calculated using data from an initial forming trial. After every iteration, the parts are measured and a new iteration is produced until the errors at all points are below a defined threshold.

This methodology is capable to not only handle multipoint forming, but also manufacturing operations with multiple process steps. Valjavec and Hardt [1999] showed that chemical milling and trimming of aircraft panels was possible with the desired accuracy by lumping together all process steps in one transfer function \( G_p \). They used a tool with 24 x 23 pins in an area of 280 mm x 300 mm and manufactured torus and toroidal parts, with a maximum shape error threshold of 0.25 mm within one or two forming trial iterations.

The method however, relies on physical forming trials and needs a system to measure rapidly and accurately the produced part shape, as well as the resulting shape error. This is expensive, as well as time consuming. Socrate and Boyce [2001] implemented a non-linear finite element based die design methodology, which uses the “spring-forward” algorithm [Karafillis and Boyce 1996], and were able to reduce the number of forming trials needed. The iterative spring-forward procedure automatically executes a sequence of finite element simulations of forming operations on a series of die geometries. Each subsequent die geometry is determined via a spring-forward calculation: the distribution of forces and moments acting on the sheet in its loaded configuration on the current die shape are used as the loading conditions on the reference part shape to “spring-forward” the part towards its configuration when applied to the next die shape. In order to reduce computing cost, they replace the complete model of the pin array with a uniform rigid surface, which artificially reproduces the physical effects of the IPL by modifying the contact stiffness at the sheet/die interface. Friction between the sheet and the interpolator is captured in the equivalent model by applying appropriate shear traction boundary conditions to the bottom surface of the sheet. The model prediction of the deformation matches experimental results within ± 0.25 mm and the shape control algorithm can produce adequate parts after just one iterative run. [Socrate and Boyce 2001]

Anagnostou and Papazian [2004] developed an optimised tooling design algorithm improving the convergence behaviour of the inverse springback approach using an interpolation scheme. Zhang et al. [2007] introduced the inverse displacement method using FE Analysis to simulate deformation and spring-back for a particular process condition (see figure 2-21). In this method the shape error \( \Delta d \) at the nodes \( N_f \) of the simulated surface \( S_f \) normal to the target surface \( S \) are calculated and a new surface \( S_c \) is obtained by reversing the displacement by a value of \( k\Delta d \) to the other side of target
surface $S$ and constructing a non-uniform rational B-spline surface. In an iterative process, this procedure can be repeated, until a threshold value at every node is undercut. Using this method, the maximum shape error of a hemispheric workpiece with a diameter of 320 mm was reduced by 66% after just one iteration.

Liu et al. [2010b] introduced a method to enhance the accuracy of their MPSF process that also uses iterative corrections according to numerical simulation results. As shown in figure 2-22, they defined the shape error $E_k$ as the vertical distance between the objective part surface $Z_{obj}$ and the corrected part surface $Z_k$ after $k$ iterations

$$E_k = Z_{obj} - Z_k$$

and calculated a new corrected tooling surface $S_{k+1}$ according to

$$S_{k+1} = S_k + CE_k$$

where $S_k(x, y)$ represents the $k$-times corrected, previous surface of the die, and $C$ is a correction coefficient matrix.

$k$ hereby is an empirically obtained optimisation parameter that can be set to 1 as long as sufficient experience values are not available.
\( E_k \) is the error between \( k \)-time correction part surface and objective surface. The forming error is then defined as

\[
e_k = \sqrt{\sum_{i=1}^{m} \sum_{j=1}^{n} \frac{E_{k,i,j}^2}{mn}}
\]

(8)

The forming accuracy of a part is then checked by comparing the forming error to a threshold value \( \delta_e \). If \( e_k \leq \delta_e \), the part meets accuracy demand. Using this method results in workpiece with a smooth surface and a shape error of approximately 0.1 mm [Liu et al. 2010b].

Later, Liu et al. [2016] refined their compensation method and improved its performance. They calculate the deviation value \( \Delta S_i \) along the drawing direction corresponding to each pin

\[
\Delta S_i = |y_0 - y_i|
\]

(9)

and calculate the new tool configuration reverse direction using a value of double \( \Delta S_i \), as shown in figure 2-23. Then the reconfigured multipoint tool was used to form the next component, and the procedure is repeated until the value of \( \Delta S_i \) is small enough. [Liu et al. 2016] For the tested geometry (bowl), the shape error was sufficiently compensated after two iterations.

![Figure 2-23 - Schematic on error compensation of the geometrical profile [Liu et al. 2016]](image)

All shape error correction methods assume that the surface produced is actually smooth. If dimpling occurs, in some cases, this will be incorporated in the algorithm and the process could become numerically unstable. All algorithms use some sort of global error as a target value. When dimpling is present, this value can be independent of the shape error but only represent dimpling. It is therefore crucial to define a dimpling-independent termination criterion for the control algorithm. Error functions only using the actual support points of the pin array will minimise the influence of dimpling and lead to a more stable control algorithm.
2.5 Surface Interpolation

The dimpling defect in multipoint tooling can be compensated by smoothing the pin array. By sufficiently interpolating the areas between the support points with an elastic layer an adequate tooling surface can be created. This layer is responsible for the surface quality of the produced part, as well as the accuracy by which this part can be produced. It is commonly used in most MPT tools and multiple studies have been conducted to find the ideal IPLs for the different MTP technologies.

The layer used has to be deformable to be able to follow the adjusted pin array, but also stiff enough to create a viable tooling surface. Eigen [1992] theorises that, if using a deformable interpolator, a softer, more flexible material will better conform to the shape of the tool. This should distribute the stresses more uniformly and have a higher resolution than harder and less flexible interpolators have. On the other hand, softer materials would need thicker layers in order to achieve a similar surface quality [Eigen 1992]. Research into the interpolation of multipoint tooling tends to also point in this direction. The first interpolation methods were proposed by Nakajima [1969]. He used a rubber sheet of 2 mm thickness to protect the sheet metal surface from scratching during the forming process. However, he did not prevent dimpling with this method. In vacuum forming of plastic sheets, he also used modelling clay to smooth out the steps between the wires. Due to the low surface pressure of below 1 kg/cm², the surface was not deformed during manufacturing. [Nakajima 1969]

Eigen [1992] himself examined the influence of hardness and thickness of the interpolation layer on dimpling in metal stretch forming. He found a premouldable IPL from ethylene vinyl acetate copolymer Elvax®, with a thickness equal to the width of the die pins to work well and produce dimple free surfaces [Walczyk and Hardt 1998]. This has also been supported by FE analysis conducted by Kutt et al. [1999] and Cai et al. [2009] who also examined pin size and part curvature as possible parameters influencing dimpling. Paunoiu et al.[2008] later used as similar material, Elvax® 460, in sheet metal multipoint forming, without premoulding. They found that depending on its thickness the uncontrolled flow of the elastic material caused a negative influence on part quality.

![Figure 2-24 - Effect of interpolation layer hardness (left) and thickness (right) on dimpling (each line represents a particular interpolation layer material) [Schwarz et al. 2002]](image)
Schwarz et al. 2002 analysed polyurethane interpolation layers with increasing hardness and different thicknesses. Their results are shown in figure 2-24. It seems that harder interpolators require greater thickness, in order to prevent dimpling, and thinner layers of softer interpolators are better suited. This is in good agreement with results by Rao and Dhande [2002], who numerically analysed the influence of IPL thickness on the process of sheet metal forming on their Flexible Surface Tooling (FST).

Walczyk et al. [2003] also examined the effects of interpolation layer thickness and material on dimpling, in diaphragm forming of composite materials. As expected, dimpling was worst when no interpolator was used. By using 6.4 mm thick polyethylene foam on their machine, with a pin size of 28.6 mm square and hemispherical tips, a much smoother surface was achieved. The best results were achieved, when using a 32 mm thick foam composite interpolator consisting of 25.4 mm thick open-cell polyurethane foam and 6.4 mm closed-cell polyethylene foam. Increased IPL thickness however, leads to a reduced tool resolution and increases the geometric deviation [Liu et al. 2016]. Hence, Prabhakara [2002] and Munro et al. [2004] showed that interpolation layers with thickness less than the pin distance could produce sufficient results in composites forming.

Gibbons et al. [2010] used superplastic formable (SPF) aluminium and shape memory polymer (SMP) as an interpolation layer, to improve the tolerances of FRP composite manufacturing in MPT. They found that, using SPF materials, the part quality is independent of the processing time, temperature and pressure applied. However, they were not able to produce dimpling free surfaces with any of these materials.

Wang et al. [2010] evaluated the influence of the pin array resolution on dimpling, with pin arrays 10×10 to 80×80 pins, on the same area of 180 mm x 180 mm. A significant drop in the dimpling (~ -60 %) could be observed between 10 and 20 pin resolution. Increasing the resolution further, from 20 to 80 pins resolution, dimpling decreases only marginally, to approximately half the initial value. Rivai et al. [2014] contradicted these findings and stated that the higher number of pins in a hexagonal packing, compared to a squared one, leads to more dimples. This however, is only true if the severity of dimpling is measured by the number of dimples per area and not via established methods incorporating the deviation from a target geometry, as described in chapter 2.3.2.

Wang et al. [2010] and Simon et al. [2013] also looked at the effect of the pin tip radius and found larger radii to reduce dimpling. They explained this with an increased contact area on the reduced curvature of larger radii that lead to a better load distribution in the IPL.

Liu et al. [2016] evaluated the effect of the forming load on dimpling, using numeric simulations. It shows that higher loads lead to more distinct dimpling in the corner areas of the workpiece. It seems that, together with the IPL, the sheet metal blank is
squeezed into the space between the pins, when very high hydraulic pressure is used. In the same areas, a jump in nominal strain could be observed in the component. This however, can be explained by the increasing effect of frictional forces, caused by the high-pressure effects, which can reduce the radial tension stress and contribute to the uniform thickness of the contact region.

![Figure 2-25 - Concept draft of the variable forming tool (Hundt et al. 2014)](image)

In their MPSF setup Yuan et al. [2004] introduced an additional steel sheet between the pin array and a polyurethane IPL. This reduced dimpling even with increased distances between the pins. For their hydroforming process, Selmi and Belhadjsalah [2013, 2017] also proposed a steel interpolator and found it to be a more efficient way to prevent dimpling in thin sheet products produced at high uniform process loads. Hundt et al. [2014] used a similar approach with multiple functional layers for their variable forming tool (see Figure 2-25). The tool itself has non-uniformly spaced, movable pins. As a tooling surface, they used an interpolation layer made of three layers of elastomer. The top layer integrates water tubes for heating and cooling the tooling surface. The middle layer prevents dimpling between the pins, and in the third layer, inserts are embedded to connect to the kinematics of the actuators.

![Figure 2-26 - The membrane is stretched and drawn down between the pins and the surrounding clamping frame; membrane material from this area can be pulled towards the tooling area (Pedersen and Lenau 2010)](image)
Simon et al. [2013] also implemented heating in their silicone rubber interpolation layer. They used heating wires to control the tooling temperature and evaluated the effects of that temperature, as well as the maximum part radii, on the thermoforming process of plastic panels. Pedersen and Lenau [2010] offset the pin array in their Variable Geometry Mould (VGM), in order to allow the tooling surface, to pull in sufficient amounts of membrane material from surrounding areas, as shown in figure 2-26.

In recent years, numeric optimisation methods were used to increase the performance of MPT designs. Multi-objective optimisation was used to reduce dimpling and wrinkling in the MPF process. Abebe et al. [2016] examined the punch speed, punch pressure, and interpolation layer thickness and were able to create a dimpling-free part, both numerically and experimentally. Subsequently, they used robustness analysis, to further validate their results [Abebe et al. 2017]. Abosaf et al. [2017] also used numeric optimisation to improve their MPF design. They analysed the IPL thickness, the coefficient of friction, the pin size and the radius of curvature of the pin-head, using a response surface method to identify significant process parameters. Thereby they identified significant interactions between parameters and were able to develop a mathematical model describing the MPF process.


2.6 Discussion and Research Questions

As shown in the previous chapters, there has been a wide range of research on multipoint tooling in general. However, this research is still limited in various areas that will be addressed in this thesis.

Extensive studies were conducted early on in the design of multipoint tools. Different possibilities for pin array design as well as the adjustment of the pins were carried out and different IPLs were examined regarding their suitability as tool surfaces. This research however, was mainly focused on forming technologies in general and in sheet metal forming in particular. Only little research has been conducted on the use of MPT technology for open mould manufacturing processes and FRP composite manufacturing. The little existing research in this area on the other hand is limited to non-standard diaphragm forming processes. Well established FRP composite manufacturing processes have not yet been demonstrated on MPT. Furthermore, all established design guidelines and recommendations are derived from the field of forming technologies. However, the changed requirements due to FRP manufacturing make it possible to go new ways and, if necessary, to revisit solutions already discarded in the literature. These possibilities must be examined in the course of VAMM development in order to find an ideal solution for this specific application. This ultimately leads to the following question:

**Q1** How can established FRP manufacturing technologies be enabled in the Vacuum Assisted Multipoint Moulding technology?

In order to answer this question, first of all it is of paramount importance to clarify these FRP specific characteristics. Chapter 2.1 presented the manufacturing processes to be considered and their specific properties. Some of these common characteristics are: The fibre materials are processed in a soft, textile-like form, in single sided moulds. They are applied to the mould manually, with no significant forces used for draping. The lay-up is consolidated, using vacuum or external pressure. Heat is applied to initiate resin solidification and to achieve good mechanical properties in the composite. The curing time constitutes a major part of the process time and ranges from some minutes to multiple hours. From this information, a list of quantifiable requirements must subsequently be derived in order to answer the following question:

**Q1.1** What are the specific requirements of established FRP processes?

The validity of this list can be checked and verified by manufacturing tests after the development of the VAMM system has been completed. If it is possible to manufacture components without difficulty on the tool specifically developed according to the requirements, it can be assumed that all important requirements have been considered.

As discussed in chapter 2.1.2, common FRP composite manufacturing processes for single item production rely on open mould tooling on which the parts are made. In Figure 2-27 the MPT tooling technologies discussed in chapter 2.2 are clustered
according to the nomenclature introduced on page 28. It shows, that most of these
technologies are forming technologies that use some sort of a double-sided tool to
deform a solid material. Thereby it does not matter whether the upper form is also
designed as an MPT or whether an alternative load introduction is used, e.g. in the
MPSF. All solutions obstruct the access to the mould surface and render it impossible
to use the specified manufacturing processes.

![Diagram of multipoint tooling technologies]

**Figure 2-27 - Different multipoint tooling technologies (including the VAMM technology proposed in this thesis) clustered according to their intended use as forming and moulding technologies**

On the other hand, only two variants of MPT are supposed to be used for moulding
operations in an open mould configuration. These MPT tools however, do not explicitly
allow for the manufacturing of convex and concave geometries with inflection points.

This lack of capabilities, in turn, would greatly limit the usefulness and range of
application of the new manufacturing system. It is therefore essential for VAMM to
enable these kinds of geometries in the target geometries. This raises the question on
how the multipoint tooling technology can be adapted for VAMM in order to enable
such manufacturing operations. Hence, the following questions has to be answered:

**Q1.2 How can components with convex and concave sections as wells as inflection points be created without an upper mould?**

This desired part complexity must be included in the list of requirements and then
taken into account in the development of the VAMM system. An acceptable solution
would be able to create these geometric features without blocking the access to the tooling surface, neither before nor during manufacturing. The developed solution can be assumed sufficient if the physical system is able to reproduce the required convex and concave geometries, and if parts with these characteristics can successfully be manufactured.

By answering the two partial questions Q1.1 and Q1.2, all necessary pieces are available to develop a system that enables the production of fibre composite components in the established open mould processes. This system can be considered adequate if components can be successfully manufactured on it and if it is scalable for industrial use. As stated in chapter 2.1.1, FRP composite materials do not exist in their final form at the beginning of the manufacturing process. Instead, they are created through curing during the manufacturing process. For the mechanical properties of the composite this means, that they are also influenced by the manufacturing process. In MPT, a pin array supports the IPL, which in turn represents the tooling surface. This means that in contrast to classical tools, where the workpiece is supported over the entire surface, MPT only supports the workpiece at the contact points generated by the pins.

In forming processes like sheet metal forming this non-uniform support of the elastic tooling surface can create stress concentrations and a varying thickness distribution in an MPT manufactured component (compare figure 2-15). For forming processes this is well documented and the effects of MPT manufacturing on the mechanical properties of the finished part could be estimated.

For FRP manufacturing on MPT, no such examinations have yet been carried out. Here however, the punctual support of the tooling surface could potentially influence the consolidation of the composite layup, especially if a vacuum is applied to the laminate. This in turn could lead to a decrease in mechanical properties and components. Due to the lack of corresponding research, the following question arises:

**Q2** How do the mechanical properties of VAAM manufactured parts compare to traditionally manufactured ones?

This question can be considered as answered, when the characteristic mechanical properties of parts made on conventional as well as on the VAMM tooling are investigated and compared and when the correlations and dependencies of the parameters on the manufacturing process and the quality of interpolation have been investigated.

Beside the mechanical properties, the MPT process also has some well-established effects on surface quality. As discussed in chapter 2.3 shape error and dimpling are two distinct system immanent defects in MPT that occur due to the elastic nature of the tooling surface and the uneven support due from the underlying IPL.
The shape error has successfully been compensated for different MPT technologies. This has been achieved using different compensation strategies as discussed in chapter 2.4. From this, it can be summarised, that from the initial *Deformation Transfer Function* to the error compensation methodology proposed by Liu et al. [2016], researchers tried to reduce the mathematical complexity of shape control in multipoint tooling. Thereby, two finding emerge. Firstly, it shows that experimental evaluations of the shape error can be substituted completely by numerical simulation and evaluation. Secondly, it can be concluded, that simpler shape control algorithms work equally well in terms of part quality and computational resources. However, simpler algorithms are presumably easier to implement in a multipoint tooling workflow. There seems to be no reason to utilise complex algorithms, when the simpler solutions are able to achieve the same part quality.

For the VAMM technology a similar shape error compensation is needed. This raises the following question:

**Q3** How can components be created with sufficient shape accuracy in VAMM?

This issue can be regarded as resolved if it is possible to compensate the shape error reproducibly and fully automatically to such an extent that it is reliably below a permissible limit value. In order to achieve this however, some interposed questions have to be answered first:

In the beginning, it is necessary to clearly define the shape error as a characteristic value. As described in chapter 2.4, the literature does not provide an unambiguous definition of the shape error. There are multiple definitions, which differ in the direction of the measurement (e.g. in vertical direction or surface normal [Zhang et al. 2007]) and the position of evaluation (e.g. over the whole surface of the tool [Karafillis and Boyce 1996] or only at the centre axes of the pins [Liu et al. 2016]). For the implementation in VAMM, it is necessary to define:

**Q3.1** How can the shape error be measured adequately?

A comprehensive solution would offer both a meaningful global measure for the shape error and a local solution for the shape error at each pin. This would both allow for comparison between components and facilitate the subsequent error compensation.

With this measuring method, it is then possible to compensate the shape error in VAMM. The feasibility of previous solutions, such as shown in figure 2-22, has to be evaluated, in order to answer the following question:

**Q3.2** How can shape error be compensated sufficiently in VAMM?

In order to answer this, first of all threshold values for a sufficient compensation have to be defined. Here knowledge from prior work can be adapted to the defined shape error measure. The shape error compensation method can then be considered sufficient, when it is capable to successfully compensate shape error for arbitrary parts.
within two to three iterations, as has already been achieved in other works. This has to be done within an automated process and without user interaction.

With these points addressed, the capability to create components with sufficient shape accuracy will be established.

From there on, the second system immanent error can be addressed. As indicated in chapter 2.5, multipoint tooling is a complex manufacturing process with a number of parameters influencing the resulting part quality and dimpling in particular. These parameters are compiled and clustered into four categories in figure 2-28: All properties that are defined by the multipoint tool itself are considered *pin array properties*. These parameters can only be changed by changing the MPT tool. The *interpolation layer* is looked at separately, since it is the hardware component, most influential in respect to dimpling and it is easy to change and replace for a given MPT tool. *Part properties* define the individual component to be manufactured and *process parameters* define the manufacturing process. These categories can be changed most easily, usually even via the user interface of the MPT, and adapted to individual parts.

![Fishbone diagram analysing parameters effecting dimpling](image)

This multitude of parameters makes the prediction and minimisation of dimpling in VAMM a challenging task. In the literature the influence of some of these parameters have already been analysed for other MPT processes (see chapter 2.5). However, these investigations were mainly experimental, always specific to a certain MPT tool and manufacturing process, and rarely comprehensive. This makes it unfeasible to transfer the known findings directly to the new VAMM application. Also, no comprehensive studies on the interactions of the parameters have yet been carried out. This raises the question:
Q.4 **How can dimpling be minimised sufficiently in VAMM?**

In order to minimize a value to an extent that is acceptable for a given situation, it is necessary first of all that this value can be measured. Even though, there were attempts to classify dimpling (see chapter 2.3.2), there is no conclusive method to actually quantify it nor is there a characteristic value which allows the comparison of dimpling in different parts. This means, that in order to answer question Q4 the following question has to be answered first:

**Q4.1 How can dimpling be measured?**

In order to quantify dimpling and define a characteristic dimpling value, two partial questions have to be answered:

- **What methods can be used to measure dimpling?**
  
  In order to evaluate viable methods for dimpling evaluation, different definitions of dimpling have to be defined and tested. Existing classifications from multipoint tooling research, as described in chapter 2.3.2, have to be included in this examination. A definition is to be accepted as viable, if it gives a meaningful information about the severity of dimpling. This also means, that no other effects are included in the value i.e. that it is independent from other influences. In case more than one definition proves to be viable this raises the following question:

- **How do these methods differ?**
  
  In order to investigate how different dimpling values are related to each other, they are compared and correlations are derived. If such correlations can be found, this means, that the dimpling evaluation methods can be converted into each other. If there is no such correlation, the reason for that has to be evaluated.

Successful measuring of dimpling implies, that there is at least one distinct dimpling value established, that is capable of capturing the severity of dimpling without unrealistically over- or underestimating certain cases.

When this is achieved, the next question is how the aforementioned parameters compiled in figure 2-28 actually influence this dimpling value. Specifically, the interactions between these parameters have to be investigated in order to gain a broad understanding of the VAMM system.

**Q4.2 Which parameters influence dimpling in VAMM and to what extent?**

Identifying the parameters, that have the main influence on dimpling, means that the influences of all parameters on the value have to be quantified. Then, with the help of limit values that define the significance, they can be grouped in relevant and non-relevant parameters. For all relevant parameters, the magnitude of their influence on the total dimpling value is also to be examined.
With this knowledge, further investigations into interpolation layer design can be conducted. Specifically, it is to be evaluated whether the well-established interpolation layer using a single layered of elastomer, as used in many other MPT tools (compare chapters 2.2.1 and 2.5), is also suitable for the different loads and requirements in the VAMM system. In order to validate that, the following question has to be answered:

Q4.3 Can dimpling be minimised sufficiently in VAMM using a single layer rubber IPL?

In order to answer this question, first of all a level of acceptable dimpling has to be defined. Established methods for geometric dimensioning and tolerancing (GD&T) of plastic moulded parts as defined in DIN 16742 [DIN Deutsches Institut für Normung e. V. 2013] have to be considered. Then tests can validate whether or not the single layer IPL can be adapted in order to meet or undercut this threshold. This leads directly to the next question:

Q4.4 What is an ideal single layer IPL for VAMM?

Developing such an IPL requires to first define what is ideal for the specific given tool. Then an IPL can be considered ideal, if it meets all these criteria and changing one of the parameters would worsen at least one of them.

As stated by Eigen [1992] (see chapter 2.5) softer and harder interpolation layers use different mechanics in order to create a smooth surface. This led researchers to investigate interpolation layers consisting of different materials, specially rubber in combination with sheet metal (as described in chapter 2.2.1). This led to a decrease in resolution and a reduction of the achievable part complexity in the tool. In order to utilize the different characteristics of soft and hard materials but prevent the negative effects of a Rubber/sheet metal combination, in VAMM a multilayer IPL consisting of multiple layers of different elastomers is to be investigated:

Q4.5 Can a multilayer IPL decrease dimpling and increase shape fidelity?

This would be the case, if the an interpolation layer with more than one different rubbers either showed less dimpling at the same total IPL thickness or if it showed similar dimpling at lower total IPL thickness compared to a single-layer solution. If this is the case, an in-depth evaluation of the dual layer IPL configuration is opportune in order to answer the following question:

Q4.6 What is an ideal dual layer IPL for VAMM?

Here, the definition of ideal has to be adapted to the dual layer configuration. A ideal solution then is found similar to Q4.4.

Answering all these questions will result in physical a proof-of-concept of the novel VAMM technology. The effects of this technology on the mechanical properties of components will be known. The capability to measure, quantify and predict the surface quality of the manufactured components and to minimise the shape error in advance
will be established. Additionally, the capabilities of a multi-layer IPL design will be established and ideal solution for a single as well as a dual layer IPL will be available.
2.7 Summary

In the first section of this chapter, the basics principles, established manufacturing methods, and mould-making procedures for manufacturing fibre-reinforced plastic composites, were discussed. It shows that FRP manufacturing is a labour and time intensive process, and that tool making can make up a significant part of the time and cost involved, in making a component.

The second section of the chapter discussed the current state of art in multipoint tooling. Previous developments were introduced showing that there have been many different tooling technologies, mostly focused on forming metal. It has been shown, that multipoint tooling was successfully used in many different cases. The design of established MPT tools was then analysed. Thereby, the density of the pin array and their cross section, the design, actuation and adjustment of the individual pins, as well as the method of interpolation to smoothen the tooling surface were identified as common design parameters. The respective potential characteristics were introduced and their individual advantages and disadvantages were discussed. In order to prove the feasibility of the technology, real world applications are compiled, where MPT was successfully used. It shows that beside applications in academic research, the only known successful commercialisation efforts are documented in the area of civil engineering.

In the third paragraph of this chapter, the two system immanent defects, shape error and dimpling were introduced, and methods for their prevention were discussed. Shape error is caused by the elastic deformation of the tooling surface. It can be compensated by readjusting the pin array to take into account the elasticity of the IPL. In previous research, this was achieved by applying different compensation algorithms, either experimentally or numerically. Dimpling on the other hand is a system immanent defect caused by pin array. Given a defined MPT tool, it can be minimised with an adequately designed interpolation layer. Previous research evaluated the influence of a variety of parameters on dimpling for different MPT processes.

In the sixth section of this chapter, the findings from the previous chapters were compiled and analysed and shortcomings were identified. It shows, that multipoint tooling, in theory, could be a more efficient alternative to solid moulds in FRP production. However, the existing MPT technologies do not fulfil the demands imposed by the established FRP manufacturing processes. Based on these insights, research questions were formulated and measures of success were defined to be able to judge the outcome of the subsequent research. These questions are compiled in Table 2-3.
In order to enable the seamless integration of the Vacuum Assisted Multipoint Moulding in an existing manufacturing process, this thesis aims at answering these questions.
Chapter 3 Research Methodology

The research questions surrounding VAMM affect several subject areas. In order to answer these questions adequately, this research project pursues a comprehensive methodological approach, which is presented in the first section of this chapter. The following sections then deal with the respective partial aspects.

In order to understand VAMM comprehensively, the VAMM hardware is developed and built in a first step. In addition to the parameters identified in the literature, initial experiments will be used to determine which parameters could be adjusted in the system. Since experiments are difficult to conduct, time consuming and expensive on a physical system, a virtual model of the technology is then developed, which also includes these input parameters. This virtual model contains all steps in the creation of a product using VAMM. It starts with the part design and evaluation of an initial pin configuration. Then the forming process is modelled using finite element analysis. The resulting component is then evaluated for shape error. A shape controller readjusts the pins and reevaluates the forming process until the shape error is eliminated. Then, the surface quality is examined using a newly defined dimpling measure. A sensitivity study is then performed on this model to determine the influence of the parameters on the dimpling response. This is done for both, a single-layer and a dual layer IPL configuration, in order to evaluate the effect of this new IPL design. Subsequently, a metamodel is created on which the critical parameters of both these configurations are optimised. This way, optimal configurations for the VAMM can be developed. Conclusively, the mechanical quality of the VAMM made components is evaluated experimentally and compared to conventionally manufactured composites.
3.1 Methodical Approach

The main objective of this work is to enable the production of high-quality components with a VAMM system. The quality of the components hereby is assessed, based on three criteria: Shape error is the first inherent quality criterion in the system. This deviation of the actual shape from the target geometry should be minimal. The second systemic error in multipoint tooling is dimpling. This golf ball effect compromises the surface quality of the components. It should therefore be minimized by adequate interpolation. The third criterion is the structural mechanical performance of the components. The mechanical parameters of the components should correspond as far as possible to traditionally manufactured composites. It is assumed that when all these three criteria are fulfilled, a good part quality can be achieved.

To meet this overall goal, the VAMM system must first be fully defined and developed. This will be realised, using the design methodology according to the VDI 2221 guideline [VDI - Verband deutscher Ingenieure 1993]. This method stipulates that definite design tasks must be specified at the beginning of the design process. Here the specific requirements of existing manufacturing processes, as well as further requirements regarding the desired target geometries, must be considered (see chapter 3.2). In this context, it is also essential to consider, that VAMM is intended only to replace established solid moulds within an existing production system. A modification of the existing manufacturing processes is not expedient. Subsequently, a small-scale prototype of the VAMM is developed, to test the concept and the individual components. Initial tests are then conducted to detect and rectify problems in the hardware. The optimised hardware is then translated in a full-scale prototype.

![Figure 3-1 - Surrogate modelling philosophy based on [Kulkarni 2006]](image-url)
In order to be able to build good quality parts on this tool, it is critical to gain an understanding of relevant system parameters and their influence on the production process. Theoretically, experiments could be conducted on the VAMM system in order to analyse it. Due to the nature of a physical system however, experiments are difficult to conduct, time consuming and expensive. Nevertheless, many of these experiments would be necessary to fully understand the system behaviour, and even more experiments would be needed in order to optimise the system. Modelling and meta-modelling are methods that can drastically reduce the time and resources needed for individual experiments. These methods reduce the large number of experiments on a physical system and enable the rapid evaluation of system responses. [Kulkarni 2006]. To implement this in the given case, a three-stage procedure, shown in figure 3-1, is proposed for this thesis.

The physical VAMM system has a relatively large number of input parameters, as described in chapter 2.5, which lead to a certain system response. For an in-depth analysis, the physical system is simulated in a computer model that mimics the physics of the original system. This model contains all the process stages of an actual product creation cycle, from parametric part creation, over preprocessing to find an initial pin configuration for the tool, to the forming simulation and the quality control at the end to evaluate dimpling. The forming process on the VAMM tool is thereby modelled using finite element analysis, as described in chapter 3.3. In order to evaluate the actual system output, a critical quality measure for multipoint tools has to be quantifiable. Hence, a dimpling parameter is developed and defined, and an evaluation methodology is implemented in the computer model. The model then has the same system inputs as the physical system and creates similar system responses. Since the input parameters of the computer model can easily be modified, it is well suited to conduct virtual experiments efficiently. This enables the precomputation of pin configurations and the implementation of a shape control algorithm, which eliminates shape error. The model can then be used in pre-processing of a physical manufacturing process in order to eliminate shape error, as well as to evaluate the dimpling for any given target part.

Subsequently, Design of Experiment (DoE) is used to scan the parameter space of the computer model comprehensively. Then, a sensitivity analysis is conducted, to evaluate the impact of certain input parameters on a system response, as described in chapter 3.4. It is used to gain an understanding of the VAMM system and the underlying coherencies between parameters and dimpling, based on experimental data, and to identify the parameters that have the strongest influence on this system response.

These critical parameters can be used to create a metamodel that captures only the relationships between the relevant input variables and dimpling, but not model any underlying processes or physics. Other than the computer model, which takes minutes, hours or even days to solve, a meta-model can be solved in fractions of a second. Parametric optimisation is then used to find an optimal configuration for the system.
For this purpose, the critical parameters are optimised in a multidisciplinary optimisation, as described in chapter 3.5, using the metamodel. In this way, several thousand optimisation computations can be performed in a reasonable timeframe. This approach enables efficient and effective optimisation [Abebe et al. 2016; Abebe et al. 2017; Abosaf et al. 2017]. In this thesis, the software OptiSLang by Dynardo\textsuperscript{11} is used to scan the design space, execute the sensitivity analysis, to create the metamodel, and to optimise the VAMM system.

Finally, the quality of components, made by VAMM, is experimentally evaluated. For this purpose, mechanical characteristics of components made using VAMM are compared to components made with an established process. The methods used for these investigations are described in chapter 3.6. This is to investigate whether the new process can produce components with equivalent mechanical properties.

\textsuperscript{11}OptiSLang 6.2. Dynardo GmbH, Weimar, Germany.
3.2 Design and Development of Manufacturing Systems

In the first section of the thesis the proposed Vacuum Assisted Multipoint Mould is developed. The design is conducted in four distinct steps [VDI - Verband deutscher Ingenieure 1993]: *Clarifying the task, conception, design and development.*

- **Clarifying the task** helps to provide information on the requirements for the particular solution, as well as on the existing conditions and their significance. The result is an informative specification of the VAMM system in a list of requirements. This includes the specific requirements introduced by established FRP processes, requirements that are related to the part geometry that can include convex and concave sections, as well as inflection points, and the capability to create moulds before the fibre lay-up.

- **Conception** is the part of the design process, which, after clarifying the task, determines the basic solution by abstracting from the essential problems, setting up functional structures, and by searching for suitable active principles and combining them in an active structure. The conceptual design is the determination of a solution in principle. A durable and successful design solution thereby results from the choice of the most appropriate principle and not from overemphasis on constructional intricacies.

- **Design** is the part of the design process that, starting from the basic solution, clearly and completely elaborates the structure of the developed system according to technical and economic aspects. Design is the creative determination of a solution. A frequent and typical process is that after evaluating the individual variants, one appears to be particularly favoured, but can be developed and improved by partial solutions of the other suggestions that do not appear so favourable in their entirety. The final overall design then already represents a control of the function, the durability, the spatial compatibility etc., whereby the requirements regarding the cost must present themselves as fulfillable.

- **Development** is that part of the design process, which supplements the building structure of a technical structure by final regulations for shape, dimensioning and surface quality of all individual parts, determination of all materials, verification of the manufacturing and assembling possibilities and the final cost, and creates the final drawings and other documents for its material realisation. The result of the elaboration is the fully detailed technical production definition of the solution.

Validated solutions from previous research are implemented when possible. To validate the general concept of VAMM, a small-scale test bench is built containing all the basic components of the full system. It is supposed to be used for testing different interpolation layer configurations and for developing the numeric system. Functional tests and manufacturing tests are conducted and evaluated. After validation, the concept is then transferred to a fully automated large-scale prototype.
3.3 Finite Element Modelling of the VAMM Processes

In order to evaluate the VAMM system, the VAMM forming process is virtually recreated using finite element analysis (FEA). During the operation of the VAMM tool, the tooling surface is deformed by a vacuum in order to conform to the pin array. This deformation is highly nonlinear. The large deformation itself is not linear and the rubber materials used in the IPL behave non-linear as well. These kinds of highly non-linear, quasi-static problems can be solved using an explicit finite element solver.

In this thesis, the software ANSYS Autodyn12 is used for this task.

In an explicit solution, the next time step \( t_{n+1} \) is determined based on the current time step \( t_n \). The integration procedure is only stable if this time step is reliably smaller than the critical time step \( \Delta t_{\text{crit}} \). This critical time step depends on the characteristic dimension \( h \) (e.g. the smallest edge length) of the smallest element in the model and the local material sound speed \( c \) in that element [Courant et al. 1967].

\[
\Delta t_{\text{crit}} = f \left[ \frac{h}{c_{\text{min}}} \right]
\]

Consequently, meshing should be as uniform as possible in order to prevent a single small element to increase calculation time significantly. In order to increase the critical time step, mass scaling can be used to artificially increasing the density of an element. This increases the speed of sound in the element, which increases \( \Delta t_{\text{crit}} \), and ultimately reduces the number of time increments required to complete a solution [ANSYS Inc. 2017a].

Most components in the VAMM model are made from metals and can easily be modelled using linear elasticity. The IPL, on the other hand, is made of a rubber material, which cannot be modelled as linear elastic. Instead, its non-linear elastic behaviour can be described in good approximation with hyperelasticity [Ogden 1997; Muhr 2005]. Hyperelastic material models use the strain energy potential \( \Psi \), to describe the stress-strain relationship. For small deformations, of up to 30 % strain, the Neo Hookean model describes the material behaviour adequately, using the first invariant \( I_1 \), the initial shear modulus of the material \( \mu \), and the incompressibility parameter \( d \):

\[
\Psi = \frac{\mu}{2} (I_1 - 3) + \frac{1}{d} (J - 1)
\]

For larger deformations of up to 150 % [Brown 2006; Hamza and Alwan 2011], the Mooney-Rivlin material model [Rivlin and Saunders 1951] describes \( \Psi \) as a series in terms of the first and second deviatoric principal invariants \( I_1 \) and \( I_2 \)

\[
\Psi = C_{10} (I_1 - 3) + C_{01} (I_2 - 3) + C_{11} (I_1 - 3)(I_2 - 3) + \frac{1}{d} (J - 1)
\]

---

12 ANSYS Autodyn 18.2. ANSYS Inc., Canonsburg, PA, USA.
where $c_{10}, c_{01}$ and $c_{11}$ are empirically determined, phenomenological material constants and $d$ is the material incompressibility parameter. The initial shear modulus $\mu$ is defined as

$$\mu = 2(c_{10} + c_{01})$$  \hfill (13)

and the initial bulk modulus $K$ is defined as

$$K = \frac{2}{d}$$  \hfill (14)

In order to replicate a real rubber application, additional to the elastic behaviour of the material, rubber specific effects have to be taken into account. Under cyclic loading, rubbers can show a more or less pronounced tendency to soften. This so-called Mullins effect [Mullins 1969] causes a material sample to respond to straining with a higher stress increase at the first load than in subsequent cycles. It is predominant within the first couple of load cycles. Above approximately ten stress cycles, depending on the material, the stress-strain curve oscillates to an almost constant curve. This effect can be integrated into a consecutive model [Diani et al. 2009], but in many cases, the added complexity in material testing and modelling can be avoided. When a silicone or other unfilled rubber material is loaded repeatedly in the real-world application, the Mullins effect is no longer relevant. In order to model the material behaviour in such cases correctly, it is paramount that in the material testing, the Mullins effect is also eliminated. This can be achieved by preconditioning the material before testing [Day and Miller 2000].
3.4 Sensitivity Analysis

Sensitivity analysis (SA) is the study of how the variation in the output of a model (numerical or otherwise) can be apportioned to different sources of variation in the model input [Saltelli 2002]. It is used to identify and quantify the contribution of each input parameter, of the VAMM system, to specific system outputs, like dimpling. A global SA requires knowledge of the system behaviour over the entire space of design variables. Design of Experiments can be applied to explore this design space comprehensively [Myers et al. 2009]. DoE schemes are used to create samples, or designs, with unique sets of parameters. There are different approaches to creating such experimental designs. Deterministic approaches, like the full factorial scheme, create a regular distribution of samples depending on the number of stages and the number of parameters. Figure 3-2 (a) shows such a sampling for two independent factors with three stages, resulting in nine designs to be tested. For a larger system, this for example means that with a number of five factors to be tested on five levels, 3,125 experiments are necessary. These methods are therefore only suited for systems with a small number of variables and linear system behaviour.

Figure 3-2 - Example of full factorial sampling (a) and Advanced Latin Hypercube sampling (b) both with nine samples in a two-dimensional design space [Könning 2005]

Stochastic sampling methods on the other hand, can be applied on systems with a high number of dimensions and nonlinear system responses [Siebertz et al. 2010]. Random sampling, also called Monte Carlo Simulation (MCS), is a simple and common method, to create independent random samples in a given design space. For small sample sizes however, this can lead to samples being clustered, or areas of the design space not covered. Latin Hypercube Sampling (LHS) can be used, to ensure a good coverage over the entire design space [McKay et al. 1979]. It is based on the "Latin Squares" principle. A $n \times n$ matrix becomes a Latin Square if the value of each cell occurs only once per row and column. LHS transfers this concept into multidimensional space. Therefore, the value range of each parameter is divided into $M$ intervals, with equal probability of occurrence. Then a random value is selected for each cell. In order to prevent correlations between the individual parameter pairings, the Advanced Latin Hypercube Sampling (ALHS) minimises the correlation errors by stochastic evolution
strategies. The result of such a sampling with two factors and nine designs is shown in Figure 3-2 (b). Compared to the full factorial sampling (a), the data points are less uniformly distributed and the gaps between the data points are smaller. This leads to a more accurate system description across the entire design space, making ALHS preferable to deterministic methods.

When used in the context of optimisation, variance based SA can provide the share of individual variables to the possible improvement of the model response. Additionally, it gives an understanding of the global system and the interactions of input parameters. Variance based SA methods however require a huge amount of sample data. This means that either a large number of experiments have to be conducted (experimentally or numerically), or the accuracy of the analysis is not sufficient. This makes these kinds of methods not well suited for high dimensional problems with many input variables. To overcome this disadvantage, metamodels, such as polynomial regression, moving least squares or Kriging [Daya Sagar et al. 2018] (isotropic [Krige 1951] or anisotropic [Boisvert et al. 2009]), can be used to approximate the system behaviour between the measured data points.

The Metamodel of Optimal Prognosis (MOP) proposed by Most and Will [2008] is a method that identifies the best suitable meta-model for an actual problem together with the optimal input variable subspace, by using the Coefficient of Prognosis (CoP), a model independent quality measure.

Usually, the approximation quality of a metamodel is estimated with the established Coefficient of Determination (CoD), also known as $R^2$:

$$CoD = \frac{SS_R}{SS_T} = 1 - \frac{SS_E}{SS_T} = R^2$$  \hspace{1cm} (15)

where $SS_T$ is the total variation of the output $Y$, $SS_R$ is the variation due to regression and $SS_E$ is the unexplained variation [Dynardo GmbH 2014]. For a small number of data points or an increasing number of input variables, however, this coefficient is too optimistic. Moreover, it is only applicable to polynomials, making it difficult to use more complex but potentially more accurate approximation methods.

In contrast, the CoP assesses the model quality independent from the model. It measures the agreement between real test data and the meta-model estimates:

$$CoP = 1 - \frac{SS^P_E}{SS_T}$$  \hspace{1cm} (16)

where $SS^P_E$ is the sum of squared prediction errors and $SS_T$ is the total variation of the outputs [Most and Will 2008]. The result of the MOP is an approximate model that contains the highest CoP for each output parameter and the corresponding most important variables [Friedrich et al. 2018].
3.5 Multidisciplinary Optimisation

Multidisciplinary optimisation is used to find ideal solutions for the single-layer and dual-layer IPL configurations of the VAMM that sufficiently prevent dimpling. A comprehensive description of the optimisation methods used in this thesis is compiled in *Methods for multi-disciplinary optimisation and robustness analysis* by Dynardo GmbH [2014].

In general, two kinds of optimisation problems can be distinguished: **Single objective optimisation problems** have one single scalar-valued objective function \( f(x) \), with \( x = (x_1, x_2, ..., x_n)^T \) being the vector of design variables. Additional restrictions and limitations to the system can be formulated with \( m_u \) inequality constraints \( g_j(x) \) and \( m_e \) equality constraints \( h_k(x) \):

\[
\begin{align*}
f(x) & \rightarrow \text{min} \\
\text{with} & \quad g_j(x) \leq 0 \quad j = 1 \ldots m_u \\
& \quad h_k(x) = 0 \quad k = 1 \ldots m_e
\end{align*}
\]

The design variables \( x_i \) thereby have to follow the condition

\[
x_i^{(L)} \leq x_i \leq x_i^{(U)}
\]

with \( x_i^{(L)} \) defining the lower limit and \( x_i^{(U)} \) defining the upper limit of each design variables range.

Real world problems however, often involve more than one objective. These **multi-objective optimisation problems** have \( M \) objective functions \( (M > 1) \) that can be formulated as follows:

\[
\begin{align*}
f_m(x) & \rightarrow \text{min} \quad m = 1, 2, \ldots, M \\
\text{with} & \quad g_j(x) \leq 0 \quad j = 1 \ldots m_u \\
& \quad h_k(x) = 0 \quad k = 1 \ldots m_e
\end{align*}
\]

Each solution \( x \) is assigned to a vector \( f(x) \), describing a single point in the \( M \)-dimensional objective space. This target vector is considered Pareto optimal when none of its components can be improved without impairing at least one other component. To decide whether a solution is Pareto optimal, a decision criterion is applied. The Pareto dominance criteria states, that a solution vector \( a \) dominates a solution vector \( b \) if it is feasible and equal or better in all objectives and better in at least one objective. If none of both solutions dominates the other, they are considered indifferent. A set of Pareto optimal solutions is called a Pareto front. It can be visualised as a (multidimensional) surface, which envelops all possible solutions. [Branke 2008]

Some of the input parameters of the VAMM system are non-continuous. For example, the material parameters describing the IPL only exist as discrete values for the individual rubber materials tested. Evolutionary algorithms (EA) are intended to
optimise systems with such non-continuous parameters. They use a population-based approach, where more than one design participates in an iteration, and develops a new solution population in each iteration. The populations are created using stochastic search methods that mimic the evolutionary process of natural species. Within the optimisation problem, individual designs are regarded as individuals, the system parameters as chromosome, and the parameter values as genes. Biological mechanisms are then applied, such as reproduction, mutation, recombination, and selection, in order to find an optimal solution to the given problem. The general flow of such an EA is shown in figure 3-3.

![Flowchart of an evolutionary algorithm](image)

In the beginning, an initial population is generated at random. The individuals of this population are then rated and ranked. A fitness function can be used to rate the fitness of the individuals. For multi-objective optimisation problems, the population can be ranked based on a domination principle [Goldberg 2012]. The fittest individuals are then selected as parents for the next generation. They produce offspring by sharing information between chromosomes of two parents using a crossover operator. Random variation is introduced to the offspring via mutation of individual genes. Subsequently, the fitness of the newly created children is evaluated and the best individuals form the next generation together with the fittest individuals of the previous generation. This procedure is repeated until there is no more improvement over a number of generations. In this case, the solution has converged to an optimum.

The utilised software OptiSLang implements two types of evolutionary algorithms, the genetic algorithm (GA) [Holland 1992] and the evolution strategy (ES) [Beyer and Schwefel 2002], that vary in the genetic representation of the individuals and details in their respective implementation. OptiSLang automatically selects the faster solution depending on the problem formulation [Dynardo GmbH 2017].
3.6 Evaluation of Component’s Mechanical Properties

When evaluating a new production technology, it is of interest how the manufactured components behave in comparison to the same components made in established production processes. Since VAMM uses an elastic silicone rubber as a tooling surface, instead of a solid block of material, an effect on the mechanical properties cannot be ruled out. In order to evaluate the influence of the VAMM process on the mechanical properties of the components, VAMM manufactured samples are compared to a reference composite, manufactured on a traditional aluminium tool. Therefore, Young’s modulus, ultimate tensile strength, bending stiffness, and bending strength are evaluated. These mechanical characteristics are considered adequate to obtain a comprehensive impression of the mechanical properties of VAMM manufactured components. Tensile tests and three point bending tests are chosen to evaluate the mechanical properties. The fibre volume fraction, and void volume fraction are additionally evaluated to determine the quality of the manufacturing process. The uniaxial tension tests are conducted according to DIN EN ISO 527-4 [DIN Deutsches Institut für Normung e. V. 1997] for fibre-reinforced composites. The three-point bending tests are carried out corresponding to DIN EN ISO 14125 [DIN Deutsches Institut für Normung e. V. 2011]. The fibre volume fraction $\varphi$ is evaluated using thermogravimetry. It can then be calculated according to

$$\varphi = \frac{V_{\text{fibre}}}{V_{\text{composite}}} = \frac{V_{\text{fibre}}}{V_{\text{fibre}} + V_{\text{matrix}} + V_{\text{cavities}}} \quad (20)$$

It is determined experimentally as follows. First, the composite is weighed in its original state and its density is evaluated. The resin is then removed from the composite in a pyrolysis process by heat-treating it at 500°C for two hours. After that only the fibre material remains, which is then weighed again. The relative fibre mass fraction $\psi$ can now be determined.

$$\psi = \frac{m_{\text{fibre}}}{m_{\text{composite}}} \quad (21)$$

Subsequently the conversion to the relative fibre volume fraction $\varphi$ is conducted as follows:

$$\varphi = \frac{1}{1 + \frac{1 - \psi}{\psi} \cdot \frac{\rho_f}{\rho_m}} \quad (22)$$

with $\rho_f$ being the fibre density and $\rho_m$ being the density of the matrix.

For all of the test procedures, samples are tested and the mean values are evaluated. The sample size needed for the experiments is determined according to ISO 2602 [ISO International Organization for Standardization 1980].

In order to determine the differences between the samples, it is examined whether the mean values of two experiments are different or not. This is done using Welch’s t-
test [Welch 1947], a modification of the Student’s t-test for two samples with unequal variances. This hypothesis test ultimately provides information on statistical significance and is well suited for small sample sizes. To apply the test, the data must be normally distributed, independent, and with similar variance (no more than twice as high). The normal distribution of the measured data is evaluated using the Anderson Darling Test [Anderson and Darling 1952].

The test is used to evaluate the following hypotheses:

- Null hypothesis $H_0$: "There are no differences in the material properties of CFRP components manufactured on conventional tools and the VAMM tool".
- Alternative hypothesis $H_1$: "There are differences in the material properties of CFRP components manufactured on conventional tools and the VAMM tool".

These hypotheses are tested by evaluating the differences in the mean values of two measurements. For a statistically significant difference between the mean values, the p-value must be less or equal to the significance level $\alpha$. This means that the null hypothesis $H_0$ has to be rejected and the alternative hypothesis $H_1$ is to be assumed. $H_1$ in this case states that there is a difference between the measured data series. The significance level $\alpha$ of 0.05 (5 %) is used in this work, as it is sufficient for significance testing in engineering applications [DeCoursey 2003; Box et al. 2005].
3.7 Summary

The development, analysis, and optimisation of the VAMM technology is outlined as a three-stage process.

In the first stage, the VAMM system is designed, developed, and constructed. Established design methodology is used, to ensure the pursuit of the best possible solution. Two variations of the VAMM system will be designed: a small-scale test bench is intended for first, simple testing and validation of the design stage. The insights gained from this will then be used to develop a full-scale prototype of the VAMM technology.

On this tool, components for will be manufactured in order to prove the functionality and feasibility of the developed solution. These components will then be tested experimentally to ensure a high mechanical performance of the manufacturing technology.

In the second stage, the manufacturing process is transferred into a parametric computer model. This model implements the same input variables as the physical system and produces similar outputs. It is used to implement a shape control algorithm to eliminate shape error. It is also used to evaluate dimpling on the tooling surface for any given configuration of the VAMM tool.

In the third stage, the VAMM process is optimised. For this purpose, a sensitivity study will be conducted first to identify those parameters that have a significant influence on the dimpling. Based on these parameters, a metamodel is then generated that describes the system behaviour of the VAMM system without considering the complex physical relationships. This metamodel is then used to optimise the critical parameters and to find an optimal setup of the VAMM system. This process is conducted twice for both, a single layer IPL configuration, and a dual layer IPL configuration. The optimal setup for both these variations can then be compared in order to evaluate the effects of the proposed multi-layer approach.

With this methodological approach, it is expected, that all research questions stated in chapter 2 can be answered comprehensively.
Chapter 4 System Design and Development

Vacuum Assisted Multipoint Moulding is a mould making technology for the manufacturing of fibre-reinforced plastic composites. This chapter introduces the technology and discusses the design, development and calibration of the hardware components of a VAMM system.

The first two parts of the chapter introduce the idea behind the VAMM technology in detail, as well as analyse the requirements for the proposed tool. The key objectives are discussed and specific requirements are deduced. Based on these specifications, in the third part of the chapter, the VAMM architecture is presented. Subsequently, the developed solutions for the pin array, the pin actuation, the interpolation layer, heating and machine control are discussed in detail.

Within this thesis, two versions of VAMM tools are described: A small-scale test bench intended for testing purposes and a full-scale prototype ready for manufacturing. They are presented in the fifth and sixth part of this chapter. The test bench has 37 hexagonal pins in a hexagonal array. It is used to validate the proposed concept, and the individual components, and for the optimisation of the manufacturing process and especially the interpolation layer. Due to the small size, it is easy to handle, and changes and experiments can be conducted in a resource and cost efficient way. The full-scale prototype has a rectangular manufacturing area of 400 mm x 600 mm with 572 pins. These pins are adjusted fully automatic with a semi-parallel pin actuation setup (SPS) with 11 active setup units. A purpose built sectional adjustable radiation heating is utilised to harden the composite parts.
4.1 Vacuum Assisted Multipoint Moulding Concept

The general design of multipoint moulds is well established (compare chapter 2.2): An array of individually height adjustable pins make up the basis of the tool. On top of that, an elastic interpolation layer creates a smooth surface that is used as tooling surface. The pins are set into position using some sort of pin adjustment method. The generally novel idea of Vacuum Assisted Multipoint Moulding is to force the interpolation layer onto the pin array via vacuum. This increases the geometric capabilities of traditional multipoint moulding. The evacuated IPL creates an open mould, e.g. for FRP manufacturing, with the capability to generate freeform surfaces with convex, as well as concave segments. This distinguishes VAMM from the previous multipoint tools discussed in chapter 1 that where either capable of creating just convex geometries in open mould configurations or needed a two sided tool to create concave/convex geometries.

In this concept, the pin array is placed in a vacuum chamber. The interpolation layer smoothens the pin array and closes the vacuum chamber at the top. The pins have a hexagonal cross section and hemispherical heads. They are leadscrew driven and arranged in a closely packed hexagonal array. For interpolation of the tooling surface, an elastic sheet is loosely placed on the pins and circumferentially fixed in a tenter frame. The frame is connected to the vacuum chamber. The concept schematics are shown in figure 4-1.

For the interpolation layer, silicone rubber sheet material is used as it combines high temperature resistance and good chemical resistance against epoxy resin, as well as good separating properties for demoulding of the manufactured parts. The tool is supposed to create concave and convex geometries and structures, including inflection points. Neither gravity nor pulling via the tenter frame is sufficient to force the IPL in the desired shapes. Instead, the space underneath the layer is evacuated. The ambient air pressure then creates the force needed to deform the IPL and create the desired shape [Wimmer et al. 2016]. This vacuum is eponymous for the Vacuum Assisted Multipoint Moulding technology.
4.2 Requirements for VAMM

The requirements for the VAMM tool arise from different sources of the process chain. First, there are the general requirements for multipoint tools and manufacturing processes itself. Then there are specific requirements based on the VAMM concept. Additionally, the manufacturing process of fibre-reinforced plastic composite further introduces specific requirements.

The general design of multipoint moulds is well established. As previously mentioned (see chapter 2.2), the most critical requirements for such a multipoint tool are a high surface resolution and a smooth forming surface. In addition, the tool is supposed to be rapidly reconfigurable to new part geometries. Hereby the individual positioning of distinct points on the forming surface has to be possible. Munro and Walczyk [2007] compiled the basic requirements for multipoint forming. In table 4-1, these requirements are adapted for Vacuum Assisted Multipoint Moulding.

<table>
<thead>
<tr>
<th>No.</th>
<th>Characteristic</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>High surface resolution</td>
<td>Allows for fine part details and minimises surface smoothing required</td>
</tr>
<tr>
<td>2</td>
<td>Smooth forming surface</td>
<td>Needed for producing high quality parts</td>
</tr>
<tr>
<td>3</td>
<td>Rapid reconfiguration of the forming surface</td>
<td>Setup faster than process time to minimise tool setup time</td>
</tr>
<tr>
<td>4</td>
<td>Individual position and velocity control of points on the forming surface</td>
<td>Allows the tool shape to be changed in real time for enhanced process control</td>
</tr>
<tr>
<td>5</td>
<td>Easily configured for a variety of manufacturing process</td>
<td>Supports the concept of a universal tool</td>
</tr>
<tr>
<td>6</td>
<td>Able to accommodate a wide range of manufacturing process temperatures</td>
<td>Allows for tooling flexibility</td>
</tr>
<tr>
<td>7</td>
<td>Allows a vacuum to be drawn within the tool cavity (i.e. air-tight chamber)</td>
<td>Necessary for certain manufacturing processes such as thermoforming and composites forming</td>
</tr>
<tr>
<td>8</td>
<td>Portable and lightweight</td>
<td>Conducive to lean manufacturing principles</td>
</tr>
</tbody>
</table>

The VAMM concept itself introduces some additional requirements. The pin array has to be placed in an airtight container, which is capable to withstand a vacuum.
However, the complexity of the tool must be kept to a minimum in order not to compromise operational reliability and to keep cost within reasonable limits. The vacuum in the chamber must be able to deform the interpolation layer to create the desired tooling surface. Therefore, the interpolation layer has to be flexible enough to be deformed by the applied vacuum. The tooling surface itself must withstand the forces applied during the manufacturing process and must not deform in an unforeseeable way.

Table 4-2 - Additional characteristics of a VAMM system

<table>
<thead>
<tr>
<th>No.</th>
<th>Characteristic</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>Low complexity of the tooling system</td>
<td>Increases reliability while reducing cost of the tool</td>
</tr>
<tr>
<td>10</td>
<td>Capable to draw vacuum underneath the IPL</td>
<td>Necessary to create the concave and convex tooling surfaces</td>
</tr>
<tr>
<td>11</td>
<td>Tooling surface capable to withstand manufacturing pressure of at least 1 bar</td>
<td>Allows high shape accuracy for evacuated manufacturing of FRPs at ambient pressure</td>
</tr>
<tr>
<td>12</td>
<td>No unpredicted deformation of the tooling surface</td>
<td>Predictable deformations can be compensated by adjusting the pins accordingly.</td>
</tr>
</tbody>
</table>

Furthermore, the manufacturing processes for fibre-reinforced plastic composites (see chapter 2.1) introduce additional requirements for the VAMM tool. In single-item production of FRP composites, single-sided open moulds are commonly used. In order to utilise these manufacturing technologies, the VAMM tool also has to create an open mould. Various fibres and resins, as well as adherents are used in this manufacturing process. Fibre-reinforced plastic composite lay-ups are placed on a mould pre-treated with a releasing agent ensuring the separation of the cured part from the mould. The tooling surface, as well as all other exposed surfaces have to be chemically compatible with these adherents and the chemically reactive resins used in the process (compare chapter 2.1.1). The uncured fibre lay-ups are either compressed by vacuum or hardened at ambient pressure. Drawing a vacuum on top of the tooling surface therefore has to be possible. In order to induce or improve curing, heat can be applied to the uncured product. This heat has to be applied evenly to the lay-up in order to ensure uniform curing and prevent burning the laminate. The tool itself also must be able to withstand this heat influx and the tool surface must not be deformed in the process.
Table 4-3 - Additional characteristics of a tool for fibre-reinforced plastic composite manufacturing

<table>
<thead>
<tr>
<th>No.</th>
<th>Characteristic</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>Open mould configuration</td>
<td>Established manufacturing processes can be utilised without changes</td>
</tr>
<tr>
<td>14</td>
<td>Air tight tooling surface suitable for evacuating</td>
<td>Enables vacuum bagging and diaphragm forming</td>
</tr>
<tr>
<td>15</td>
<td>Chemical compatibility to thermostet resins and release agents</td>
<td>In FRP release agents, as well as chemically reactive resins are used. The tooling surface must not react with these.</td>
</tr>
<tr>
<td>16</td>
<td>Even heat application</td>
<td>Enables consistent hardening of FRP parts</td>
</tr>
</tbody>
</table>
4.3 VAMM Architecture

The VAMM architecture is developed as a modular system. It consists of five separated functional units as shown in figure 4-2:

- An array of pins placed inside a vacuum container,
- a pin actuation system consisting of actuator units for moving the pins into position, and a X-Y table holding the actuator units and positioning them underneath the pins,
- an interpolation layer within a tenter frame covering the pin array and sealing off the vacuum container,
- a heater unit with individually controllable radiators for evenly heating the FRP composites, and
- a control system coordinating the individual components consisting of two programmable logics controllers (PLCs) and a human-machine interface (HMI).
At the centre of the proposed multipoint tool, the individually height adjustable pins create the discrete representation of the desired tooling surface. These pins are passive, meaning that they are not equipped with individual active adjustment or position control devices themselves. This reduces tool complexity and thus the overall cost. The pin array is placed in an air-tight vacuum container. On the bottom side of the vacuum container, the pins have a docking point where the external positioning device can be mechanically linked. Below the vacuum container, an array of actuator units can connect to the pins and adjust them in height. Each unit has a coupling device to connect to the pins, and a coupling actuator used to open and close the coupling. A drive is connected to this device via a transmission. This drive eventually positions the docked pin to a desired height.

The number of actuator units is equal to the number of pins in one line of the pin array. The array of actuators is mounted on a linear unit. This unit can move continuously in X-direction and move between two stable states in Y-direction. This enables each pin in the pin array to be reached by an actuator.
The system is controlled via two programmable logic controllers (PLC). One controller operates the VAMM tool itself, driving the X- and Y-axis, the actuators and the tenter frame, as well as controlling the vacuum pump. The second PLC controls the individually regulated radiators in the heater module. Both PLCs are connected to a human machine interface (HMI) that is operated via a touch screen display. The HMI communicates with the VAMM via Ethernet and with the heater via Wi-Fi. The PLC communicates with the drives in real-time via a CAN bus using the CANopen protocol\textsuperscript{13}. A central power supply powers all the electric devices.

The VAMM tool PLC mainly controls the systems degrees of freedom (DOF). As in every computer numerically controlled (CNC) system these DOFs represent the systems axes of motion, which are defined as follows: the X- and Y-axis describe the motion of the linear unit with the actuator array. The vertical direction of each pin is considered the pin’s Z-axis. To differentiate individual pins, the axes are numbered $Z_{i,j}$ where $i$ represents the line of pins in X-direction and $j$ represents the pin’s row in Y-direction. Each actuator $k$ has a claw clutch moving along a vertical Z axis designated as $W_k$-axis to differentiate and a rotational axis designated as $C_k$-axis. The tenter frames vertical motion is designated as the B-axis. All axes and their directions of motion are compiled in Table 4-4.

The second PLC controls the adjustable radiation heater. It inhabits an array of individually controllable heater elements and temperature sensors applicable to the tooling surface or part, enabling even heating of the manufactured 3D curved parts.

Table 4-4 - Axes of a VAMM system

<table>
<thead>
<tr>
<th>Axis</th>
<th>Description</th>
<th>Motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-axis</td>
<td>Axis moving the actuators along the long side of the pin array</td>
<td>forwards/</td>
</tr>
<tr>
<td></td>
<td></td>
<td>backwards</td>
</tr>
<tr>
<td>Y-axis</td>
<td>Axis moving the actuators along the short side of the pin array</td>
<td>right/left</td>
</tr>
<tr>
<td>$Z_{i,j}$-axis</td>
<td>Vertical axis of pin in $i$-th line ($X$-axis) and $j$-th row ($Y$-axis)</td>
<td>up/down</td>
</tr>
<tr>
<td>$W_k$-axis</td>
<td>Vertical axis of $k$-th actuator; used for coupling to pin</td>
<td>up/down</td>
</tr>
<tr>
<td>$C_k$-axis</td>
<td>Rotational axis of $k$-th actuator; used to adjust height of pins when coupled</td>
<td>clockwise/</td>
</tr>
<tr>
<td></td>
<td></td>
<td>counterclockwise</td>
</tr>
<tr>
<td>B-axis</td>
<td>Vertical axis of tenter frame</td>
<td>up/down</td>
</tr>
</tbody>
</table>

\textsuperscript{13} British Standards. 2002 Industrial communication subsystem based on ISO 11898 (CAN) for controller-device interfaces. CANopen. BSI, BS EN 50325-4:2002.
The intended operation of the VAMM system is described in figure 4-3. In a first step (1), the IPL is removed from the pin array. Therefore, the tenter frame is elevated to its maximum height (2). This removes the load from the pins and makes them easily accessible and adjustable. Subsequently the pins are adjusted to represent the new part to be manufactured (3). When finished (4), the tenter frame is lowered (5) and the interpolation layer is pulled over the pin array sealing off the vacuum chamber. This chamber can then be evacuated (6) forcing the interpolation layer into the geometry created by the pins (7) and creating the final tooling surface. Steps (8) and (9) depend on the actual FRP manufacturing process being utilised. For prepreg moulding, in the first step, the lay-up and process materials are applied to the tooling surface and then are evacuated to compress the composite. Afterwards, the radiation heater is lowered to its operation height (10) and turned on (11). Through the application of heat, the resin hardens and the part is cured. After the curing time, the heater is retracted (12-13) and the finished product can be removed from the mould (14).
Figure 4-3 - Manufacturing process in VAMM
4.4 Design and Development of System Components

The five functional units defined in the VAMM architecture are discussed in detail in the following chapter.

4.4.1 Pin Array

In Vacuum Assisted Multipoint Moulding, a hexagonal pin cross section is utilised. As discussed in chapter 2.2, a high surface resolution is a desired tool characteristic. Assuming the fixed characteristic length $a$ (see figure 2-9, page 33) is the distance between the axes of two adjacent pins, the hexagonal cross-section provides the best resolution of all regular tilings\(^{14}\) for a defined area. The cross-section of hexagonal pins is $A_{\text{hex}} = a^2 \times 0.87$ compared to $A_{\text{sqr}} = a^2 \times 1.00$ for a squared and $A_{\text{tri}} = a^2 \times 1.30$ for a triangular configuration. This means that, compared to a square cross section, in a given area the number of pins can be increased by 13% without downsizing the pins and attached components by using hexagonal tiling and even 49% compared to a triangular tiling.

One could argue that, according to Walczyk and Hardt [1998], pins with a square cross section are ideal for multipoint tools. They consider laterally clamping the pin array into a rigid tool a necessity. Since only a square cross section ensures two isolated load paths it is the only configuration enabling reliable clamping. Lateral clamping however is only needed in forming processes, where huge forces are applied to the pin array. In VAAM, the loads on the pin array are considered low and limited by the

\[^{14}\text{A tilling is considered regular if a single geometry can be used to cover an area without gaps. This is only the case with triangular, quadratic and hexagonal tiling.}\]
vacuum pressure (e.g. 1 bar) making lateral clamping unnecessary. It is therefore possible to use the geometrically superior hexagonal cross-section.

The characteristic pin size $a$ can also be considered the width across flats (A/F) for a hexagonal cross section. For the VAMM prototype, the pin size is set to $a = 24 \text{ mm}$. Pre-products in this size are widely commercially available. In addition, similar size pins have proven to be sufficient in other multipoint tools [Walczyk and Hardt 1998; Walczyk et al. 2003; Simon et al. 2014b]. In general, an area $A$ with length $l$ and width $w$ can be completely covered with $N$ hexagonal tiles with a pin size of $a$. It has to be taken into account that the calculations are dependent on the orientation of the hexagonal array (compare figure 4-4). The number of tiles needed to cover a single row $N_i$ (in X-direction) is calculated by

$$N_i = \left\lceil \frac{l}{\frac{a}{2}} \right\rceil + 1$$

(23)

with $[x]$ being the ceiling function

$$[x] = \min\{n \in \mathbb{Z} | n \geq x\}$$

(24)

and

$$r_i = \frac{a}{2}$$

(25)

The number of tiles in a line $N_w$ (in Y-direction) can be calculated using

$$N_w = \left\lceil \frac{w}{\frac{3a}{\sqrt{3}}} \right\rceil + 1$$

(26)

with the circumradius $r_o$

$$r_o = \frac{a}{\sqrt{3}}$$

(27)

The total number of tiles then multiplies to

$$N = N_i N_w$$

(28)

In order to prevent gaps in the desired area, the real dimensions exceed the desired dimensions, if $2a$ is not an integral divider of the dimensions of the area. The real width $w^*$ is then calculated using

$$w^* = (N_w - 1 + 0.5) \times r_o = (N_w - 0.5) \times \frac{a}{3r_o}$$

(29)

and the real length $l^*$ is calculated using

$$l^* = \left(\frac{N_i}{2} - 0.5\right) \times a$$

(30)

As stated in chapter 2.2, spherical pin tips are advantageous when using loaded elastic interpolation layers. The following considerations must be taken into account when selecting the radius $R$ of the spherical pin tip:
• A radius smaller than the circumradius of the pin base area creates a shoulder between the head and body of the pin. The resulting sharp transition can damage the interpolation layer.

• The larger the radius selected, the smaller the indentation depth of the pin into the interpolation layer gets as shown in figure 4-5. It can therefore be assumed that the largest possible radius leads to a higher surface quality.

• A very large radius (in extreme cases $r \to \infty$) leads to a sharp edge between the head and body of the pin. Since a tangential contact is intended between pin and interpolation layer, only the smallest exit angle between the pin’s head and body can be created as a gradient $\beta$ in a desired part. A large pin radius therefore restricts the possible complexity of the parts that can be created.

![Figure 4-5 - Indentation depth $d$ of a rigid sphere with radius $r$ in an elastic half space at a constant force $F$ (calculated according to Johnson [1985])](image)

For a hexagonal cross-section with a pin size $a = 24 \, mm$ the circumradius is $r_0 = 13.86 \, mm$. As shown in figure 4-5 the indentation depth does not decrease significantly for radii larger than $R = r_0$. However, the gradient $\beta$ that can be created decreases with larger $R$. Hence the circumradius of the hexagon $r_0$ is sufficient as a pin tip radius for pins with a hexagonal cross-section.
4.4.2 Pin Actuation

As discussed in chapter 2.2 - design of multipoint tools, lead screw driven actuation has proven to be precise, reliable and relatively cost efficient. Especially systems with directly driven pins with a dedicated drive for each pin (e.g. in Figure 2-11, page 35) are utilised in some research projects. However, this concept also has some critical disadvantages:

- Direct drives for each pin are a significant cost factor.
- It induces space and resolution limitations, fixing the minimum pin size to the size of the motors used.
- With one individual drive per pin, each pin can be considered an independent NC-axis. According to Seames [2002] the complexity of a numerically controlled machine increases rapidly with the number of axes leading to multiple drawbacks like reduced operational reliability and increased maintenance efforts.

Alternatively, sequential drive concepts like the SSU developed by Boas [1997] have advantages in cost and complexity [Im et al. 2000]. Combining the technical advantages of directly driven lead screw actuation with advantages of sequential drive concepts results in a novel actuation design. This Semi Parallel Setup (SPS) [Wimmer 2017] uses passive sensorless pins adjusted row by row with an array of actuator devices. A setup algorithm ensures precise adjustment of each pin. The connection between the pins and the actuators is realized with a specifically designed form lock claw clutch.

A coupled pin - actuator pair is shown in figure 4-6. The pins are positioned in height using a lead screw. This lead screws are designed to be self-locking under load, meaning that the internal friction of the lead screw-nut combination is designed to be

![Figure 4-6 - Semi Parallel Setup actuator unit](image-url)
sufficient to prevent unintended motion when a force is applied. This eliminates the need for external clamping of the pin array. Instead, the pin array can be rigidified and all pins can be fixed relatively to each other just by applying the vacuum thereby applying load to the pins and fix the leadscrews in position. The pins are mounted in the baseplate of the vacuum container using slide bearings. O-ring seals are used to feed the pins through the baseplate while maintaining the vacuum\footnote{O-rings are automatic, double-acting sealing elements. The contact forces caused by the installation in radial or axial direction cause the initial seal. They are superimposed by the system pressure. This result in a total sealing pressure that increases with increasing system pressure. They are typically used in static sealing scenarios. Dynamic use is only recommendable for low loads limited by the speed and the pressure to be sealed, e.g. for sealing reciprocating pistons, rods, plungers, etc. or for sealing slowly pivoting, rotating or helical movements on shafts, spindles, rotary feedthroughs, etc. To ensure the sealing, the air tightness of the O-rings in use is tested in appendix A - 3, Evaluation of O-ring seals.}. Outside of the vacuum container, each pin has a torque bar to connect to the clutch claw of the actuator unit. The claw itself can be elevated for coupling using a double acting pneumatic cylinder with end position sensors. The cylinder position is controlled via an electronically controlled pneumatic 3/2 port solenoid valve. When engaged, the pins height can be adjusted using the stepper motor. Closed loop control, using a rotary encoder embedded in the motor, ensures the precise motion of the drive. This motion is transferred to the pin utilising a purpose built form lock clutch. This ensures precise adjustment of the pin without slip, leading to a theoretical accuracy of a single step of the stepper drive (0.002 mm).

\textit{Figure 4-7 - Concept of the form locking clutch claw}
Generally, a form lock cannot reliably be engaged without the precise alignment of the coupling partners [Muhs et al. 2007]. Without that, collision of the coupling partners cannot be reliably prevented. In the VAMM concept, the pins are sensorless, meaning that there are no position control sensors monitoring the current position of each individual pin. Instead, sensors are placed in the actuator module in form of coupling sensors and an encoder. This reduces the number of sensors needed and therefore reduces the complexity, and cost of the individual pins and ultimately the tool. However, this means that the position of a pin and its torque bar is not defined at the beginning of a coupling procedure. To overcome this limitation, a claw clutch is designed to create a form lock coupling that minimises the risk of collision of the two coupling partners (see figure 4-6). This claw can be coupled with one partner being stationary (the pin) and the other partner being in a clockwise rotation (the claw).

Figure 4-7 shows the intended operation of the claw clutch. During the rotating upwards motion, the claws vertical surface moves towards the stationary torque bar. From there, the two components can come into contact in three ways: the torque bar either touches the claw at the skewed surface, the vertical surface, or the tip. When it hits the skewed surface, it slides along until it hits the vertical surface at the top of the snap-in groove and from there slides in the resting position. When it hits the vertical surface, it directly slides down into this resting position during the remaining upwards motion. When the tip of the claw is hit and the torque bar does not slip off to one side, the clutch interlocks and the coupling process is considered a failure. The claw geometry is designed to prevent this and due to the pointedness of the claw, it is considered to happen very infrequent. However, the risk of interlocking remains.

This remaining risk is eliminated with a failure tolerant pin adjustment algorithm. This control algorithm (see figure 4-8) ensures the successful closing of the clutch and the precise pin adjustment. The adjustment of each pin or row of pins respectively, starts with the positioning of the linear unit. Therefore, a check is conducted ensuring that none of the actuators is coupled. If a clutch is coupled, the corresponding $W$-axis is moved down by opening the respective pneumatic valve. When all clutches are disengaged, the movement of the $X$- and $Y$- axis is permitted. The actuators are positioned under the pins by moving the actuator carriage. With the actuators in position, the claw clutch starts turning clockwise with a defined rotational coupling velocity. Then the pneumatic valve is set moving the $W$-axes upwards. When the upper positional sensor is not triggered within a time $t_2$ named pin coupling timeout, the process is considered unsuccessful. The valve is then closed and the system waits until a disengage timer $t_2$ passes. The process is then repeated until either the sensor is triggered within $t_2$ or the maximum number of coupling trials is reached. When the clutch is not able to close within these conditions, it is considered a coupling error. This normally indicates a mechanical failure that requires some form of interaction from the operator.
During the coupling process, the claw clutch is turning. This rotation is transmitted to the leadscrew and it causes an upward motion in the pin. After the clutch is fully engaged, the direction of rotation is reversed and the pin starts moving downwards. At this point, the pin has no defined position and has to be homed to a reference point.
The downward motion continues until the pin hits the baseplate. This leads to an increase in power consumption in the motor drive that can be detected by the motor controllers’ internal circuitry. The pin is now on block. The rotation is stopped and the position of the pin is set to $Z_{i,j} = 0$, where $i$ and $j$ is the line and row of the pin respectively. The pin is now homed and can be positioned precisely.

When the pin is adjusted to the precise desired height, the clutch is disengaged by lowering the corresponding $W$-axis. Therefore, the pneumatic valve is switched to retract the cylinder. Success is detected, when the lower positional sensor on the pneumatic cylinder is triggered. At this point, the setup of the pin is finished.

In table 4-5 the robustness of three pin actuation concepts (introduced in chapter 2.2), as stated by Im et al. [2000], is compared to the SPS concept. It shows that the SPS concept has the highest number of active drives but no external position control devices. With a total of 34 sensors, the VAMM system uses significantly more sensory devices than the compared systems. Of those 34, twelve are rotary encoders integrated in the drives and 22 are positional sensors on the pneumatic cylinder used for controlling the coupling process.

For the SPS concept, two potential sources of error are identified: Similar to the SSU design, coupling can potentially fail. This triggers a retry, increasing the chance of success. Depending on the coupling success rate however, it is theoretically possible that multiple successive coupling tries fail. This would increase wear in the clutch and can eventually lead to malfunction.

The homing on block is identified as the second major source of potential error: When coupling is successful, unsuccessful homing is the most likely source of error for the precise positioning of the pin. The detection of the home position of each pin is conducted “on block” meaning that the drive turns the pin downwards until it hits the baseplate. Subsequently the power consumption of the drive spikes which is recognised by the drive controller and interpreted as reaching the home position. When the friction in the leadscrew increases, e.g. due to a foreign object (chips or other dirt) or insufficient lubrication, the drive tries to overcome the friction also resulting in a spike in power consumption. The drive controller cannot differentiate between high power consumption due to hitting the baseplate and trying to overcome friction. Hence, it is possible that the home position is detected somewhere along the leadscrew leading to an incorrectly positioned pin. This however can be prevented by thoroughly cleaning the components before assembly and choosing sufficient parameters for the homing on block (compare stepper drive manual [Nanotec Electronic GmbH & Co KG 2014]).

Even though, direct comparison can lead to the impression, that the SPS design is more complex due to the number of drives and sensors and similarly error prone, it can still be considered superior by the means of cost and precision [Wimmer 2017]. The actuation concept has great impact on the total cost of a multipoint tool. For the actuation concepts in table 4-5, a comparison of cost referenced on the desired manufacturing area is compiled in appendix A - 2. It shows that the SPS design is by
far the most cost-efficient approach. This is mostly due to the simple pin design. However, this simplified design makes additional efforts for precise coupling and adjustment necessary. Additional sensors in the actuator units do not significantly increase the complexity of the system and the potential problems can be solved in the control software (see chapter 4.7).
Table 4.5 - Design robustness of three pin actuation concepts (see figure 2-12) [Im et al. 2000] compared to the Semi Parallel Setup (SPS) concept

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>SSU</th>
<th>HA</th>
<th>SDL</th>
<th>SPS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pin array size</strong> (pin cross section)</td>
<td>14 x 22</td>
<td>16 x 24</td>
<td>14 x 22</td>
<td>(2*11) x 26 (24 mm hexagonal)</td>
</tr>
<tr>
<td></td>
<td>(28.6 mm)</td>
<td>(25.4 mm)</td>
<td>(28.6 mm)</td>
<td></td>
</tr>
<tr>
<td><strong>Number of actuators</strong></td>
<td>9 (6 drive motors, X, Y, Z axes)</td>
<td>1 (hydraulic pump)</td>
<td>11 (driver motor for each row)</td>
<td>25 (11 driver motors, X-axis, 11 pneumatic cylinders, Y-axis)</td>
</tr>
<tr>
<td><strong>Number of position control devices</strong></td>
<td>0</td>
<td>384 (servo valve for each pin)</td>
<td>308 (clutch for each pin)</td>
<td>0</td>
</tr>
<tr>
<td><strong>Number of sensors</strong></td>
<td>9 (encoders on each drive)</td>
<td>1 (setting platen)</td>
<td>11 (encoders on each drive)</td>
<td>12 (encoders on each drive); 22 coupling sensors</td>
</tr>
<tr>
<td><strong>Potential major source of error</strong></td>
<td>Backlash between coupler and leadscrew</td>
<td>Insufficient platen stiffness</td>
<td>Backlash between worm and gear</td>
<td>Number of coupling cycles</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Clutch slippage</td>
<td>Homing of pins using torque control</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Rotational compliance of driveshaft</td>
<td></td>
</tr>
<tr>
<td><strong>Setting mode</strong></td>
<td>Serial with 6 pins set at a time</td>
<td>parallel</td>
<td>parallel</td>
<td>Serial with one line of pins (11 pins) set in parallel</td>
</tr>
<tr>
<td><strong>Control mode and potential problems</strong></td>
<td>Closed loop in coupled mode</td>
<td>Closed loop if moving pins are in contact with setting platen</td>
<td>Closed loop if clutches do not slip</td>
<td>Closed loop in coupled mode</td>
</tr>
</tbody>
</table>
4.4.3 Interpolation Layer

The primary task of an interpolation layer is smoothing the discrete surface created by the pin array. Regarding part quality, it is one of the most critical components in multipoint tooling. Insufficient interpolation leads to dimples in the areas between the supporting pins while excessive interpolation reduces the resolution of the tool and increases shape errors.

An ideal IPL would smooth out the discrete surface created by the pin array and thereby create a surface that ideally conforms to the desired geometry. This could be achieved in two ways: The IPL could either fill the gaps between the pins. Figure 4-9 shows such an ideal interpolation layer. Alternatively, it could cover them, spanning over the unsupported areas. In both cases, a smooth surface should be created. To achieve this however, it would have to meet conflicting requirements. On the one hand, it must be soft enough so it can follow the contour of the pins. On the other hand, the tool surface should be as hard as possible in order to achieve high repeatability and durability. A thick interpolation layer furthermore reduces the resolution of the tool and thereby the complexity of the parts that can be created. Hence, the thickness of the interpolation layer should to be as low as possible to minimise that loss. For a physical material however, it seems to be impossible to meet all the demands at the same time. Therefore, an interpolation layer can only be a compromise that achieves the different tasks well enough for a certain application.

Multiple parameters influence the ability of an IPL to provide a surface with sufficient accuracy and smoothness while not compromising the machines resolution and hence the possible geometric complexity of parts.
As established in chapter 2.3.2, rubbers are the most suitable materials for the interpolation layer. In this context, all materials with rubber-like behaviour are to be classified as rubber. According to Treloar [2005] these behavioural traits include:

- high extensibility of up to 500 % - 1,000 % with non-linear stress-strain curve
- low modulus (Young’s modulus can only be applied in the area of small deformation) in the order of $10^{-N/mm^2}$
- thermoelastic effects: rubber in a constantly stretched state contracts when heat is applied

Rubbers are commonly characterised by their durometer (hardness). A durometer scale is a type of measurement for rubber material hardness. The rubber durometer chart in Table 4-6 compiles the rubber hardness in the durometer scale of Shore A for some common applications. [Mycin Inc. 2016].

<table>
<thead>
<tr>
<th>Shore Hardness [ShA]</th>
<th>Feels Like</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 ShA</td>
<td>Rubber Band</td>
</tr>
<tr>
<td>40 ShA</td>
<td>Pencil Eraser</td>
</tr>
<tr>
<td>60 ShA</td>
<td>Car Tire Tread</td>
</tr>
<tr>
<td>70 ShA *</td>
<td>Running Shoe Sole</td>
</tr>
<tr>
<td>80 ShA</td>
<td>Leather Belt</td>
</tr>
<tr>
<td>100 ShA</td>
<td>Shopping Cart Wheel</td>
</tr>
</tbody>
</table>

*Most common durometer

In the particular case of VAMM, the FRP manufacturing process introduces additional demands on the tooling surface. Firstly, it has to be heat resistant and should not deform under increased temperature. During the hardening process heat is applied. The operating temperature range of different rubbers is compiled in Table 4-7. As shown there, many elastomers can only safely be utilised below 100°C. However, only more heat resistant rubbers can be used in VAMM. The characteristics of common rubbers are compiled in appendix A - 4 Properties of Different Elastomers. There, it also shows that together with fluoro-rubbers, silicone-rubbers have a significantly higher heat resistance and chemical stability compared to other rubber compounds. Due to the high prices of fluoro-rubbers however, only silicone rubbers are chosen as interpolation layer in VAMM.
Table 4-7 - Operating temperature range of different elastomers [Mycin Inc. 2016]

<table>
<thead>
<tr>
<th>Elastomer</th>
<th>Low [°C]</th>
<th>High [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buna-N (Nitrile)</td>
<td>-40</td>
<td>121</td>
</tr>
<tr>
<td>Styrene Butadiene</td>
<td>-46</td>
<td>100</td>
</tr>
<tr>
<td>Butyl</td>
<td>-46</td>
<td>121</td>
</tr>
<tr>
<td>Chloroprene (Neoprene®)</td>
<td>-43</td>
<td>127</td>
</tr>
<tr>
<td>Ethylene Propylene</td>
<td>-51</td>
<td>127</td>
</tr>
<tr>
<td>Fluorocarbon (Viton®)</td>
<td>-32</td>
<td>204</td>
</tr>
<tr>
<td>Fluorosilicone</td>
<td>-73</td>
<td>202</td>
</tr>
<tr>
<td>Hydrogenated Nitrile</td>
<td>-34</td>
<td>166</td>
</tr>
<tr>
<td>Natural Rubber / Isoprene</td>
<td>-48</td>
<td>99</td>
</tr>
<tr>
<td>Polyacrylate</td>
<td>-32</td>
<td>149</td>
</tr>
<tr>
<td>Silicone</td>
<td>-73</td>
<td>232</td>
</tr>
</tbody>
</table>

Preliminary investigation of interpolation in VAMM and the potentials of the multilayer IPL approach to improve IPL performance

This thesis proposes two different concepts for the interpolation layer:

- The **single layer** rubber IPL is the most established way of interpolation in multipoint moulding (compare chapter 2.2). When designed correctly, this solution has proven to be sufficient for many applications.

- The **multilayer** approach, introduced by the author in [Wimmer 2016; Wimmer and Maurer 2017], combines two or more layers of elastomer with different thicknesses and mechanical properties. The layers are bonded to each other either mechanically or chemically. Each layer has a distinct function. For example, a soft bottom layer could be used to fill the gaps between the pins and a harder top layer should create a more rigid tooling surface. It is expected, that the new approach with layers of different thickness and with tailored mechanical properties can reduce the minimum thickness of the IPL significantly while increasing the maximum resolution of the tool.

To qualitatively evaluate the feasibility of these two proposed concepts, a preliminary study was conducted by Wimmer and Maurer [2017]:

In this study finite element analysis was used to evaluate the influence of the thickness, of the single layer IPL, on dimpling. Additionally, the effect of the multilayer approach was evaluated and compared to the single layer. The VAMM test bench (see chapter 4.5) with 37 hexagonal pins with a 24 mm width A/F in a hexagonal assembly
was modelled in the Mechanical module of ANSYS Workbench\textsuperscript{16} and solved with the ANSYS implicit solver.

The model for the single layer IPL model consists of ~88,000 elements. The interpolation layer itself is modelled with ~52,000 SOLID285 3-D, 4-node elements using a mixed u-P elements, with a linear displacement and hydrostatic pressure behaviour. The element is well suited for modelling irregular meshes and incompressible materials. The IPL is modelled as a generic Neoprene\textsuperscript{®} rubber using the Neo Hookean material law with an initial shear modulus $M_u = 0.759 \text{ MPa}$ and an incompressibility parameter $D_1 = 0 \text{ MPa}^{-1}$. The vacuum is modelled as a pressure of 0.9 bar on the top surface of the IPL.

The pin positions are derived from a spherical segment with

$$r^2 = x^2 + y^2 + (z - z_0)^2$$  \hspace{1cm} (31)

with $r = 218 \text{ mm}$ leading to a maximum contact angle of $45^\circ$ between the outer pins in the array and the IPL. Four IPL thicknesses are evaluated: 6 mm, 12 mm, 18 mm and 24 mm. The resulting shape error is compensated for each IPL thickness, by adjusting the pin positions by hand so that the deformed geometry matches the desired shape.

![Figure 4-10](image)

*Figure 4-10 - Surface of a sphere shape with $R_p = 218 \text{ mm}$ with different IPL thicknesses (shape error compensated) [Wimmer 2016]*

Figure 4-10 shows the deformed IPL top surface along the cross-section A-A, as shown in the lower left corner of the figure. For an IPL with 6 mm thickness, the support points, as well as the sag between them is well visible. This dimpling is

\textsuperscript{16} ANSYS Workbench 18.2. ANSYS Inc., Canonsburg, PA, USA.
decreased with increasing IPL thickness. At 12 mm dimpling is still visible, but at 18 mm and 24 mm no more visible dimpling can be observed.

However, the increased thickness also leads to an increase in shape error. At the corner of the manufacturing area ($X > 70 \text{ mm}$) the deviation from the desired shape is most prominent. Here, the deviation is lowest with 6 mm IPL but increases with 12 mm and 18 mm. With 24 mm the IPL can no longer conform to the desired shape. The deviation here is on the upper side of the desired geometry.

For the multilayer elastomer IPL, the same model is used. However, the IPL is split into two bodies with different material properties. For comparison, the total thickness is set to 12 mm since this configuration has still some visible dimpling in a single layer setup. The IPL layers are defined as 10 mm of soft material at the bottom and 2 mm of hard material at the top. The soft material is the same generic Neoprene® rubber used for the single layer IPL. The hard material is an arbitrary rubber with ten times the initial shear modulus leading to $M_u = 7,590 \text{ Mpa}$ and an incompressibility parameter $D1 = 0 \text{ Mpa}^{-1}$.

![Figure 4-11](image-url) - Comparison of dimpling with single-layer $D_s$ and multilayer $D_{ml}$ IPL of same thickness; target geometry is a sphere with radius 218 mm (shape error compensated)

Figure 4-11 shows the comparison of dimpling with a single-layer IPL and the multilayer IPL both with a total thickness of 12 mm. In the magnified area in the middle of two adjacent pins, it is visible that the single layer IPL produces significantly greater dimpling than the multilayer IPL. The multi-layer approach shows 56 % less sag. In contrast, a larger shape error occurs in the edge area of the tool. In this example, it is 52 % larger than with a single layer. However, since no full-fledged shape controller was implemented in the preliminary investigation, further improvements can be expected in real applications.
It shows however, that the multilayer approach has potential to decrease dimpling without increasing the thickness of the interpolation layer. This is particularly promising since high thicknesses tend not to conform fully to the target geometry as shown by the 24 mm IPL. Thus, this approach can increase the manufacturing capabilities of the VAMM tool without compromising the part quality. This justifies further investigation.
4.4.4 Adjustable Radiation Heating

Fibre-reinforced plastic composites are cured during the manufacturing process. When using thermosets, the application of heat is either desirable in terms of process time or necessary to initiate the curing process. High performance thermoset resins even have to follow rather precise temperature profiles for curing (compare figure 4-12) to achieve optimum performance in the components.

In VAMM, the curvature of the mould, as well as the stationary design of the tool makes heating the components challenging. An evaluation of heating methods by Schweiger [2015] showed, that radiation in this case is superior to heat conduction and heat convection. For efficient curing, a high heat flux density $q$ is desirable to speed up the heat up process and reduces cycle time. Heat transfer by radiation offers this high heat flux density. Additionally, using multiple radiators in a radiator array, the contactless heat transfer can easily be configured to heat new geometries evenly by adjusting the power input of individual radiators. The fundamental feasibility of curing CFRP components using heat radiation has already been demonstrated by Nakouzi et al. [2010, 2011; 2012].

In order to incorporate this technology in the VAMM process, a flexible heater system with multiple individually controllable radiators was developed, using infrared radiation, to heat the workpiece [Ertl 2016]. The basic mechanical system consists of two linear units and an aluminium frame construction, carrying the heating elements. Hollow ceramic long wave emitters generate the heat radiation with a wavelength of $3 – 15 \mu m$. The selected radiators are well suited for rapid heating of plastics due to the wavelength of the heat radiation emitted. Solid-state relays control the energy supplied to the heating elements. Six type-K thermocouples transmit the current temperatures to the heater PLC where PID-controllers regulate the power to the radiators depending on the component temperature.

The radiators emit the heat radiation radially. The resulting heat flux from the radiator to a section of the tool surface is proportional to its distance in the second power. This can result in an uneven tooling temperature when using uniform radiation. Figure 4-13 (a) schematically shows an example heating situation. The freely curved
tool surface (grey) is heated by a uniformly powered radiator array (orange). This creates a temperature distribution that exhibits significantly higher temperatures at the elevated points of the tool surface compared to its valleys (see figure 4-13 (b) and (c)).

Figure 4-13 - Heating situation (a) with evenly powered radiator field (orange) and heated tooling surface (grey); resulting heat distribution on the tooling surface from top (b) and from the side (c).

To achieve an even temperature distribution on the tool surface, more energy has to be directed to the cooler areas. This is achieved by locally increasing the temperature of the radiator field above the cold areas. Since the real emitters now also heat the sufficiently warm areas next to the cold areas more intensely, the temperature of the emitter field over the sufficiently warm areas must be reduced accordingly. In order to achieve an even temperature distribution, as well as an adequate temperature profile, a state controller is used to control the individual radiators according to the input of the sensors. The controller parameters are optimised for each components geometry using a simulation model of the heating process [Gruber 2017]. With this, the components are examined for their geometric properties with regard to the heat radiation process and suitable controller parameters are created.
4.4.5 Machine Control System

Programmable logics controllers are commonly programmed according to IEC 61131-3\textsuperscript{17}. The functionalities for motion control are standardised in the PLCopen-Soft Motion\textsuperscript{18} specifications. In the VAMM tool, PLCs of type TM258 and a HMI of type HMIG5U from Schneider Electric GmbH (Ratingen, Germany) are used. The drives of type PD-4C in the actuators and PD-6-N89 in the linear unit and tenter frame are made by Nanotec Electronic GmbH & Co. KG (Feldkirchen, Germany). For these drives however, there is no library for the Schneider motion control available. Hence, the needed functionalities are implemented from scratch in IEC 61131-3 conform function blocks. A comprehensive list of implementations is listed in appendix B - 1.

![Diagram of power state machine controlling the Nanotec drive control units](image)

Figure 4-14 - DS402 power state machine controlling the Nanotec drive control units
[Nanotec Electronic GmbH & Co KG 2014]

The Communication between the PLC and the motor controllers is implemented via the CANopen protocol. According to this protocol, PDOs (process data objects) are continuously exchanged between the devices in the system and SDOs (service data objects) are exchanged on request whenever required. As defined in the CANopen standard DS402\textsuperscript{19} each drives’ status is controlled via a power state machine (see figure 4-14). This state machine needs to be passed through to activate the motor and to

\textsuperscript{17} INTERNATIONAL ELECTROTECHNICAL COMMISSION. 2013 Programmable controllers - Part 3: Programming languages, IEC 61131-3:2013.


switch the motor control unit to the state Switched On to be ready for operation. Status changes are requested via the PDO Controlword. The actual state of the state machine is monitored from the PDO Statusword. The behaviour of the motor and the operating modes are configured via SDOs.

The motors are switched ready for operation via a function block FB_Power and the high-level power is activated as shown in figure 4-15. This function block controls and monitors the drives power state machine. All successive function blocks then work with a motor ready for operation.

The motors in the system are mainly used for positioning. Therefore, operation in closed-loop mode is recommended, as this enables and ensures precise positioning. This mode however requires initial referencing to a defined point. A function block FB_Home was developed for this purpose. It supports all homing methods provided by the Nanotec motor controller (e.g. homing on block, on end-switches clockwise or anticlockwise [Nanotec Electronic GmbH & Co KG 2014]), and can be configured via a number of parameters (e.g. speeds, currents, acceleration etc. as shown in figure 4-15).

After referencing, the drives can be used for positioning and, as an example, move to an absolute position. Function blocks have been developed to control this targeted movement of the motor. For operation in the system, the operating modes FB_Velocity (speed-controlled operation), FB_MoveAbsolute (moving to a position in reference to the zero point) and FB_MoveRelative (moving to a position in reference to the current position) are required. All function blocks are implemented fully parametrically to allow easy configuration of acceleration, deceleration, speed, jerk, current, etc. during operation.

Complex machine functions can be performed by simply adding basic functions to one another. A test sequence for initiating, referencing and positioning a drive is shown in figure 4-15.

![Figure 4-15](image)

**Figure 4-15 - Test sequence for positioning a motor in the system:**
the motor is started in the first block, referenced in the second block and then moved to a position

Each actuator is equipped with a valve to control the pneumatic cylinder and two sensors to read its status. These devices are connected to the inputs/outputs (I/Os) of the motor control and are integrated into the PLC via the motor controllers. Appropriate function blocks have been developed for reading and writing the respective inputs and outputs.
The coupling and decoupling process is implemented in a function block \texttt{FB_ActuatorClutch} as described in detail in chapter 4.4.2:

- The clutch claw starts spinning.
- When the coupling velocity is reached, the pneumatics are activated.
- The clutch extends, and the motor is stopped when the upper sensor is reached.
- If the upper sensor is not reached within a defined time, the pneumatic cylinder is retracted again and the process is repeated when the lower sensor is reached until a critical number of coupling attempts are reached. Then an error is returned.

After engaging the coupling, the pins are moved downwards “on block” onto the base plate with the function block \texttt{FB_Home}. The position is then used as a reference for the positioning of the pin with \texttt{FB_MoveAbsolute}. These functionalities for setting a pin are implemented in a function block \texttt{FB_SetPin} that allows the fully automatic adjustment of an individual pin. It is user-configurable so that e.g. speeds, accelerations and currents can be configured during commissioning to allow for optimum operation. This function block is executed once for each actuator in order to set 11 pins simultaneously.

To position the actuator array under the punch field, a function block for controlling and positioning the linear unit was also developed. This \texttt{FB_SetXYAxes} checks via an input \texttt{MotionPermitted} whether all actuators are uncoupled and in rest position and then positions the linear axis (X-axis) precisely under a desired pin row. The Y-axis is controlled via the pneumatics connected to the motor controller I/Os.

By combining the function blocks described, all the operations of the machine from positioning the linear unit to positioning the pins, as well as moving the tenter frame can be controlled fully automatic.

\textbf{Transfer of component data to the controller}

Industrial controls programmed with CODESYS based development environments [International Electrotechnical Commission 2013] use so called recipes, which are organised in recipe groups, for the exchange of process parameters. Up to 256 recipes with 1,024 ingredients each, can be created in a recipe group. In each recipe, each ingredient must be assigned a value (see table 4-8). The VAMM tool requires set heights for each of the 572 pins to set a target geometry. In addition, further information about the part is transfers to the HMI for user interaction (e.g. name of the component, version, curing parameters, general information).
Table 4-8 - Relationship between recipe group, recipes and ingredients

| Recipe group (e.g. Part) | recipe 1 | recipe 2 | ...
|--------------------------|----------|----------|-----
| (sphere)                 | value 1-1| value 2-1| value ...-1 |
| (saddle)                 | value 1-2| value 2-2| value ...-2 |
| ...                      | value 1-...| value 2-...| value ...-... |
| Ingredient 1 (height Pin 1) | value 1-573| value 2-573| value ...-573 |
| Ingredient 2 (height Pin 2) | value ...-...| value ...-...| value ...-... |
| ...                      |          |          |     |
| Ingredient 573 (information) |          |          |     |
| End                      |          |          |     |

As shown in figure 4-2, the PLCs and HMI in the system communicate over Ethernet. The HMI additionally has an Ethernet connection to an external LAN. This network connection also enables the transfer of machine data between a PC and system in the form of recipes or recipe groups. If a recipe group is located on the HMI, it can be downloaded to a PC with a tool from Schneider Electric in a proprietary file format (.rcp file). There it can be converted to a simplified recipe format as comma-separated-values file (.csv file). The tool however, does not support the automatic download, extension and re-upload automatically.

![Program flow to modify/add recipe data on the HMI](image)

To add additional recipes e.g. for additional parts to the machine, a dedicated Matlab tool was developed (see figure 4-16). It can be supplied with a list of pin coordinates and additional parameters about the part. It then looks for the HMI in the network and downloads the current recipe file. The file is then converted to a human readable .csv file format that can be edited. Subsequently, the new receipt is added to the list and previous receipts can be modified or removed at will. Finally, the .csv file is converted back to the proprietary .rcp format and uploaded to the HMI.
4.5 VAMM Test Setup

The small-scale VAMM test setup was developed and built to validate the feasibility of the developed machine concept, as well as to test and optimise the individual components. It incorporates all the components specified in the VAMM concept, but uses manual operation instead of automatic control and complex automation. The tool schematic is shown in figure 4-17. It has 37 hexagonal pins with a width A/F of 24 mm and spherical heads. They are arranged in a close packed hexagonal array with an array diameter of 168 mm and an array width A/F of 144.5 mm. The maximum configuration height of the pins is 320 mm. The vacuum container has a diameter of 350 mm. On top of the pins, an interpolation layer made from one or more layers of industrial grade silicon rubbers closes the vacuum container and creates the tooling surface.

![Schematic of the VAMM tool test bench](image)

The pins are positioned by manually positioned sequential lead screw driven actuation. They are mounted in a base plate using sleeve bearings. Outside of the vacuum container, each pin has a specifically designed coupling. A stepper motor driven actuator unit is connected to it to adjust the pins. Radial shaft seals are used to feed the pins through the base plate while maintaining the vacuum. The TR-8\textsuperscript{20} corrugated steel spindles within the pins have a thread pitch of 2 mm. The threaded nut within the pin is made from brass. This material combination is self-locking under load, with and without additional lubrication, eliminating the need for external

\textsuperscript{20} trapezoidal threaded spindle with an outer diameter of 8 mm
clamping to rigidify the pin array. Instead, the pin array can be rigidified and all pins can be fixed relative to each other just by applying a vacuum. However, to prevent the pin array from moving and the pins from separating under the load applied by the IPL, a vacuum actuated wedge clamping system is introduced (Figure 4-18). This system uses 3D printed clamps that slide on an inclined surface to fix the pins in position. The wedges are mounted on springs. These springs retract the wedge when no pressure is applied from above. When the interpolation layer is pressed on the wedges by the vacuum, they slide in the positioning plate and circumferentially clamp the pin array.

![Figure 4-18 - Wedge clamping system for the VAMM test bench](image)

The pins are adjusted using a manually positioned actuator device (see figure 4-19-left). The clutch is actuated by a pneumatic cylinder controlled by a manual valve. A stepper drive with internal encoder, controlled by a computer, is used to adjust the pins. The drives used in the test bench are compiled in table 4-9.

<table>
<thead>
<tr>
<th>axis</th>
<th>type</th>
<th>manufacturer</th>
<th>series</th>
<th>type</th>
<th>transmission</th>
<th>ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-axis/</td>
<td>manual positioning</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Y-axis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Actuator</td>
<td>stepper motor</td>
<td>Nanotec</td>
<td>PD-4</td>
<td>C60</td>
<td>gear drive</td>
<td>1:1</td>
</tr>
<tr>
<td>C-axis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Rotation)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Actuator</td>
<td>pneumatic cylinder</td>
<td>Festo</td>
<td></td>
<td>direct</td>
<td></td>
<td>1:1</td>
</tr>
<tr>
<td>Z-axis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The vacuum container is sealed off with an elastic rubber sheet used as interpolation layer. Due to the elevated process temperatures in FRP composite manufacturing, silicon rubber is used since it has a high temperature resistance of up to 300°C. The rubbers used are silicon sheet material from GaFa-Tec\(^\text{21}\) (see appendix C - 1 Silicon Rubber Data Sheet). The materials are commercially available in a thickness of 5 mm in a translucent and a red variant, both with a hardness of 40 Shore A and 60 Shore A respectively. In order to get a desired IPL thickness, the sheets are stacked accordingly. The staked sheets are clamped between two steel rings acting as a tenter frame. The frame is then pulled over the adjusted pin array and fixed to the test setup using screw clamps.

Initial tests, conducted in chapter 5.1, also show that silicone rubber also has a good chemical resistance against epoxy resin and good separating properties for demoulding of the manufactured parts.

\(^{21}\) GaFa-Tec Handels GmbH, Schwierlowsee, Germany
4.6 VAMM Full-Scale Prototype

The test setup introduced in chapter 4.5 proved the feasibility of the VAMM concept. Hence, an automated production ready prototype of the technology is developed. This prototype incorporates the previously introduced concepts and is able to build parts directly from 3D CAD files. The full system is shown in figure 4-20. Three components make up the system: the VAMM tool itself (in the centre), the radiation heater (on the right side) and the control cabinet with the human machine interface (HMI) (on the left side).

The tool itself (see figure 4-21) has a squared pin array. For the desired manufacturing area of 400 mm x 600 mm, the number of pins per line can be calculated to be $N_w = 11$, the number of pins per row is $N_l = 52$ and the total number of pins is $N = 572$. The actual manufacturing area with this configuration results to 612 mm x 436.5 mm. The dimensions of the VAMM pin array are compiled in table 4-10.
Table 4-10 - Dimensions of the VAMM prototype

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>length of pin array</td>
<td>$l$</td>
<td>600 mm</td>
</tr>
<tr>
<td>width of pin array</td>
<td>$w$</td>
<td>400 mm</td>
</tr>
<tr>
<td>pins per row</td>
<td>$N_t$</td>
<td>52</td>
</tr>
<tr>
<td>pins per line</td>
<td>$N_w$</td>
<td>11</td>
</tr>
<tr>
<td>total number of pin</td>
<td>$N$</td>
<td>572</td>
</tr>
<tr>
<td>actual length</td>
<td>$l^*$</td>
<td>612 mm</td>
</tr>
<tr>
<td>actual width</td>
<td>$w^*$</td>
<td>436.5 mm</td>
</tr>
</tbody>
</table>

The pins are placed in a vacuum chamber that is sealed off on the top side by the interpolation layer. The chamber has a wall thickness of 20 mm. An automatically controlled vacuum pump is used to evacuate the chamber. A pressure sensor and a pneumatic valve in the feed line of the vacuum pump are used to control the vacuum in the container to a precision of $< 10$ mPa and a total pressure of 50 mPa (absolute).

At the closing edge of the vacuum chamber, the pin tips line up with a circumferential plate that acts as the zero plane for the pin array. It holds the wedge
clamping system that compacts the pin array when vacuum is applied. Fourteen clamps are positioned around the pin array (three on each short side and four on each long side of the array). The plate circumferentially exceeds the pin array by 120 mm, creating a buffer zone for the interpolation layer to stretch freely when being deformed.

Adjustment of the pins is conducted using eleven actuator units (see figure 4-22 bottom), as introduced in chapter 4.4.2. These units are placed on the linear unit as shown in figure 4-2. This unit can move continuously in X-direction and move between two stable states in Y-direction. Due to the hexagonal character of the pin array, two consecutive lines of pins are shifted in Y-direction by a constant value. It is therefore not necessary for the Y-axis to have more than two adjustable positions. Hence, a pneumatic actuator is utilised, instead of an electric motor. Compared to a continuous axis with a drive motor and motor controller, this reduces the machine complexity significantly.

The actuators themselves use stepper motors with integrated rotary encoders and motor controllers for the positioning of the pins. The drives are operated in 1/16 step mode with 400 steps/revolution. The encoder has a resolution of 1,024 cycles/revolution. With a leadscrews pitch of 2 mm, this leads to a control resolution on the Z-axes of 0.0019 mm. The coupling is actuated with a pneumatic cylinder and controlled by a pneumatic valve. The drives used in the full-scale prototype are compiled in table 4-11.

A multilayer IPL is placed on top of the pin array. The same silicon rubber sheet materials are used as for the test setup. Two translucent and two red silicon materials,
both with a hardness of 40 Shore A and 60 Shore A respectively from GaFa-Tec (see appendix C - 1) are used. These sheet materials are commercially available with a thickness of 5 mm. The desired IPL thickness is created by stacking multiple sheets accordingly.

Table 4-11 - Drives used in the VAMM full-scale prototype

<table>
<thead>
<tr>
<th>axis</th>
<th>type</th>
<th>manufacturer</th>
<th>series</th>
<th>type</th>
<th>transmission</th>
<th>ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-axis</td>
<td>stepper motor</td>
<td>Nanotec</td>
<td>PD-6</td>
<td>N89</td>
<td>planetary gearbox</td>
<td>1:80</td>
</tr>
<tr>
<td>Y-Axis</td>
<td>pneumatic cylinder</td>
<td>Festo</td>
<td>ADN</td>
<td>25-25 A-P-A</td>
<td>direct</td>
<td>-</td>
</tr>
<tr>
<td>Actuator C-axis (Rotation)</td>
<td>stepper motor</td>
<td>Nanotec</td>
<td>PD-4</td>
<td>C60</td>
<td>timing belt drive</td>
<td>1:1</td>
</tr>
<tr>
<td>Actuator Z-axis</td>
<td>pneumatic cylinder</td>
<td>Festo</td>
<td>ADNGF</td>
<td>21-40</td>
<td>direct</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>pneumatic valve</td>
<td>SMC</td>
<td>SYJ</td>
<td>3243T</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

An automatically height adjustable tenter frame holds the interpolation layer (see figure 4-20 (holding the red IPL)). The frame itself can be removed from the tool for easy access and replacement of the interpolation layer. It is placed on a secondary frame and fixed with latch clamps (see figure 4-21 (aluminium extrusion frame with red latch clamps)). The secondary frame is mounted to the tool with four spindle jacks, one for each corner of the frame. The two spindle jacks on each side of the frame are each synchronised by a connecting shaft. The two sides are connected by a toothed belt and driven by a stepper motor. This configuration allows all four edges of the tenter frame to be lifted and lowered synchronously. The spindles used are self-locking TR 20x4 trapezoidal spindles with a diameter of 20 mm and a thread pitch of 4 mm. They are 500 mm long resulting in a maximum stroke, of the tenter frame, of 400 mm.

A user interface enables the exchange of information between operator and system. In the VAMM prototype, the entire production process is controlled from a central HMI of type HMIGTU Open Box, with a 15” HMIGTU touch panel, from Schneider Electric22. A purpose built user interface provides all functionalities necessary to control the VAMM system. These functions are compiled in appendix User Interface Functions. Based on these, Pu [2017] developed a prioritised structure for a user centric user interface (UI) based on the demands and requirements of experienced machine operators. To investigate the usability of this structure, mock-ups were

22 Schneider Electric SA, Nanterre (Hauts-de-Seine), France
developed and tested by different machine operators. It was examined whether the particularities of the FlexForCFK HMI corresponded with the ideas of the machine operators, and whether the operators could monitor and adjust the production process without difficulty. Based on their feedback the layout and structure were optimised and implemented in a consistent design in accordance to the DIN EN 894-2. The main screen, as well as a selection of production-, maintenance- and settings-screens are shown in figure 4-23. A consistent colour scheme with green, blue and orange identifiers clarifies the current options.

Figure 4-23 - User Interface of the VAMM prototype, main screen (top left, with select buttons for production (green), maintenance (blue) and settings (orange)), a maintenance screen (top centre) a settings screen (top right) and a collection of production screens (bottom)

Figure 4-24 shows the fully implemented manufacturing process on the VAMM full-scale prototype. In the beginning, the pin array is adjusted automatically according to the desired target geometry. Subsequently, the tenter frame is lowered on the pin array, stretching the interpolation layer over the pins (here a 5 mm layer of translucent GaFaTec silicone rubber is used). The vacuum is applied and the IPL conforms to the adjusted target geometry. Then, the CFRP prepreg material lay-up is applied to the tool and a vacuum bag placed on top of it. The radiation heater is then placed over the VAMM tool and the heater array lowered to the working position. The radiators are then heating the CFRP lay-up evenly to cure the component. After the process time, the component is ready and can be demoulded. In this case, due to insufficient interpolation, the component features severe dimpling as shown in the bottom right image.

Figure 4-24 - Manufacturing of a carbon fibre reinforces plastic component in the VAMM tool.
4.7 System Calibration

During built up and calibration of the VAMM tool the pin coupling process proved to be unreliable. In some cases, the number of failed coupling attempts exceeded the number of successful ones. As expected (see table 4-5 - potential errors), failed attempts in coupling are one of the potential errors in the VAMM system compromising system reliability. They occur randomly and are not preventable with the used actuator design. They are also not an essential problem as long as their occurrence is rare, since the pin adjustment algorithm is designed to handle these failed attempts (see figure 4-8). However, the reduction of failed coupling processes is still desirable to reduce wear in the components and speed up tool adjustment.

To achieve a better understanding of the coupling process, high-speed camera images (figure 4-25) were recorded. They show a successful (top), as well as an unsuccessful coupling process (bottom). When the coupling is not successful, the claw interlocks with the pins torque bar during the upwards motion. This state can be considered stable and can only be resolved by retracting the claw.

In order to improve coupling, the process is optimised by using statistical optimisation. Therefore, four process parameters are initially identified that influence the behaviour of the claw clutch [Richter 2017; Wimmer 2017]:

- rotational velocity; the clockwise velocity of the clutch claw spinning [rpm],
- torque; the torque the electric motor produces during coupling [Ncm],
- air pressure; the air pressure in the pneumatic system defines the upward force of the claw clutch [bar] (\(\cong 10^5 \text{ Pa}\)),
- airflow setting; the air flow into the cylinder defines the upward velocity of the claw clutch. [-] (dimensionless pressure valve setting)

For each of this parameter an upper and lower boundary, as well as a reasonable interval are defined and compiled in table 4-12.
Table 4-12 - Parameter boundaries for claw clutch optimisation

<table>
<thead>
<tr>
<th>factor</th>
<th>initial</th>
<th>lower boundary</th>
<th>upper boundary</th>
<th>interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>rotational velocity [rpm]</td>
<td>600</td>
<td>0</td>
<td>600</td>
<td>1</td>
</tr>
<tr>
<td>torque [Ncm]</td>
<td>1,000</td>
<td>600</td>
<td>2,200</td>
<td>1</td>
</tr>
<tr>
<td>air pressure [bar]</td>
<td>3</td>
<td>2.0</td>
<td>4.0</td>
<td>0.2</td>
</tr>
<tr>
<td>airflow setting [ ]</td>
<td>1.5</td>
<td>0.5</td>
<td>4.0</td>
<td>0.25</td>
</tr>
</tbody>
</table>

The coupling success rate $s_c$ is defined as the system's response. It is defined as the arithmetic mean of the number of attempts needed for a successful coupling

$$s_c = \frac{1}{n} \sum_{i=1}^{n} N_i$$  \hspace{1cm} (32)

where $N_i$ is the number of attempts needed to successfully engage in one coupling process.

Using Advanced Latin Hypercube Sampling, a Design of Experiment with 80 sampling points is created. For each sampling point, 1000 coupling processes are conducted to evaluate the couplings performance. Subsequently sensitivity analysis is used to evaluate the influence of each parameter on the coupling performance. Therefore, a Metamodell of Optimal Prognosis (MOP) is created incorporating all the parameters. Then for each parameter, the Coefficient of Prognosis (CoP) is calculated and used to evaluate the influence on the MOP.
Parameters with little to no influence, e.g. little CoP, can then be removed from the model to create a reduced order model of the evaluated system. This helps to reduce the complexity and improves the prognosis quality of the metamodel.

It shows that torque (4 %) and air pressure (5 %) only have a minor influence on the coupling performance. On the other hand, airflow (24 %) and rotational velocity (39 %) have significant influence on the output of the full model. A reduced Metamodell of Optimal Prognosis with only these two parameters is then derived. Figure 4-26 shows this metamodel created with Non-linear Programming by Quadratic Lagrangian (NLPQL) in a non-smoothed (left) and smoothed (right) mode. Where the original full model has a CoD of 83 % and a CoP of 57 %, the reduced order MOP has a CoP of 77 % and a CoD of 99 %. This is sufficient to optimise the system.

The Non-linear Programming by Quadratic Lagrangian (NLPQL) algorithm [Schittkowski 1986] is used on the reduced order metamodel for optimisation of the coupling parameters. Table 4-13 shows the ideal set of parameters identified by the optimisation for both, the smoothed and non-smoothed model. Additionally, for both optima, the parameters were tested on the physical system with 1,000 coupling attempts each. It shows that the model predictions are in good agreement with the real system. The system responses vary, compared to the model predictions, by 0.01 (non-smoothed) and 0.02 (smoothed) respectively. Compared to the original parameters, which were chosen at random, the ones optimised on the smoothed and unsmoothed metamodel lead to a 60 % improved coupling performance in the VAMM system.

<table>
<thead>
<tr>
<th></th>
<th>rotational velocity [rpm]</th>
<th>airflow [ ]</th>
<th>$s_c$ model prediction</th>
<th>$s_c$ tested</th>
</tr>
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<tr>
<td>Original</td>
<td>600</td>
<td>1.5</td>
<td>-</td>
<td>1.1415</td>
</tr>
<tr>
<td>Optimised (not smoothed)</td>
<td>449</td>
<td>1.75</td>
<td>1.05879</td>
<td>1.0691</td>
</tr>
<tr>
<td>Optimised (smoothed)</td>
<td>424</td>
<td>2</td>
<td>1.0824</td>
<td>1.0621</td>
</tr>
</tbody>
</table>
4.8 Summary

In this chapter, a novel multipoint tooling technology for FRP manufacturing was introduced. The defined requirements for this Vacuum Assisted Multipoint Moulding (see research question Q1.1) consist of the requirements of already established multipoint tooling systems and are complemented by requirements of the VAMM concept and CFRP process. They are summarized in table 4-2 and table 4-3.

Based on these requirements, a system architecture was developed. It divides the system in five functional modules: an array of pins placed inside a vacuum container, a pin actuation system, an interpolation layer, a radiation heater unit and a control system with an intuitive human-machine interface. These modules are interchangeable and offer a scalable solution that can be adapted to many applications.

Subsequently, each module was introduced and design considerations were discussed:

- The pin array was developed with a hexagonal pin cross-section in order to maximise the tool resolution. The pin heads are designed hemispherical in order to minimise indentation in the IPL and to prevent sharp edges from getting in contact and damaging the IPL.
- A novel leadscrew driven pin actuation concept was introduced that uses a passive low complexity pin design and an array of sensor equipped actuators for adjustment. A form lock claw clutch was developed that enables coupling during rotational motion and ensures precise transmission of moments from the actuators to the pins. The design was compared to established pin actuation concepts and shows to be more cost efficient and expected to be more reliable due to reduced complexity. Optimisation of the clutch parameters improved the operational reliability of the system by nearly 60%.
- Two interpolation layer concepts are introduced. The single layer concept uses a silicon rubber sheet with a distinct thickness to create a smooth tooling surface. The multi-layer approach stacks layers of different elastomers with specific functions in order to improve the interpolation and decrease the total thickness needed for creating a smooth surface. A preliminary FEA study shows, that this approach could decrease dimpling and increase shape fidelity, as proposed in Q4.5.
- A radiation heater with individually controllable radiators was introduced. A simulation tool was developed to control the radiators in order to heat freeform surfaces evenly.
- A modular control system was set up to control all machine functions of a VAMM system. A user-centric human machine interface ensures the accessibility of all these functions via a touchscreen monitor.
This architecture is intended to raise the capability to create geometries with concave as well as convex sections and infliction points, thereby answering the research question Q1.2.

Based on these modules two versions of VAMM were designed:

- The **VAMM test setup** is a small proof of concept with 35 pins and a manually adjusted actuator. It is intended for further experimental research and virtual optimisation. This tool was used in chapter 5.1 to prove the feasibility of the developed concept and the individual components.

- The **VAMM full-scale prototype** is an industrial scale tooling system adapted from on the successful tests of the test setup. It has a pin array with 572 pins, which are adjusted automatically by an array of eleven actuators. This system proves the scalability of the developed concept. The manufacturing of FRP components is demonstrated using a vacuum bagging process with CFRP prepregs.

In summary, the partial research questions were answered in the first parts of the chapters. Based on this, the VAMM test bench was constructed and tool surfaces with convex and concave geometries were created. In addition, components were successfully manufactured. This proves the validity of the formulated answers for both Q1.1 and Q1.2. The VAMM concept was then scale-up to an industrial scale and again components were successfully manufactured. The VAMM concept thus represents an adequate solution for the research question Q1.
Chapter 5  Experimental Evaluation of Part Quality

The VAMM technology is intended as an alternative to established rigid tooling. This expectation can only be fulfilled, if the new process has no negative influence on the quality of the manufactured components. The previous chapters investigated this influence on the geometric quality on a virtual model. However, in fibre-reinforced plastic composite manufacturing, the composite material is created during the manufacturing process through curing. The mechanical properties of the final component only develop in this hardening process. The tooling therefore has a profound effect on the part quality. In this chapter, the effects of the elastic tooling surface in the VAMM process is to be examined. Therefore, the part quality is evaluated in two separate fields:

The first two sections of the chapter evaluate the geometric quality of the parts manufactured using VAMM. In the first part, the physical influence of IPL thickness and forming pressure on the surface quality are evaluated in order to define a reasonable value range for the optimisation process.

The second part of the chapter investigates the mechanical quality of VAMM manufactured components. For this purpose, mechanical parameters such as strength and stiffness, as well as the fibre volume content of VAMM manufactured components are compared to components made on conventional moulds.
5.1 Initial Interpolation Tests

A functional test is conducted on the VAMM test bench in order to validate the capability of the VAMM concept to produce parts of a sufficient surface quality. Additionally, the general influence of IPL thickness and forming pressure on the surface quality are evaluated, in order to define a reasonable value range for the optimisation process.

5.1.1 Objective

This test aims to give a first impression on how the VAMM system performs. It is investigated, whether the concept immanent vacuum below the interpolation layer is able to reliably create convex geometries. Additionally, the influence of the mould vacuum and the IPL thickness on the quality of the mould surface is to be practically evaluated. In addition, information is to be obtained about the value range, in which the two parameters can be varied in a technically reasonable way.

5.1.2 Experimental Set Up and Procedure

In order to test the influence of the interpolation layer in Vacuum Assisted Multipoint Moulding, the tool is set to a concave hemispheric shape with a radius of 100 mm and an offset, from the zero plane, of 60 mm. Transparent silicon rubber of hardness 40 ShA (see appendix C - 1) is used for the interpolation layer. The thicknesses $t_{IPL}$ tested are 5 mm, 10 mm, 15 mm and 20 mm. The vacuum pressure $\Delta p$ is varied from 300 hPa over 600 hPa to 900 hPa (vacuum pressure). The created surfaces are then scanned using a DAVID SLS2 3D scanner. The setup is similar to the one described in chapter 6.4.3. The surface quality of the tooling surface is evaluated qualitatively, by visual inspection.

5.1.3 Results and Discussion

Figure 5-1 shows the scanned surfaces of the mould created with the VAMM. It can be seen that in all configurations the interpolation layer is able to converge fully to the set convex shape. This means, that all pins are in contact with the rubber sheet. However, at an IPL thickness of 5 mm, the pins push through the rubber and an extensive golf ball like dimpling pattern is created on the surface. By increasing the thickness of the IPL to 10mm, the effect can be significantly reduced. The dimpling effect can still be seen on the entire surface, but it is much less pronounced. With an IPL thickness of 15 mm, the defect is mainly visible at the edges of the adjusted shape. In most technical applications, this surface quality is still not sufficient for the
production of immaculate parts. With an IPL thickness of 20 mm, no more dimpling is visible. The tool surface is smooth in the centre area, and shows only slight dents at the edges, if very high pressure of $\Delta p = 900 \text{ mBar}$ is applied.

However, the disadvantage of extensive interpolation also becomes apparent. In all experiments, the pin arrangement is fixed to the defined shape. Only the IPL is changed without resetting the pins. When the thickness of the IPL is increased, it acts like an offset on the set geometry. Since the minimum radii that can be adjusted are defined by the given pin array, the actual minimum radii are thus increased by this offset. This reduction of the tools resolution becomes clear, when comparing the configurations with IPLs with 5 mm and 20 mm of thickness. The actual component radius of the latter is significantly smaller.

![Figure 5-1 - 3D scans of different interpolation layer thicknesses $t_{\text{IP}}$ at different vacuum pressures $\Delta p$](image)

The surface quality is also influenced by the applied pressure $\Delta p$. This is most obvious at the 5 mm IPL and 10 mm IPL. There the dimpling increases steadily with increasing vacuum pressure. With both configurations, only slight dimpling can be detected at 300 mBar. At 900 mBar, on the other hand, the effect is much stronger. With the higher IPL thicknesses of 15 mm and 20 mm, however, this effect is no longer clearly visible. Figure 5-2 shows a component being manufactured at 900 mBar pressure with a 20 mm IPL (left) and the final component after demoulding (right). Perpendicular lines are drawn on the black surface to improve the visibility of dimpling. However, the part does not exhibit any signs of visible dimpling.

At high pressure, it is also evident that the interpolation layer conforms better to the pin array. This can be clearly seen on the sides of the pin array (for example at 5 mm
IPL thickness and 900 mBar pressure). This effect also occurs with thicker IPLs, but is less obvious there.

Figure 5-2 - Manufacturing of a component on the test bench with 20 mm IPL and 900 mBar pressure
5.2 Mechanical Properties of VAMM manufactured parts

In this chapter, the mechanical properties of VAMM manufactured CFRP parts made with different interpolation layer thicknesses are evaluated and compared to components produced on a conventional aluminium mould. It is to be evaluated if VAMM manufactured components are mechanically equivalent to their traditionally manufactured counterparts. In addition, the influence of the interpolation layer thickness on the mechanical properties of parts is to be evaluated.

5.2.1 Objective

The aim of this investigation is to find out how VAMM influences the mechanical properties of components compared to parts manufactured in a traditional process. The following mechanical properties are examined for this purpose:

- Young’s modulus
- ultimate tensile strength
- bending stiffness
- bending strength
- fibre volume fraction
- void volume fraction

The determined data are intended to answer the following questions: Does VAMM decrease the modulus of components, compared to traditional tooling and at which IPL thickness can an equal modulus be expected? Does VAMM decrease the tensile strength of components compared to traditional tooling? Can VAMM components have equal tensile strength, and what is the threshold IPL thickness, at which equality can be assumed? Does VAMM influence the bending stiffness and strength of components, compared to traditional tooling? Can VAMM components have equal bending stiffness and strength, as ones made on traditional tooling? What IPL thickness is needed for that? Does VAMM influence the fibre volume fraction and void volume fraction of the composites?

5.2.2 Experimental Set Up and Procedure

The mechanical properties are evaluated using four different CFRP panels: The reference panel is manufactured on an aluminium tool. The three other panels are made on the VAMM tool, each with interpolation layers of different thickness (15 mm, 20 mm, and 25 mm of red silicon rubber with 60 ShA).
Test Set Up

Uniaxial tension tests are conducted to evaluate the Young’s modulus and ultimate tensile strength. Bending stiffness and bending strength are analysed using a three-point-bending test. The fibre volume content and shrinkage cavity fraction are evaluated using thermogravimetry. The form and distribution of the shrinkage cavities is subsequently evaluated using microsection.

- uniaxial tension test

The uniaxial tension tests are conducted, as described in chapter 3.6. For the tests, strip samples with a size of 250 mm x 25 mm and a thickness of 2 mm are used. 150 mm of the specimen length are used for clamping, leaving 100 mm as testing length. The tests are conducted on a universal tensile testing machine RetroLine 1465/50 with a multiXtense extensometer and a 50 kN load cell. The samples are preloaded with a force of 5 N and tested till fracture at a strain rate of 1 mm/min.

- three-point bending test

For the bending test of multidirectional composite materials, DIN EN ISO 14125 [DIN Deutsches Institut für Normung e. V. 2011] specifies a sample length of 100 mm and a width of 15 mm. The given specimen thickness of 2 mm is identical to the required specimen thickness of the tensile test. The tests are conducted on a tensile testing machine RetroLine 1465/50 with a 50 kN load cell, equipped with a three point bending mechanism. The support width is defined, as the distance between the support pins, and is set to 80 mm. The centre-loading pin has a width of 5 mm. It exerts a preload of 3 N on the specimen, and then bends the specimen till fracture, at a test rate of 5 mm/min.

- thermogravimetry

Thermogravimetry is used to evaluate the fibre volume fraction $\phi$ and void volume fraction of the composites. Therefore, in a first step, the composite is weighed in its original state and its density is evaluated using a TLE204E Analytical Balance. The resin is then removed from the composite in a pyrolysis process by heat-treating it at 500°C, for two hours. After that only the fibre material remains, which is then weighed again. The relative fibre mass fraction $\psi$, as well as, the fibre volume fraction $\phi$ can then be calculated according to equations (20) to (22) in chapter 3.6.

- microsection

Microsection is used to evaluate the distribution and size of the shrinkage cavities, within the composites. Therefore, the prepared samples are examined under a

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24 ZwickRoell GmbH & Co. KG, Ulm, Germany
25 Mettler Toledo, Columbus, Ohio
measuring microscope Nikon MM-40, with a lens EDF20100\textsuperscript{26}, with 10x magnification, using reflected light. Image series are taken using a digital image sensor Olympus SC30\textsuperscript{27} and combined to achieve a larger image section. The images can then be evaluated qualitatively using visual inspection.

**Test Specimen**

The specimens for the tests are made from a carbon fibre prepreg with a manufacturing width of 320 mm and a resin mass content of ~42%. The fibre material used is a 12k-2/2 twill weave carbon fibre, with a fibre areal weight of 650 g/m\textsuperscript{2}. The resin used in the prepreg is an epoxy resin FT1091\textsuperscript{28}. In order to obtain the thickness of 2 mm, needed for testing, the prepreg is stacked to a three-layer [0° 90°]\textsuperscript{3} laminate. Manufacturing of the samples is conducted in a prepreg vacuum moulding process. For each of the IPL configurations, one flat panel is manufactured on the VAMM full-scale system using the process, as shown in figure 4-24. The forming vacuum under the IPL is set to 900 mBar. The reference panel is manufactured on a 20 mm thick sheet of aluminium acting as a conventional mould. On the VAMM, as well as on the aluminium mould, the adjustable radiation heating system (chapter 4.4.4) is used to cure the laminate at 85°C for 8 h 45 min. The process parameters are compiled in table 5-1.

From the panels, specimens for the tensile test, the three-point-bending test, the thermogravimetry and for microsection are cut according to the specimen cut plan shown in figure d-3, in appendix D - 1. This is done using a water-cooled circular saw. After cutting, the test specimens have partially frayed edges. To eliminate the influence of these frayed edges on the test procedure and to protect against injuries, the edges are deburred under running water, using 320 grit wet sand paper.

<table>
<thead>
<tr>
<th>Table 5-1 - CFRP production data for mechanical testing samples</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>material</strong></td>
</tr>
<tr>
<td><strong>resin</strong></td>
</tr>
<tr>
<td><strong>process</strong></td>
</tr>
<tr>
<td><strong>curing</strong></td>
</tr>
</tbody>
</table>

\textsuperscript{26} Nikon, Tokio, Japan

\textsuperscript{27} Olympus Soft Imaging solutions GmbH, Munster, Germany

\textsuperscript{28} SGL Carbon Group, Germany (The corresponding data sheet is in appendix C - 2)
The samples for the microsection have to be sanded and polished. Therefore, the cut specimen (size 10 mm x 20 mm) are first placed vertically in a casting mould, with a diameter of 40 mm, and embedded in a rapidly curing epoxy resin. The cured samples are then demoulded and subsequently sanded, and polished using a SAPHIR 520 single wheel sander, and polisher with top-mounted sanding and polishing head Rubin 500\(^{29}\). Sanding is done in two steps using 400 grit and 800 grit wet sand paper. The specimen are then polished using a diamond suspension with a nominal grain size of 1 \(\mu\)m. Both sanding and polishing are done at a force of 10 N with speed of 200 U/min for three minutes. Figure 5-3 shows the samples before casting (left) and after polishing (right).

![Figure 5-3 - Sample preparation for microsection](image)

**Data Evaluation**

In order to allow a statistically relevant assessment of the mechanical properties measured for a particular manufacturing process, it is important to evaluate whether the mean values of two experiments are different, or not. This is done using a modification of the two sample t-test for independent samples - namely Welch's t-test [Welch 1947]. This hypothesis test ultimately provides information on statistical significance and is well suited for relatively small sample size. To apply the test, the data must be normally distributed, independent, and with similar variance (no more than twice as high). The experiments produce completely independent results and the evaluation showed that the variances are similar with a factor of 1.7, proving this approach viable. The normal distribution, of the measured data, is evaluated using the Anderson Darling Test [Anderson and Darling 1952].

The hypotheses to be tested are:

- Null hypothesis \(H_0\): "There are no differences in the material properties of CFRP components manufactured on conventional tools and the VAMM tool".
- Alternative hypothesis \(H_1\): "There are differences in the material properties of CFRP components manufactured on conventional tools and the VAMM tool".

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\(^{29}\) ATM GmbH, Mammelzen, Germany
These hypotheses are tested by evaluating the differences in the mean values of two measurements. For a statistically significant difference between the mean values, the \( p \)-value must be less than, or equal to the significance level \( \alpha \). This means that the null hypothesis \( H_0 \) has to be rejected and the alternative hypothesis \( H_1 \) is to be assumed. \( H_1 \) in this case states that there is a difference between the measured data series. The significance level \( \alpha \) is defined as 0.05 (5%). For this significance level, the adequate sample sizes are calculated to be ten for the tension tests and bending tests and three for the fibre volume content evaluation.

5.2.3 Results and Discussion

Only successful measurements are evaluated. This means, that measurements are not considered in the evaluation when for example failure occurs outside of the measurement area or when the specimen slips in the fixture during testing. For the tensile test, seven (25 mm IPL), nine (15 mm IPL), and ten (20 mm IPL and aluminium tooling) specimens, respectively, are successfully tested. In the three-point bending test the number of successfully tested samples is nine (15 mm IPL), ten (aluminium tooling), eleven (20 mm IPL), and twelve (25 mm IPL) respectively. The fibre-volume content is tested using three specimens for each composite. The microsections are evaluated on a single sample and are only used for visual inspection. All measured results are compiled in Appendix D.

**Young’s Modulus**

On the conventional mould the composite has a Young’s Modules of 53280 MPa with a standard deviation \( \sigma = 2336 \) MPa (see figure 5-4). For the VAMM manufactured panels the mean values range from 45677 MPa for the 15 mm IPL to 54840 MPA for the 20 mm IPL.

![Figure 5-4 - Young’s modulus of CFRP composites manufactured on aluminium mould and VAMM with different IPL thicknesses](image-url)
The sample made on 15 mm silicone has a statistically significant lower modulus of elasticity, compared to the sample made on aluminium plate. The measured values show 14% lower modulus of elasticity. Additionally, it shows statistically significant differences of -14% to the 20 mm and 25 mm samples.

For the samples manufactured on 20 mm or 25 mm silicone mats, no significant statement can be made at the defined significance level. However, from an IPL thickness of 20 mm it can be assumed, with 30% certainty, that the plates produced on VAMM have a comparable modulus of elasticity to those produced on conventional tools.

It can be assumed that the reduced modulus is caused by dimpling. The fibre material in the dimpled regions of the component is not straight but has a wave like shape. This means that when a load is applied, the fibre is not stretched directly, but the waviness is straightened. This effect seems to reduce the modulus of the composite, at least when the dimpling is very pronounced, as in the case of the 15 mm IPL.

**Ultimate tensile strength**

The ultimate tensile strength of the composites is shown in figure 5-5. For the panel made on the aluminium mould it is 757 MPa with $\sigma = 27$ MPa. All VAMM manufactured panels show a significant decrease in tensile strength. For the specimens made on 15 mm silicone IPL it is 15% lower, with a mean value of 642 MPa and $\sigma = 43$ MPa, and for the 20 mm IPL it is 14% lower, with a mean value of 648 MPa and $\sigma = 42$ MPa. The 25 mm IPL produces 13% lower tensile strength compared to the aluminium mould, with a mean value of 657 MPa and $\sigma = 61$ MPa.

The tensile strength seems to decrease with thinner interpolation layers. However, the difference between the VAMM manufactured samples themselves is not statistically significant.

*Figure 5-5 - Ultimate tensile strength of CFRP composites manufactured on aluminium mould and VAMM with different IPL thicknesses*
Similar to the modulus, the waviness of the dimpling could be expected to cause some reduction of strength. When applying a load, the fibres are first stretched straight before they can be tensioned along the load direction. At their ultimate tension, this leads to fibres not only being stretched but also bent from their initial wavy form. This superimposed stress state could result in the laminate failing at lower technical tensile stress. Since the reduction in strength is present in all VAMM made specimen, including the dimple free panel made on a 25 mm IPL, this explanation however is not completely conclusive. Additional unknown effects must also have an impact.

**Flexural modulus**

The flexural modulus of the specimens ranges from 39 % to 47 % (see figure 5-6). The aluminium made panel gives a modulus of 45.1 GPa and a standard deviation of 3.5 GPa. Between the VAMM manufactured specimens, statistically significant differences are identified, stating that the flexural modulus increases with increasing IPL thickness. The VAMM manufactured panel made with the 15 mm IPL shows a modulus significantly reduced by 5.2 GPa or -12 %, compared to the aluminium mould made part. For the 20 mm IPL, a difference of only -5 % (42.7 GPa absolute) can be determined, with a statistical confidence of 86 %. For the CFRP panel made on the 25 mm IPL, a significant difference, compared to the traditional mould, cannot be verified.

![Graph showing flexural modulus of CFRP composites](image)

*Figure 5-6 - Flexural modulus of CFRP composites manufactured on aluminium mould and VAMM with different IPL thicknesses*

This behaviour correlates well with the dimpling phenomenon. More dimpled components exhibit lower flexural modulus than non-dimpled ones.
**Flexural strength**

The flexural strength of the VAMM made panels is 628 MPa (15 mm IPL), 635 MPa (20 mm IPL), and 676 MPa (25 mm IPL), respectively (see figure 5-7). The standard deviation for these samples is 47 MPa (15 mm IPL), 27 MPa (20 mm IPL), and 44 MPa (25 mm IPL). The reference panel has a flexural strength of 614 MPa with $\sigma = 75$ MPa.

![Figure 5-7 - Flexural strength of CFRP composites manufactured on aluminium mould and VAMM with different IPL thicknesses](image)

The 15 mm and 20 mm IPL made samples show no significant difference to the ones made on conventional tooling. The panel made on the 25 mm IPL, however, shows a statistically significant increase of $+10\%$. However, this result must be considered with caution. The reference panel shows a high variance, which could indicate flaws in the material. It is assumed, that the high variance of the reference panel is caused by the relatively high void volume fracture (see figure 5-8) of the composite. When achieving a higher manufacturing quality, the reference pane is expected to exhibit a bending stiffness similar to the one made on a 25 mm IPL.

**Fibre volume content**

The fibre volume fraction and void fraction are calculated from the measured weights of the composite, before and after annealing. The results are shown in figure 5-8. The reference component, manufactured on the aluminium tooling, has a fibre volume content of 53 %. For VAMM manufactured parts, it is 51 % for the 15 mm IPL, 54 % for the 20 mm IPL and 52 % for the 25 mm IPL. The standard deviations range from 0.3 % to 1.3 %, as indicated by the almost undetectable error bars, making this a very accurate method. All values are within a small range of 2 %, indicating a high consistency in the manufacturing process.

The void fractions of the VAMM manufactured parts are lowest with 3.7 % for the 15 mm IPL. It increases to 4.2 % for the 20 mm IPL and 4.5 % for the 25 mm IPL. The
highest void content of 5.3% is found in the reference panel made on the aluminium tooling. This equals an increase of 27%, compared to the VAMM manufactured panels.

It is well known, that the little resin flow in prepreg laminates, makes it difficult to avoid voids in the composite [Grove 2018]. In the components manufactured on the aluminium mould, this formation of voids is particularly pronounced. In this experiment, the adjustable radiation heating system is used to introduce heat into the lay-up. The aluminium has a much higher heat capacity and heat conduction value than the silicone IPL. This leads to a higher heat dissipation into the mould. The heat is introduced to the lay-up from the top but is dissipated into the mould at the bottom immediately. This ultimately results in a lower heat input into the composite material. As a result, the component heats up less quickly and less evenly and the resin does not flow as well. The lower resin flow, in turn, favours the formation of voids.

**Microsection**

Microsection and microscopy give an impression of how the laminate is actually constructed within a component. Figure 5-9 shows such an image of a composite made from $[0\ 90]^3$ 12k-2/2 twill weave carbon fibre. The brighter horizontal stripes in the image show fibres parallel to the image plane, whereas the dotted grey areas show fibres perpendicular to the image plane. The uniform grey areas show resin accumulations between the layers or individual fibre strands. The black dot is an undesired cavity or void in the laminate.

The microsection of the tested samples are shown in figure 5-10. The laminates made on VAMM with IPL thickness of 15 mm (a), 20 mm (b), and 25 mm (c) show small voids evenly distributed through the laminate. In all samples, the wave pattern of the fibres in the twill weave is visible, with the weft fibres running longitudinal to
the image plane. The weft overlies two warp yarns before piercing through the warp and underlying the next two yarns. In the transition area, pointed sections are formed in which, preferentially, voids occur. Furthermore, voids appear at the interface between fibre layers. This is most dominant in the laminate made using aluminium tooling (figure 5-10 (d)) which shows large cavities at these interfaces. They are created when air is trapped between the layers during the lamination process. The prepgs used are almost impermeable to air. When two layers are joined together and are not deaerated properly, the enclosed air cannot escape during the evacuation and hardening process.

![Figure 5-9 - Microsection of a [0 90]³ laminate of 12k-2/2 twill weave carbon fibre](image)

![Figure 5-10 - Microsection of laminates made on VAMM with IPL thickness 15 mm (a), 20 mm (b), 25 mm (c) and on an aluminium mould (d), voids appear as black spots](image)
The size and distribution of the inclusions, is in good agreement with the measured void volume content, as shown in figure 5-8. The component manufactured on the thinnest 15 mm IPL shows the smallest and lowest number of voids, the reference component on the other hand, depicts the largest and highest number of voids. The 20 mm IPL and 25 mm IPL manufactured components fall in-between, concerning size and number of voids.

**Discussion**

In summary, VAMM can be used to manufacture components with mechanical properties generally similar to those achieved on conventional tooling. This, however, depends strongly on the interpolation layer thickness used. Only the tensile strength is lower in all the VAMM manufactured components tested. The Young’s modulus is equal to the reference tool, at a thickness of 15 mm. The bending stiffness becomes equal at 20 mm and the bending strength even increases at 25 mm. This however, has to be considered with caution, due to the relatively high variance of the measured data.

All measured values for the fibre volume fraction are within a small range of 2 %, which is adequate for prepreg composites, in a manual manufacturing process. The void fraction however is high in all samples and highest in the reference panel. The high heat dissipation in the aluminium reference tool seems to reduce the composite quality. In this context, the silicon rubber tooling surface seems to be beneficial in the curing process due to the decreased heat transfer.

The high void volume content in all samples –using VAMM and conventional tooling– indicates that the manufacturing process is suboptimal. This may be caused by the prepreg material used for these tests. The resin used, does not exhibit optimum flow properties, at the applied processing temperature. According to the data sheet, higher temperatures could improve this. The VAMM tool however, only allows for a process temperature of up to 85°C on the composite. At this temperature, the areas of the IPL surrounding the process area, (which is not covered by the composite) can reach temperatures of up to 200°C. This is the maximum specified temperature of the silicone rubbers used (see appendix C - 1). For future experiments, the use of wet lamination or different prepregs, using resins with lower viscosity at lower temperature, is recommended. These materials should be able to better fill voids in the fibre material and produce components with more consistent material parameters.

In order to increase the accuracy of future test results, the position of the samples; in relation to the pin array; could also be taken into account. This way, local effect of individual pins could also be investigated. Furthermore, the sample size could be significantly increased in order to improve the statistical relevance of the results. However, the associated additional effort is considered inappropriate for this investigation, not least because of the high production tolerances of the samples.
5.3 Summary

In this chapter, two sets of experiments were performed in order to physically test the feasibility of VAMM technology for production and to evaluate the effects of the technology on the mechanical properties of components.

In the first set of experiments, the effect of VAMM parameters on the geometric quality of parts, was evaluated. Critical pin array parameters and their influence on the surface quality of the tooling were investigated. The interpolation layer thickness and the vacuum pressure have proven to have a distinct effect on dimpling. Increasing IPL thickness leads to a decrease in dimpling. The forming pressure on the other hand increases dimpling, with increased vacuum. At an IPL thickness of 20 mm or more, smooth surfaces with little to no dimpling can be created. At lower thicknesses, the dimpling effect can be severe. This can be viewed as a partial answer to the question Q4.2. Summarizing, the tests show the following two points:

- The VAMM concept works. It actually enables the creation of concave geometries on an open mould. The designed pin concept is capable of holding the system vacuum and the dimensions are sufficient to cope with the occurring loads. This again confirms the validity of the solutions already described in chapter 4 for the research question Q1 and the associated sub-questions.
- The IPL thickness and vacuum pressure have an effect on the VAMM manufacturing process. However, in order to fully answer the research question Q4.2 further investigations are necessary.

In the second set of experiments, the mechanical properties of VAMM manufactured parts were compared to traditionally manufactured ones in order to answer Q2. Tensile tests, bending tests and thermogravimetry tests were conducted on specimens cut out of three CFRP panes made on the VAMM full-scale prototype at 15 mm, 20 mm and 25 mm IPL thickness, respectively. The reference values were gathered from specimens cut out of a panel manufactured on an aluminium tooling. It shows that at an IPL thickness of 20 mm or more, the mechanical properties are close to, or corresponding to, the reference values. The laminate quality even appears to benefit from the rubber tooling. The void fraction of all VAMM made panels is lower than in the reference panel and decreases with increasing IPL thickness.

It can be concluded that VAMM technology is capable of manufacturing components with high geometrical and mechanical quality. In this respect, dimpling is the most critical factor. If the smoothing of the tool surface is sufficient to produce dimpling free components, the mechanical properties are presumably not negatively affected by the manufacturing process.
Modern computation methods and increasing computational power enable the time efficient simulation of forming processes. Modification of parameters in a manufacturing system and analysis of large numbers of variants in a short time are nowadays possible with manageable effort. This can be utilised to achieve a greater understanding of such systems and the parameters that have a significant influence on its behaviour. In order to utilise this, a virtual representation of the VAMM production process is introduced in this chapter. This virtual process chain can be utilised to optimise the pin configuration for a particular CAD component, as well as evaluate effects of variations in part properties, process parameters, pin array parameters and interpolation layer properties. The first subsection of the chapter introduces the architecture of this virtual manufacturing process chain. Subsequently, the individual components and their implementations are described. This virtual process chain can determine the expected component quality depending on the desired component and the manufacturing process. At the beginning, individual parts are designed based on a set of part parameters. Then, initial pin coordinates for the VAMM system are calculated and transferred to a forming simulation that incorporates the machine and process parameters. For the resultant tooling surface, the expected shape error is evaluated. Subsequently, an optimised pin configuration with acceptable shape error can be obtained by iteratively adjusting the pins accordingly and recalculating the forming simulation. The resulting tool surface is reproduced one-to-one in fibre composite production and thus corresponds to the component surface. In a final quality assessment step, the component surface is extracted and examined for dimpling. A qualitative dimpling parameter is therefore introduced.
6.1 Virtual VAMM Manufacturing Model Architecture

In order to conduct analysis on a virtual model of VAMM, the virtual representation of the tool and the associated manufacturing process is supposed to incorporate all essential steps and parameters of the physical tool and process, respectively. The VAMM product creation process can be broken down into three major steps:

- part design
- part manufacturing
- quality control

The quality of the produced parts is measured via the dimpling and shape error. As described in chapters 2.3.1 and 2.3.2, these errors are influenced by parameters associated with the manufactured components, the multipoint tool - most critically the interpolation layer - and the moulding process. In order to incorporate all these parameters in a virtual system model, all of the three process steps have to be virtualised. The virtual VAMM manufacturing model (see figure 6-1) implements these three steps to evaluate a system response for any set of parameters. Each step in this virtual process incorporates the respective parameters of the physical process. This enables the investigation of the influence of variations of these parameters on the final product.

In the part design stage, a target part has to be created automatically based on a set of parameters describing the geometry. In the part manufacturing stage, an initial pin configuration is calculated for this target part. This is then transferred to a shape control algorithm that optimises the individual pin positions until the target part is reproduced accurately. Within the shape controller, the forming process is numerically simulated using finite element analysis. This process results in a deformed tooling surface that is then analysed for shape error.

![Figure 6-1 - Flowchart of the virtual VAMM manufacturing model](image-url)
In the quality control stage, the component is then analysed for dimpling. For the FRP moulding process under investigation, the simplified assumption is that the component is an exact reproduction of the mould. In reality, residual stress can cause warpage in the composite. These stresses are for example induced by resin shrinkage due to the temperature difference through the part thickness. These effects however are well known [Wang et al. 1992], and there are well established methods to minimise residual stresses in composites [Zobeiry and Poursartip 2015] and compensate remaining residual stress [Shokrieh and Kamali Shahri 2014] using constitutive models. For simplification of this model, it is assumed that these compensation steps have already been performed and the target geometry incorporates them. This allows the resulting tool geometry to be directly evaluated for dimpling in order to estimate the part quality.

Different software tools are necessary for the virtualisation of this process. The creation, processing and analysis of 3D geometric data is handled in a purpose-built toolbox developed in Matlab\(^{30}\). The specific solutions for part creation (chapter 6.2), calculating initial pin configurations (chapter 6.3), evaluating shape error (chapter 6.5) and evaluating dimpling (chapter 6.7) are implemented in this toolbox. The software architecture is described in detail in appendix B - 3 MATLAB Geometry Evaluation Toolbox.

The forming simulation is conducted in ANSYS Workbench\(^{31}\) using its explicit dynamics module and the AUTODYN explicit solver. It is described in detail in chapter 6.4. The automatic execution of the FE analysis, as well as the export of results is controlled using the ANSYS Workbench scripting capabilities. The developed VAMM update script is described in appendix B - 5 ANSYS Update.

In order to create an automated model of the full VAMM system these otherwise unrelated software components have to interact with each other. OptiSLang\(^{32}\) is an optimisation toolbox that is capable of interconnecting different solvers and software environments. It can transfer parameters and responses from one module to another and trigger the execution of modules according to predefined rules. It is used for implementing the virtual VAMM manufacturing model, and controlling the Matlab and ANSYS components. Additionally, the custom shape controller described in chapter 6.6 is implemented in OptiSLang using the OptiSLang Python API\(^{33}\). The implementation of this controller is described in appendix B - 4 OptiSLang Custom Shape Control Algorithm (Python).

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\(^{30}\) Matlab R2016b. The MathWorks Inc., Natick, MA, USA.

\(^{31}\) ANSYS Workbench 18.2. ANSYS Inc., Canonsburg, PA, USA.

\(^{32}\) OptiSLang 6.2. Dynardo GmbH, Weimar, Germany.

\(^{33}\) OptiSLang Python API 6.2.0. Dynardo GmbH, Weimar, Germany.
Beside the communication established by OptiSLang, the modules interact via files, which are created, read and modified. These interactions are compiled in the UML component diagram in figure 6-2. The CreateGeometry module reads vamm_config. This Matlab file contains the size of the pin array, the number of pins and the position of the pins in the pin array, as well as their size. The target.stl file is created with this information and the parameters describing the target geometry. This is read by InitialCoordinates that creates an extrapolated version of the target geometry target_extrapolated.stl and modifies the target.stl to match it.

The initial coordinates are then read by the ShapeController together with vamm_config. This information is used to modify the FormingSimulation. After successful simulating the forming process, the deformed_ipl.stl is exported and read by EvaluateShapeError together with target_geometry_extra-polated.stl for further analysis. The evaluated shape error for each pin is transfered to ShapeController and used to update FormingSimulation. When the ShapeController converges, deformed_ipl.stl is read by EvaluateDimpling where it is compared to target.stl.

All components, except the FormingSimulation, are executed on a single UserMachine. The FormingSimulation however is implemented in ANSYS Workbench, which offers remote solver capabilities. It is therefore possible to execute it on an ANSYSCluster either local on the user machine or remotely on a solver cluster. Since this component is the most resource intensive, with runtimes of up to three hours per design, compared to a few seconds for all other components, this can be reasonable depending on the hardware configuration of the UserMachine.

![Figure 6-2 - UML component diagram of the virtual VAMM manufacturing framework](image-url)
Combined, the described modules create a modular and automated model of the VAMM process that is capable of optimising the tool configuration for an individual component, analyse dimpling for a variety of machine configurations and/or process parameters or predict the forming limits of a certain tool configuration for a variety of components.
6.2 Parametric Part Design

The VAMM process is intended to manufacture parts with freeform surfaces. In order to evaluate the influence of critical parameters describing these components, these parts are automatically created in the VAMM manufacturing model. Geometric primitives are simple, mathematically described geometric shapes like plates, spheres or saddles. They can be described with only a few parameters and are therefore well suited to study the influence of different geometric properties on the manufacturing process. The creation of such parts is implemented in the Geometry Evaluation Toolbox and used in the model in the create geometry module (see figure 6-1). This module creates 3D parts from these primitives based on a set of parameters. In a real world application of the VAMM system, this step would be replaced by the actual components that are to be manufactured on the system.

The 3D geometry data describing the parts is stored in the STL files format. An STL file represents a geometry as a closed triangulated surface of its outer shell. It consists of an unstructured list of triangular faces defined by a normal vector and vertices. It can be stored in both a human readable ASCII and a binary format [3D System Inc. 1989]. Figure 6-3 shows an example of an ASCII file created for a sphere with a radius of 180 mm. The file starts with the identifier solid followed by the file name and description. Subsequently, for each face, a normal and three vertices are stored in the format vertex x y z. With x, y and z being floating point numbers.

```
solid TARGETPART sphere_180 by Matthias Wimmer
facet normal 2.1276243E-02 2.5274528E-02 -9.9945420E-01
  outer loop
  vertex 2.6886530E+00 3.2880840E+00 4.1216553E+01
  vertex 3.7082162E+00 4.2795095E+00 4.12063329E+01
  vertex 2.7814512E+00 3.2099659E+00 4.1216553E+01
  endloop
endfacet
facet normal -5.1472329E-02 -6.6517773E-03 -9.9865228E-01
  outer loop
  vertex -7.0052705E+00 -1.0072058E+00 4.1323460E+01
  vertex -8.4360323E+00 -9.6794450E-01 4.1396942E+01
  vertex -7.0311751E+00 -8.0675220E-01 4.1323460E+01
  endloop
endfacet
.
.
endsolid
```

Figure 6-3 - STL file in ASCII format; first line defines a solid part, second line defines a face and its normal direction (calculated by the right-hand-rule), the following lines define the x-, y- and z-coordinates of the vertices
Virtualisation of the VAMM Process

Reading and writing these files is handled in the Geometry Evaluation Toolbox using a modified version of the stlTools toolbox. The target geometries are created as shell bodies within the model, in order to simplify the creation and evaluation of the 3D geometries.

The primitives implemented in the model are spherical segments and saddles. Spherical segments are defined by a radius, a chord length and an offset from the zero plane. A positive radius describes a convex spherical segment that is open to the bottom and a negative radius describes a concave segment that is open to the top. The geometry is described by

\[ z = \sqrt{r^2 - x^2 - y^2} + z_0 \]

\[ D = \{(x, y) \in \mathbb{R}^2 | x^2 + y^2 < a_c^2 \} \]

where \( r \) is the radius, \( a_c \) is the chord length and \( z_0 \) is the offset from the zero plane.

The saddle shape is defined by

\[ z = c_1 \ast (\cos(a \times) - \cos(b \times)) + z_0 \]

where \( c_1 \) defines the amplitude of the saddle, \( z_0 \) is the offset from the zero plane and \( a \) and \( b \) defining the size of the saddle according to

\[ a = \frac{2\pi}{l_x} \]

\[ b = \frac{2\pi}{l_y} \]

with \( l_x \) and \( l_y \) defining the period length of the saddle in x and y direction respectively.

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34 stlTools 1.1.0.0. Micó, P. MATLAB Central File Exchange
Depending on the primitive, the vertices for the desired geometry are calculated using the equations above. Delaunay triangulation [Delaunay 1934] is then used to create a mesh with triangular faces, as needed for the STL file format. Figure 6-4 shows examples of a convex hemispherical segment and a saddle geometry.
6.3 Initial Pin Configuration

The desired part defines the target shape of the tooling surface $S_*$. It is assumed, that this surface already accounts for necessary compensations for manufacturing process specific effects like warp and shrinkage. For this surface, the initial pin configuration $Z_0$ has to be calculated. This initial configuration is later used as a starting point to compensate shape error.

With ideally thin pins, the contact points would be aligned with the axes of the pins. With a finite pin sizes however, the geometry of the pin, as well as the interpolation layer have to be taken into account. In a first approximation, the IPL is considered incompressible. In this case, as shown in figure 6-5, the pins have tangential contact with the IPL. Depending on the target geometry, the contact point can be located anywhere on the hemispherical pin surface.

The coordinate $z_{i,0}$ for a pin $i$ is calculated in an iterative process. It calculates the remaining distance at a potential contact point, moves the pin towards the IPL according to the result and repeats the process until a residuum is reached.

\[
\frac{2}{\sqrt{3}} \cdot WS
\]

\[
\text{Figure 6-5 - Identifying the ideal contact point}
\]

In the first stage of the process, for each pin a relevant area on the target part is determined, in which the contact can be located. As established in chapter 4.4.1, the diameter of the pin tip corresponds to the diameter of the circumference radius of the pins hexagonal cross section $R = r_{ct}$. A defined contact of the interpolation layer and the pin can only take place in the curved part of the pin tip. The maximum adjustable pitch $\beta$ for a workpiece is the angle where a tangential contact is ensured all over the pin tip. It results from the shape of the pins themselves as shown in figure 6-6. The calculation of the angle $\beta$ is performed according to (37) - (38). As is evident from (37), the maximum pitch angle ultimately results from the hexagonal shape of the pins.
\[ \alpha = \cos^{-1}\left(\frac{a}{2 \cdot \frac{\sqrt{3}}{2}}\right) = \cos^{-1}\left(\frac{\sqrt{3}}{2}\right) = 30^\circ \]  

\[ \beta = 90^\circ - \alpha = 60^\circ \]  

The permissible points are located within a cone with the apex coincident with the centre of the pin tip radius as shown in figure 6-6. For each pin, these points are selected and then evaluated in the second stage.

In the second stage, all pins are set to the zero plane. From there, the minimal distance \( d_c \) of each pins pin tip centre to the respective, permissible contact area on the target part is calculated. As shown in figure 6-5, the distance between the target geometry and the pin-head centre, is the pin-head radius \( R \) plus the thickness of the IPL \( t_{IPL} \). Hence, subtracting these two from \( d_c \) gives the actual distance \( d \)

\[ d = d_c - (R + t_{IPL}) \]  

A new pin position \( z_{i,k} \) is then calculated by

\[ z_{(i,k)} = z_{i,k-1} + d \]  

This process is repeated \( k \) times until a residuum is reached. The resulting \( z \)-coordinate \( z_{i,k} \) is the initial height of this pin. Experiments show a residuum of 1.0E-6 mm to produce sufficiently accurate results in an acceptable computing time (under 60 seconds for the VAMM test bench).

The initial coordinates, together with the pin positions, are then saved to a file \texttt{InitialCoordinates.txt} (see figure 6-2). This file can be read by subsequent process steps or directly be transferred to the VAMM tool for manufacturing.
6.4 Finite Element Modelling of VAMM

Finite element analysis is used to evaluate the physical behaviour of VAMM in the manufacturing process and to simulate the deformation of the interpolation layer. Due to the computational complexity and computation time, simulations are conducted for the VAMM test bench and not the full-scale prototype. Due to the similar design of the two tools however, the results are considered valid for both. Numeric modelling and simulation is conducted using ANSYS Workbench\textsuperscript{35} simulation software. The simulations are conducted in the ANSYS Explicit Dynamics module using the Autodyn explicit solver module. Explicit finite element analysis is chosen in favour of an implicit scheme since it is well suited for the simulation of nonlinear structural mechanics applications involving large deformations and geometric nonlinearities, as well as complex contact conditions and complex material behaviour all occurring in the forming process of VAMM.

The test bench model consists of a hexagonal array of 37 hexagonal pins covered by an elastic interpolation layer. The interpolation layer is modelled parametrically to comprise of one or two layers with individual material properties. Each layer consists of an inner and an outer section. The parts to be created are hemispherical segments with opening to the top (negative radius) or bottom (positive radius) with the centre perpendicular to the tools centre axis. They are configured in the tool by the \(z\)-coordinates of the individual pins. Due to symmetry of the tool and the desired configurations, evaluating a quarter model (as shown in figure 6-7) is sufficient.\textsuperscript{36} For post processing however, a full model is needed. Hence, the results of this quarter model are mirrored before exporting the deformed geometry.

The pins, as well as the base plate, are modelled as shells. They are supported with fixed supports as shown in figure 6-7 in blue. The IPL is modelled as a solid. It is supported frictionless circumferentially and clamped between a lower and an upper tenter frame. At the beginning of the simulation, the upper frame moves 25\% of the IPLs thickness towards the lower frame using a remote displacement (yellow). This clamps the IPL tightly between the two frames. Subsequently, both frames move downwards until the IPL touches the base plate. Then, the process pressure is applied to the top surface of the IPL shown figure 6-7 in red.

Frictional contacts are defined between the IPL and each pin. Additional frictional contact pairs are defined between the IPL and the lower and upper tenter frame, as well as the IPL and the base plate. The friction coefficients for the IPL/pin pairs and all others are individually defined as variable parameters. The friction coefficient default is measured as described in appendix A - 5 and set to \(\mu = 0.328\). The contacts between

\textsuperscript{35} ANSYS Workbench 18.2. ANSYS Inc., Canonsburg, PA, USA.

\textsuperscript{36} Due to the symmetry, a sixth model would also be possible. However, the Autodyn solver only allows perpendicular symmetry planes.
the individual layers of the IPL are modelled as bonded contacts using a *Body Interaction* with a penalty formulation.

![Image](image.png)

*Figure 6-7 - VAMM model loads and supports; fixed supports (blue), remote displacements (yellow) and pressure load (red)*

The centre of the IPL (the area inside the tenter frame as shown in figure 6-7) is the main area of interest in this model since this is the actual tooling area used for manufacturing which is later evaluated for shape error and dimpling. It has to be meshed more finely than the rest of the model in order to reproduce the tooling surface adequately. Since the time step of the solver is directly influenced by the size of the smallest elements this refinement would drastically increase calculation time. In order to keep the time step to a sensible size, mass scaling is used to increase dynamically the mass of the smallest elements in the model. An initial investigation of the Eigenfrequencies of the system results in a minimum time step of \( \sim 1.8 \times 10^{-7} \) s. The target time step reached by the automatic mass scaling is supposed to be five to ten times this value [ANSYS Inc. 2017a] and is therefore set to \( 1.0 \times 10^{-6} \) s.

The simulation type is defined as quasi static. Loads are applied within 0.2 s and the model is set to run for another 0.2 s to allow for occurring oscillations to die away. In order to eliminate constant frequency oscillations, static dampening with a parameter value of \( 1.0 \times 10^{-4} \) proved to be sufficient.
The model is solved and the deformed interpolation layer is exported as an STL file using the update-script described in appendix B - 5 ANSYS Update.

### 6.4.1 Meshing

The model is meshed with linear elements. The default maximum face size is defined via a user defined *Physical Relevance* parameter\(^{37}\). Since stresses and other local effects are of no significant interest in the simulation, a low value of -60 is sufficient for mesh independent convergent results. This setting results in a maximum global face size of around 7.3 mm.

![FE mesh of the VAMM test bench model](image)

*Figure 6-8 - FE mesh of the VAMM test bench model*

The pins and the base plate are modelled as rigid shell bodies. The pins are meshed with a *MultiZone* method with 8,181 quadratic shell elements of type QUAD4 and triangular elements of type TRI3 using the *Pave* strategy. The general size is set to 0.6 times the global size (4.4 mm) with a proximity size function to create a finer mesh in the areas between the hemispheric pin head and pin side surfaces. These edges are critical since they are predominantly in contact with the IPL. Refinement in these areas is necessary to reduce penetration of these contacts. The base plate is refined to a general face size of 4.4 mm (0.6 times the global size) with additional refinement at the

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\(^{37}\) Detailed information on the meshing algorithms and settings can be found in the ANSYS Meshing User’s Guide [ANSYS Inc. 2017b].
outer edge to prevent contact penetration. Depending on the size of the IPL diameter, 450 - 850 shell elements are used for meshing the base plate.

The tenter frame is modelled as two solid bodies. These are meshed with hexagonal solid elements of type HEX 8 using the Sweep method. The general maximum face size is defined as 0.5 times the global setting (3.7 mm). The top frame is additionally refined at the fillet to 0.25 times the global size (1.8 mm) to create a sufficient contact area for the IPL. The lower and upper frames consist of 2,000-4,000 elements each, depending on the IPL diameter.

The IPL is meshed using the MultiZone method with hexahedral elements of type HEX8 using the Pave strategy. The size of the central area of the IPL is set to 0.35 times the maximum global face size (2.6 mm) with a uniform size function. Figure 6-9 shows the results of a convergence study conducted on the model. The maximum principal stress and strain maxima in the centre of IPL top surface are used as convergence indicators.38 Both indicators converge to a boundary value at a mesh size of 3.2 mm. The chosen size of 2.6 mm is well within the 5 % convergence interval and is therefore considered a sufficient compromise between model accuracy and calculation time.

![Figure 6-9](image)

*Figure 6-9 - Maximum principal stress and strain maxima in the center of IPL top surface depending on mesh size; the dotted lines show the 5 % convergence intervals*

The outer ring is meshed with the global face size. This area has no significant influence on the evaluated area and only serves as load introduction in the inner tooling

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38 Even though this model is focused on the deformation of the IPL, the maximum principal stress and strain are more sensitive to meshing and are therefore considered adequate indicators for mesh convergence.
area. Mesh resolution and model accuracy are therefore of subordinate importance in this area.

The number of nodes and elements are compiled in table 6-1, for the illustration model shown in figure 6-8 with a three layer IPL and a diameter of 268 mm at a total thickness of 27.3 mm. With this mesh configuration, the model has a runtime of approximately 52 minutes on a workstation with an Intel Xeon CPU E5-2630@2.40 GHz (6 cores) and 32 GB of RAM running Windows 10. For other IPL configurations, this can however increase up to 120 minutes and more.

Table 6-1 - Number of Nodes and Elements in the VAMM test bench model

<table>
<thead>
<tr>
<th>Part</th>
<th>Nodes</th>
<th>Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tenter Frame Top</td>
<td>5,452*</td>
<td>2,541*</td>
</tr>
<tr>
<td>Tenter Frame Bottom</td>
<td>3,760*</td>
<td>2,511*</td>
</tr>
<tr>
<td>Pins</td>
<td>8,493</td>
<td>8,181</td>
</tr>
<tr>
<td>Base Plate</td>
<td>738*</td>
<td>675*</td>
</tr>
<tr>
<td>IPL</td>
<td>38,878*</td>
<td>29,777*</td>
</tr>
</tbody>
</table>

*values vary depending on model parameters

6.4.2 Material Modelling

Two different kinds of materials are used in the model. The pins, tenter frame and base plate are modelled as isotropic linear elastic steel with a Young’s Modulus of 200,000 MPa, a Poisson’s ratio of 0.3 and a density of 7,850 kg/m³. The IPL is made from a rubber material, which is strongly deformed during the forming process. As described in chapter 4, four rubber sheet materials are available to be used in the IPL: translucent and red silicone rubbers from GaFa-Tec, both with a nominal hardness of 40 Shore A and 60 Shore A, respectively (see appendix C - 1). They are modelled using the Mooney-Rivlin hyperelastic material model with three parameters. This model is well suited for non- to lightly filled rubber compounds and strains of up to 150%. Preliminary tests show, that this strain value is not reached in the model.

The Mooney-Rivlin material model describes the strain energy potential $\Psi$ as a series in terms of the first and second deviatoric principal invariants $\tilde{I}_1$ and $\tilde{I}_2$

$$\Psi = C_{10}(\tilde{I}_1 - 3) + C_{01}(\tilde{I}_2 - 3) + C_{11}(\tilde{I}_1 - 3)(\tilde{I}_2 - 3) + \frac{1}{d}(J - 1)$$  \hspace{1cm} (41)

where $C_{10}$, $C_{01}$ and $C_{11}$ are empirically determined phenomenological material constants and $d$ is the material incompressibility parameter. The initial shear modulus $\mu$ is defined as

$$\mu = 2(C_{10} + C_{01})$$  \hspace{1cm} (42)
and the initial bulk modulus $K$ is defined as

$$K = \frac{2}{d}$$  \hspace{1cm} (43)

In order to calibrate the material model, uniaxial test data are not sufficient. When only using uniaxial test data, the model can have a low predictive quality in multiaxial load cases [British Standards 2004]. For the Money-Rivlin material model, at least one more test is needed, describing the second invariant. In order to model the material precisely, equibiaxial tension tests and pure shear tests are conducted, additionally to uniaxial tension test.

The tests are conducted on a Galdabini\textsuperscript{39} Quasar 2.5 tensile testing machine, with a maximum tensile force of 2.5 kN. The tensile forces are measured using a calibrated 3 kN load cell of type Galdabini TSTM. The strain is recorded using a Galdabini Microplast extensometer. For the equibiaxial tension tests, the Aramis 5M grey scale digital image correlation (DIC) system by GOM\textsuperscript{40} is used. It features two cameras with a CCD image sensor and a resolution of 2,448 x 2,050 pixels. The maximum acquisition frequency is 15 Hz, and 29 Hz with enabled data binning. Titanar 2.8/50 lenses with a focal distance of 50 mm are used for the tests. The system is calibrated using a calibration cube CP 20 / MV 55 x 44 mm$^2$.

According to ISO 4664 [ISO International Organization for Standardization 2011] all tests are performed after six load cycles to the desired strain value. This initial conditioning is performed to minimise the influence of the previously described Mullins effect.

\textit{Uniaxial Testing}

Uniaxial testing of the rubber specimen is conducted according to BS ISO 37 [British Standards 2017]. Instead of the dumbbell test piece however, a parallel sided strip is used as specified in BS 903-5 [British Standards 2004]. The specimens used are 150 mm x 10 mm with a thickness of 5.0 mm. For preconditioning, the specimens are extended to 100 % strain with a strain rate of 300 mm/min and then unloaded to a load of 2.0 N. This procedure is repeated ten times. Subsequently, a pre-force of 2.0 N is applied and the extensometer is connected to the specimen. The measurement is then conducted with a strain rate of 300 mm/min until material failure.

\textit{Pure Shear Testing}

Pure shear tests of the rubber specimen are conducted based on BS 903-5 [British Standards 2004]. A rubber strip with a width of 150 mm and a height of 110 mm are clamped along the width and then strained. The specimen is glued in the fixture at the

\textsuperscript{39} Galdabini SPA, Cardano al Campo (VA), Italy

\textsuperscript{40} GOM GmbH, Braunschweig, Germany
top and bottom and clamped additionally. The resulting free test area is 150 mm x 30 mm. This is in agreement with BS 903-5 which specifies a width to height ratio of at least 1/5. The specimens are strained five times to 100 % strain at a strain rate of 100 mm/min. During preconditioning, the fixture clamping force is adapted after each repetition to prevent slippage. Afterwards, a pretension of 2.0 N is applied and subsequently the stress-strain measurement is conducted up to 100 % strain at a strain rate of 100 mm/min.

**Biaxial Testing**

Equibiaxial tension tests are conducted on a purpose built test rig [Wimmer et al. 2019] on the universal tensile test machine. Slotted cross-shaped test specimens with a total size of 105 mm x 105 mm and a thickness of 5 mm are used. Each of the four arms of the cross is 40 mm x 25 mm, with five slots of 30 mm x 2 mm each, resulting in a specimen centre of 25 mm x 25 mm. DIC requires a random grey-scale value pattern on the evaluation area of the specimen. For the red silicon rubber applying the pattern with white spray coating is sufficient. The translucent silicon rubber has to be primed first with a layer of white acrylic coating and subsequently sprayed with black acrylic spray coating. The tests are then performed with a nearly dried coating to allow displacement of the speckles while avoiding cracks of the coating.

The measurements and the initial conditioning are performed after the specimen is centred between the four fixtures by pre-straining each side with the fixture’s adjusting mechanism. A small tensile load (2.5 N) is applied on each side to ensure an even load distribution over all teeth of the comb fixtures. The specimens are then stretched 120 mm, with a strain rate of 60 mm/minute, for five times. The test is then conducted with the same configuration. The displacement of the specimen centre is recorded with the ARAMIS system and stresses are calculated as described in Wimmer et al. [2019].

For each material, five specimen are tested and a mean stress - strain curve is evaluated. Figure 6-10 shows the resulting stress - strain curves of the uniaxial, pure shear and equibiaxial tensile tests for the red silicone materials. The translucent silicone materials are shown in figure 6-11.
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**Figure 6-10** - Stress-strain curves of red silicon rubbers, left: soft with 40ShA, right: hard with 60ShA

![Stress-strain curves of red silicon rubbers](image)

**Figure 6-11** - Stress-strain curves of translucent silicon rubbers, left: soft with 40ShA, right: hard with 60ShA

![Stress-strain curves of translucent silicon rubbers](image)

Using the ANSYS Workbench curve fitting capabilities, the Money-Rivlin-3 parameters are fitted to the respective measured stress-strain curves. The resulting parameters used in the FE model are compiled in table 6-2.

**Table 6-2** - Mooney-Rivlin (3 parameters) material constants of elastomers used

<table>
<thead>
<tr>
<th>Material</th>
<th>C10</th>
<th>C01</th>
<th>C11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon Rubber red 40ShA</td>
<td>0.20675</td>
<td>0.02625</td>
<td>0.00309</td>
</tr>
<tr>
<td>Silicon Rubber red 60ShA</td>
<td>0.20356</td>
<td>0.11279</td>
<td>0.00205</td>
</tr>
<tr>
<td>Silicon Rubber translucent 40ShA</td>
<td>0.15575</td>
<td>0.05350</td>
<td>0.00242</td>
</tr>
<tr>
<td>Silicon Rubber translucent 60ShA</td>
<td>0.26413</td>
<td>0.13673</td>
<td>0.00097</td>
</tr>
</tbody>
</table>
6.4.3 Model Evaluation

In order to validate the model, the deformed interpolation layer from the simulation is compared to 3D scans of the physical system. The test setup used for measuring the physically deformed IPL is shown in figure 6-12. Three designs are analysed using this setup:

1. a convex hemispherical segment $S_{t1}$ with radius $r = 219.3\, mm$ and offset $z_o = 100\, mm$, with a translucent 60 ShA silicone rubber IPL (see chapter 4.5), with thickness $t = 2\, mm$,

2. a concave hemispherical segment $S_{t2}$ with radius $r = -219.3\, mm$ and offset $z_o = 100\, mm$, with a translucent 60 ShA silicone rubber IPL, with thickness $t = 2\, mm$, and

3. a concave hemispherical segment $S_{t3}$ with radius $r = -219.3\, mm$ and offset $z_o = 100\, mm$, with a dual layer IPL, with a layer of translucent 40 ShA silicone rubber, with thickness $t = 5\, mm$ at the bottom and a translucent 60 ShA silicone rubber, with thickness $t = 5\, mm$ on top.

Figure 6-12 - Model validation test setup
The IPL is deformed using a membrane vacuum pump of type Vacuubrand\textsuperscript{41} MZ 2C with a pump volume of 1.7 m\textsuperscript{3}/h. The vacuum in the VAMM tool is set to at 600 mbar with an allowed delta of ±20 mbar. It is controlled using a Vacuubrand CVC24 vacuum controller. The tooling surface is measured using a structured light 3D scanner DAVID\textsuperscript{42} SLS 2. This scanner uses a 1.3 megapixel (1,280 x 960) camera with a frame rate of 25 Hz and a projector with a resolution of 1,280 x 800 at 500 ANSI Lumen. It has a maximum scan size of 500 mm and a maximum precision between ±0.15 mm (absolute; at ideal viewing angle and with a matt surface) and ±0.5 mm.

The resulting physical tooling surfaces $S_{mi}$ are then measured. Therefore, the deformed interpolation layers are scanned resulting in a point cloud. This point cloud is converted into a closed surface geometry and saved as an STL file, using the software MESHLAB\textsuperscript{43}. The result for the convex geometry of design (1) is shown in figure 6-13.

![Figure 6-13 - Deformed interpolation layer (ShA 60, 2,0 mm) scanned using David SLS2 and processed in MESHLAB](image)

Each design is also simulated using the FE model. The virtually deformed IPLs $S_{fi}$ are exported as STL files and compared to the corresponding measured geometries. This comparison is conducted using the software GOM Correlate\textsuperscript{44} applying a method developed by Hellmer [2015]. The error between the virtual tooling surface $S_f$ and the physical tooling surface $S_m$ are evaluated for each of the three designs $i$. Then, the mean error $\mu$ over the whole tooling surface, and the standard deviation $\sigma$ are calculated. The results are compiled in table 6-3.

It shows that the mean error between the target geometry calculated using FEA and the actual geometry for designs 1 and 3 are in the same order of magnitude as the

\textsuperscript{41} Vacuubrand GmbH & Co KG, Wertheim, Germany

\textsuperscript{42} HP Development Company, Palo Alto, California, USA

\textsuperscript{43} MeshLab 2016. National Research Council (Italy) (CNR).

\textsuperscript{44} GOM Inspect. GOM GmbH, Braunschweig.
measurement precision of the camera system. The errors are therefore considered negligible. For design 2 however, the mean error is several times larger. The experiments were conducted in the given order, with the second experiment conducted shortly after the first. The IPL was not changed between the two experiments. It is assumed that the deformation of the material after the first experiment was not fully reversed. This effect however is not reproduced by the FE model. In order to produce reliable results, it is therefore recommended to ensure the use of an undeformed or fully relaxed IPL.

<table>
<thead>
<tr>
<th>design</th>
<th>target geometry</th>
<th>IPL configuration</th>
<th>mean error $\mu$ [mm]</th>
<th>standard deviation $\sigma$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$S_{t1}$</td>
<td>1 layer, translucent 60 ShA, 2mm</td>
<td>0.05</td>
<td>0.12</td>
</tr>
<tr>
<td>2</td>
<td>$S_{t2}$</td>
<td>1 layer, translucent 60 ShA, 2mm</td>
<td>0.85</td>
<td>0.26</td>
</tr>
<tr>
<td>3</td>
<td>$S_{t3}$</td>
<td>2 layers, translucent 40 ShA and 60 ShA, 5mm each</td>
<td>0.15</td>
<td>0.53</td>
</tr>
</tbody>
</table>

In summary, the accuracy of the model is considered appropriate for the intended use. The model shows good agreement of the deformation with the measured surfaces, within the bounds of the measurement accuracy. However, effects not contained in the model, such as load sequences, cannot be reproduced. Instead, they must be excluded during the operation of the physical system.
6.5 Shape Error Evaluation

Shape error is the deviation of the tooling surface to the target geometry in vertical direction. This definition is most useful, since the shape error is to be compensated in the next step and this is done by readjusting the pins in the same direction. In order to evaluate this error, the tooling surface $S_f$ produced by the forming simulation is compared to the target geometry $S_t$ and the distance over the whole area of interest $\Delta z_A$ between the two is evaluated for each vertex of the tooling surface.

$$\Delta z_A = S_t - S_f$$  \hspace{1cm} (44)

For each pin then, the relevant vertices are selected and the shape error for this pin $\Delta z_i$ is determined.

In a first step, the vertical distance of each vertex of the deformed IPL to the target geometry is evaluated. For this vector-based distance calculations, a modified MATLAB version\textsuperscript{45} of the open-source collision detection library OPCODE\textsuperscript{46} is used. It utilises Axis Aligned Bounding Boxes (AABB) for collision detection. An AABB is a box wrapping an object in a way that its surface (2D) or volume (3D) is minimal. For each axis, two separating planes are defined, one touching the object in its minimum dimension and one in its maximum dimension. In 2D space, this results in a rectangle, in 3D space in a cuboid. Figure 6-14 shows two examples of 2D AABBs for different objects.

![Figure 6-14 - 2D Axis Aligned Bounding Box (AABB) of a star and a rectangle (red)](image)

The ray-AABB-intersection method from the OPCODE library calculates the distances from a point of origin to a target geometry along a defined vector. In a first step, this algorithm checks if the ray hits a certain AABB. If so, in a second step a more detailed verification checks whether the wrapped object is also intersected. The Euclidean norm between the resulting intersection point $p_f$ and the point of origin $p_0$.


\textsuperscript{46} OPCODE. Optimized Collision Detection 1.3. PIERRE TERDIMAN http://www.codercorner.com/Opcod.htm.
\[ \|d\|_2 = \sqrt{p_0^2 + p_i^2} \]  

(45)
gives the desired distance at \( p_0 \). The application of this algorithm for the calculation of the distance between the actual geometry and the target geometry is shown in figure 6-15. An AABB is constructed around each face of the target mesh. In the first step, only AABBs are selected that are intersected by the ray. In the next step, the corresponding faces are checked for intersection. When an intersection point is found, the resulting distance is evaluated.

In order to calculate the shape error over the whole region of interest, rays are cast in \([0 \ 0 \ 1]\) direction to evaluate the distance \( \Delta z_+ \) in positive \( z \) direction. In case the two surfaces permeate each other, the target surface however can be below the tooling surface. Therefore, the distance \( \Delta z_- \) in negative \( z \) direction \([0 \ 0 \ -1]\) is also evaluated. Together, the positive and negative distances give the areal shape error \( \Delta z_A \) between the two surfaces:

\[ \Delta z_A = \Delta z_+ \cup \Delta z_- \]  

(46)

Figure 6-16 shows this shape error for an example interpolation layer.
Then, for each pin \( i \) the relevant vertices in a hexagon with a width \( A/F \)

\[
a_{\text{eval}} = a + t_{\text{IPL}}
\]

are selected from \( \Delta z_+ \) and \( \Delta z_- \). From the resulting \( \Delta z_{i,+} \) and \( \Delta z_{i,-} \), the shape error is evaluated depending on the permeation state of the two surfaces:

- When the tooling surface is fully below the target surface in the evaluated area around the pin, the specific shape error for this pin is
  \[
  \Delta z_i = \min(\Delta z_{i,+})
  \]

- When the tooling surface is fully above the target surface or permeates the target surface, the specific shape error for this pin is
  \[
  \Delta z_i = \min(\Delta z_{i,-})
  \]

This results in one distinct error value \( \Delta z_i \) for each pin. The shape error for the full tool \( \Delta z \) is then

\[
\Delta z = \begin{pmatrix}
\Delta z_1 \\
\vdots \\
\Delta z_i \\
\end{pmatrix}
\]

This value is subsequently used to readjust the pin array in order to minimise the shape error.

In order to compare different configurations, a global shape error parameter would be desirable. As stated in chapter 2.3.1 the use of a global RMS and AVAB for a global evaluation of the shape error is possible but not very meaningful since it also incorporates dimpling.
On the other hand, RMS and AM values which only considering one value per pin, do not include dimpling that may occur. Instead, these values give a good impression of the actual shape error. The root mean square error $e_{RMS}$ thereby is defined as

$$e_{RMS} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \Delta z_i^2}$$  \hfill (51)

and the absolute maximum error $e_{AM}$ as

$$e_{AM} = |max(\Delta z_i)|$$  \hfill (52)
6.6 Shape Error Compensation

Based on the closed loop shape controllers discussed in chapter 2.4, an advanced shape control algorithm is implemented in the VAMM process. The flowchart in figure 6-17 shows the algorithm used for the shape error compensation. Starting from the target geometry (the desired part), the initial pin coordinates are calculated as explained in chapter 6.3. The resulting tool configuration is used as a starting point for an iterative numeric optimisation of the pin positions. Therefore, the system response for the initial configuration is calculated. The local deviation between the simulated IPL and the target geometry is evaluated for each pin, and an updated pin configuration is calculated and fed back to the numeric model. This process is repeated until the predefined convergence criteria are fulfilled.

The shape error compensation works as follows: Starting with the initial configuration \( Z_0 \), the forming simulation produces the tooling surface \( S_0 \). For this surface, the shape error \( \Delta z \) is calculated. With this, a new pin configuration \( Z_{k+1} \) is then calculated based on Liu et al. [2010b] with

\[
Z_{k+1} = Z_k + C \Delta z
\]

(53)
The factor \( \mathbf{C} \) is a correction coefficient matrix that can be used to optimise the convergence behaviour of the shape controller. In case of this matrix being an identity matrix, the algorithm is reduced to

\[
\mathbf{Z}_{k+1} = \mathbf{Z}_k + \Delta \mathbf{z}
\]

This procedure is repeated until the convergence criteria for shape error parameters \( e_{RMS} \) and \( e_{AM} \) are satisfied.

Figure 6-18 shows the shape error compensation on an example design. In the first iteration with initial pin coordinates, errors of up to 7.64 mm occur in the tooling area. This maximum error is reduced to 1.01 mm in the second iteration and to 0.46 mm in the third iteration.

![Figure 6-18 - Progress of the shape error compensation on an example design over three iterations](image)

Figure 6-19 shows the convergence behaviour of the shape controller of two interpolation layers with 10 mm and 20 mm thickness. The target geometry in this case is a hemispheric segment with a radius of 400 mm. For the 10 mm IPL, the initial pin configuration was calculated using the proposed algorithm. For the 20 mm IPL, the initial configuration however is deliberately poorly conditioned with an offset of 10 mm. It shows that the shape controller converges to similar precisions within four iterations. The performance of the controller is comparable to other shape control algorithms (see chapter 2.4). After one (10 mm) and two (20 mm) iterations respectively the shape error is reduced to:

\[
e_{RMS} < 0.25 \text{ mm}
\]

\[
e_{AM} < 0.5 \text{ mm}
\]

These threshold values are similar to comparable solutions from literature and are subsequently adopted.
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The noise in the convergence history (figure 6-19 and figure 6-20) results from the mesh resolution in the FE analysis and the linear interpolation. Changes in mesh size however do not have a profound effect on the convergence behaviour. Figure 6-20 shows that an increase in global mesh size (from the initial 7.3 mm, as described in chapter 6.4.1) leads to slightly higher noise (2x) and even failure in convergence of the FE analysis (4x), after four iterations. A decrease on the other hand does not improve the convergence behaviour significantly. It can therefore be concluded, that the defined mesh size leads to a sufficiently stable convergence behaviour of the shape controller.
For some geometries, the shape controller cannot converge, as they exceed the capabilities of the VAMM tool. When the contact between the IPL and a pin is not established after applying the process loads, then readjusting this pin has no effect and the shape error in this area cannot be reduced. This happens predominantly with concave geometries. In such cases, the IPL cannot deform sufficiently under the applied load. The inner pins of a concave section do not have contact with the IPL. Instead, the IPL is spanned over them only contacting the outer pins. Readjusting the inner pins then has no effect and the shape controller cannot reach a termination threshold. In this case, the geometry exceeds the manufacturing limit.

To reduce unnecessary calculation time in the shape controller, by recalculating iterations that do not improve the shape accuracy, a contact detection algorithm (see figure 6-21) is implemented in the shape controller. The contact forces in the vertical direction on each pin are evaluated in the forming simulation. The maximum value

$$\text{maximum contact force } z_i = \max(|\text{contact force } z_i|)$$  \hspace{1cm} (55)

for each pin $i$ is then exported as a system response. From all the contact forces, the contact status is calculated to evaluate the contact status using

$$\text{contact status} = \min(\text{maximum contact force } z_i)$$  \hspace{1cm} (56)

If this contact status is below a contact status threshold, at least one pin is not in contact with the IPL. Since reconfiguration under these circumstances does not have the desired effect, the shape controller is terminated and the target geometry has to be considered non-producible with the specific VAMM tool. A contact status threshold of $0.01 \, N$ proved to be sufficient to detect contact reliably while not being susceptible for numeric noise.

![Figure 6-21 - Contact detection algorithm implemented in the shape controller](image-url)

The shape controller is implemented in OptiSLang using the software’s custom algorithm functionality. A detailed description of the implementation is compiled in
appendix B - 4. The controller uses the ANSYS model described in chapter 6.4 to evaluate the physical response of the VAMM tool and the shape error evaluation, described in chapter 6.5, to evaluate the remaining shape error for each individual pin. The ANSYS model is executed via an update script. This script handles data storage, changes the materials of the individual layers of the interpolation layer, controls the update of the forming simulation and exports the deformed geometry, as well as images for preprocessing. It is described in detail in appendix B - 5 ANSYS Update.
6.7 Dimpling Evaluation

Dimpling is the most critical system immanent defect in multipoint tooling. As already discussed in chapter 2.3.2 it is defined as the local deviation around each individual pin resulting from the discontinuously supported tooling surface. This error is considered a consequence of the combination of process parameters and an insufficient interpolation. Since there is no established method for measuring this dimpling in multipoint moulding, four different methods for quantifying are proposed in this chapter.

The shape control algorithm discussed in the previous chapter can suppress shape error sufficiently. After the compensation, the actual tool shape is therefore assumed to represent the target shape at one point per pin at least. Dimpling consequently is considered a function of the remaining distance between the target surface and the compensated actual tooling surface. For freeform surfaces however, there is no conclusive definition of distance. Hence, to evaluate dimpling, first a definition of distance has to be established. Therefore, four different distance evaluation methods are developed and implemented. From these, a one-dimensional dimpling parameter can then be derived.

The distance between two freeform surfaces can be evaluated in various ways. In metrology, the evaluation of minimal and orthogonal distances is well established [Jiang et al. 2010]. In MPT, due to the vertical re-adjustability of the tool, the vertical distance has also been used [Liu et al. 2016]. Figure 6-22 shows these three definitions of distance between the actual tool surface and the target part surface. The hatched area no. 4 in the figure describes the volume between the two geometries that is proposed as an additional new measure for dimpling.

![Figure 6-22 - Different ways to evaluate distance between freeform surfaces on different points of the geometry](image-url)

1: vertical distance, 2: orthogonal distance, 3: minimal distance, 4: volume between surfaces
Along the entire process chain, geometries are handled in the STL file format that represents 3D geometries as triangular meshes. The evaluation of distances and dimpling is therefore also conducted on this mesh basis.

The orthogonal and vertical distance methods can be clustered as vectorial distances, as they measure distance along a predefined direction or vector. Evaluation therefore is very similar. This leads to three distinct classes of distances:

- **Minimal distance**
- **Vectorial distance**
  - Orthogonal distance
  - Vertical distance
- **Volume between geometries**

The evaluation thereby always takes place from the actual geometry to the target geometry.

### 6.7.1 Minimal Distance

The *minimal distance* is defined over the whole surfaces of the actual geometry as the shortest distance of each point to the target surface. It is calculated for each vertex of the actual surface. The algorithm is based on the `distanceVertex2Mesh` algorithm that calculates the distance from one or many vertices, to the surface of a 3D object identified by a mesh. The algorithm calculates the distance of a vertex to a given mesh in three steps:

1. Vertex-to-Vertex
2. Vertex-to-Edge
3. Vertex-to-Face

In the first step, the vertex-to-vertex distance is calculated using a nearest neighbour search algorithm utilising a k-D-tree. This tree is a binary data structure for storing k-dimensional data. The data points are separated along a plane perpendicular to the separating dimension. This separation plane is placed through a random data point on the corresponding dimension. [Bentley 1975] This leads to a different number of data points on both sides of this plane, which is why this kind of k-D–trees are called unbalanced. When the separating plane is placed at the geometric mean of the data points in the distinct dimension, as shown in figure 6-23, the k-D–tree is called balanced. This balanced tree needs fewer separating planes than an unbalanced tree ultimately increasing search speed [Friedman et al. 1977].

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For the evaluation of the minimal distances between the actual and target geometries, a balanced 3-d-tree containing the vertex coordinates is used. The minimal distance of every vertex of the actual geometry to the mesh of the target geometry is evaluated using a nearest neighbour search algorithm. To look for the nearest neighbour of a given vertex (e.g. the star in figure 6-23 (left)) this algorithm searches the corresponding k-D-tree (figure 6-23 (right)) from top to bottom for the point with the smallest distance. In point A the distances of the star to points B and C are compared. The search is then continued in the branch with the smaller distance. When all successor points have a larger distance to the given vertex then the current point itself, it is the nearest neighbour and the search is complete.

Due to the triangulation of the target geometry however, the nearest neighbour vertex is not necessarily the nearest point on the geometry (compare figure 6-24 (left)). The minimal distance can also occur as vertex-to-edge or vertex-to-face distance. Hence, in the subsequent steps all adjoining edges and faces of the nearest neighbour are determined. Subsequently for each edge and face, the vertex-to-edge or vertex-to-face distances respectively are calculated. The smallest of the three distances is then the minimal distance $d_{min}$ for the given vertex.
6.7.2 Vectorial Distances

Distances between two freeform surfaces can also be evaluated along a predefined direction. Therefore, the intersection of a vector with the target surfaces is calculated. For the evaluation of dimpling, two such measures are examined: the orthogonal distance from the actual geometry to the target geometry, as shown in figure 6-22 (2), and the vertical distance between the two geometries (from actual to target), as shown in figure 6-22 (3). For these vector-based distance calculations, as for the shape error evaluation, the MATLAB toolbox OPCODE is used (see chapter 6.5).

**Orthogonal Distance**

The orthogonal distance is defined as the distance of the target surface to the actual surface orthogonal to the latter. It is determined for each triangular face of the actual geometry originating from its centroid. The concept is shown in 2D in figure 6-25. The normal vector \( \mathbf{n} \) for each face is calculated using

\[
\mathbf{n} = \overrightarrow{\mathbf{p}_1\mathbf{p}_2} \times \overrightarrow{\mathbf{p}_1\mathbf{p}_3}
\]  

(57)

The centroid of the triangle is used as the point of origin for the ray casting. For a triangle \( \mathbf{p}_1\mathbf{p}_2\mathbf{p}_3 \) it is defined as

\[
\mathbf{c} = \frac{1}{3} (\mathbf{p}_1 + \mathbf{p}_2 + \mathbf{p}_3)
\]  

(58)

The OPCODE library is then used to calculate the distances between each face of the actual geometry to the target geometry.

![Figure 6-25 - Orthogonal distance from actual to target geometry originating from centroids of the actual geometries face](http://www.codercorner.com/Opcode.htm)
**Vertical Distance**

The vertical distance is defined as the distance from the vertices of the actual surface to the target surface in $[0 \ 1]$ direction (2D) or $[0 \ 0 \ 1]$ direction (3D) respectively [Liu et al. 2012]. The evaluation procedure is shown in figure 6-26.

![Figure 6-26 - Vertical distance from actual to target geometry](image)

Similar to the orthogonal distance calculation, the vertical distance is calculated using the OPTCODE library. The individual vertices are used as the points of origin. The search vector is the vertical unit vector in upward and downward direction $[0 \ 0 \ \pm 1]$.

**6.7.3 Volume between Surfaces**

Another way to measure distance between two surfaces is the volume they enclose. This volume is zero if the geometries align perfectly and rises, the more they differentiate. In order to compare different geometries and parts however, the projected area of the part also has to be taken into account to create a generalised and part independent parameter.

As shown in figure 6-27, initially a vertical distance $d_z$ (indicated by the green arrows) is evaluated for each face $i$ of the actual geometry. Other than the vertical distance parameter in the previous chapter, here the centroids (blue dots) are used as points of origin.

For each triangular face $p_1p_2p_3$ with $p = [x \ y \ z]'$ a projected area $A_i^*$ is calculated by ignoring the $z$-coordinates of the points and using the determinant formula for calculating the surface area of 2D triangles.
\[ A_i^* = \frac{1}{2} \left| \det \begin{pmatrix} x_1 & x_2 & x_3 \\ y_1 & y_2 & y_3 \\ 1 & 1 & 1 \end{pmatrix} \right| \]  \hfill (59)

**Figure 6-27 - Volume between surfaces: for each centroid, a vertical distance is calculated and multiplied with the projected surface of the face**

With this an approximate volume for each face is calculated using

\[ V_i = d_x * A_i^* \]  \hfill (60)

The total projected area \( A^* \) is then calculated summing up all \( k \) projected areas

\[ A^* = \sum_{i=0}^{k} A_i^* \]  \hfill (61)

The total volume between the two geometries is

\[ V = \sum_{i=0}^{k} V_i \]  \hfill (62)
6.7.4 Dimpling Parameters

Based on the definitions of distance, a one-dimensional dimpling parameter can be established. This parameter can then be used as a measure of part quality. This parameter has to be independent of the parts size and area, as well as independent of the actual freeform geometry of the part in order to be universal. For the planar distance measures, the root mean square over all measuring points fulfils these requirements. For the minimum distance, this gives a dimpling parameter

\[
D_{\text{min}} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} d_{\text{min},i}^2}
\]  

(63)

For the orthogonal distance the dimpling parameter is defined as

\[
D_{\text{orth}} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} d_{\text{orth},i}^2}
\]  

(64)

and for the vertical distance it is defined as

\[
D_{\text{vert}} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} d_{\text{vert},i}^2}
\]  

(65)

The volume between surfaces, as defined in chapter 6.7.3, is dependent of the size of the geometry evaluated. In order to make the volumetric parameter independent of the part size, the surface normalised volumetric distance parameter \(D_{\text{vol}}\) is defined as

\[
D_{\text{vol}} = \frac{V}{A^*}
\]  

(66)

where \(A^*\) is the evaluated area. This parameter represents the volume between the two surfaces per area.

All four parameters describe the severity of dimpling in [mm].
6.7.5 Comparison of Dimpling Evaluation Methods

In the previous chapter, four dimpling parameters were established. In order to choose one parameter, it is essential to know the behaviour of the different parameters for different geometries. A study of two hundred spherical segments, with different interpolation layers, is conducted in order to evaluate and compare the four dimpling parameters. Figure 6-28 shows the correlation of the different dimpling parameters for these 200 designs. It shows that all four parameters are linear dependent. Linear regression is used to create linear predictor function. For each, the coefficient of determination $R^2$ is calculated. The closer this value is to one, the better the linear regression fits the approximated data. For the dependencies between dimpling parameters, this value ranges between 0.986 and 0.994. This implies that each dimpling parameter can reliably be converted in any other using the conversion factors shown in the figure.

![Figure 6-28 - Correlation of dimpling parameters with regression lines](image)

The decision for or against a particular dimpling factor can therefore be considered a matter of choice. In this work however, the minimum measure $D_{min}$ will subsequently be used to measure dimpling. It is least sensitive to flaws in the evaluation software and produces the most reproducible results.
6.8 Summary

In this chapter, a virtual model for predicting, quantifying and optimising the VAMM system behaviour was developed and implemented. This modular model incorporates the complete manufacturing process from part design over manufacturing, to quality control. The modular architecture of the VAMM manufacturing model is introduced and the interaction of the individual modules is defined.

- A parametric part design module at the beginning of the process chain can create geometric primitives based on a set of parameters.
- A module for evaluating initial pin configuration for the VAMM tool was developed. It can handle the created primitives from the previous module, as well as general CAD data. The initial pin configuration can be transferred to either the VAMM system or the VAMM model.
- A finite element model of the manufacturing process on the VAMM test bench is used to predict the tools behaviour. A convergence study was conducted in order to ensure correct discretisation of the tool. The rubber materials for the interpolation layer were tested in uniaxial tension, pure shear and biaxial tension in order to model adequately the material behaviour of that critical component. 3D scans of the actual tool were conducted and compared to the results of the model. The model is in good agreement with the real system, as long as no additional effects, like load sequences, are applied.
- A module for evaluating shape error was developed and implemented. The shape error is evaluated using the deviation in vertical direction between a target shape \( S_t \) and the actual shape of the tooling \( S_f \). For each pin a characteristic value is determined, which indicates the deviation to be corrected. In order to obtain one characteristic dimpling value for a given tool configuration the RMS and AM errors \( e_{RMS} \) and \( e_{AM} \) as are proposed. They are calculated using the pin-wise shape error. This methodology provides the global and local shape error metrics required to answer question Q3.1.
- A shape controller module compensates the shape error by creating new pin configurations in an automated iterative process. The control algorithm implemented is based on Liu et al. [2010b] and enhanced with VAMM specific termination criteria. The threshold values for acceptable shape error are to be 0.25 mm for the \( e_{RMS} \) and 0.5 mm for \( e_{AM} \). With these, it has been shown, that when physically possible, this controller can effectively eliminate the shape error within two to four iterations. The capabilities of the controller are proven by effectively compensating the shape error in 200 different VAMM configurations as shown in chapter 6.7.5. This approach is therefore considered an appropriate solution for Q3.2.
- An evaluation module assesses the expected part quality by means of dimpling severity. Four dimpling parameters were proposed in order to evaluate the
severity of this dimpling. Evaluation of two hundred different designs shows, with a high coefficient of determination, that these four parameters are linear dependent. This shows, that each of the proposed measuring methods is equally suitable to give a meaningful impression of the severity of dimpling and that they only differ by a pre-factor. This answers the question Q4.1 on how dimpling can be measured. The decision for a specific dimpling factor in consequence is case-dependent.

All modules are incorporated in a fully automated virtual process chain, which allows any number of designs to be entered and analysed. The steps two to five thereby ensure that the tooling geometry actually represents the desired geometry within the defined tolerances. This resolves the research question Q3. The ability to adequately measure dimpling in step six of the process chain will ultimately answer the question Q4 on how to minimize it.

The full process chain can subsequently be used as a pre-processor in a productive environment or for conducting experiments, parameter studies, and for optimisation.
In this chapter, the VAMM system is analysed and the interpolation layer, as well as the process parameters, are optimised. Therefore, in a first step, the design space is defined, which consists of all the system parameters with their individual boundaries, or admissible discrete values, as well as the system responses. Then, the actual optimisation targets are discussed. In the third section of the chapter, an optimisation workflow is introduced that is capable of finding the global best solution for the given system.

The optimisation then is done separately, for the single and dual layer IPL configuration. On both the single- and dual-layer VAMM system, a sensitivity analysis is conducted in order to identify the parameters, which most contribute to the optimisation target. For this purpose, experiments are conducted on the virtual VAMM manufacturing model, for the two IPL configurations (see chapter 6), according to a Design of Experiment scheme. This way, the design space is scanned comprehensively and the results can be used for a sensitivity analysis. This analysis identifies the most critical system parameters, which in turn are used to develop a metamodel of optimal prognosis (MOP) for the two systems. Through stochastic optimisation on these metamodels, an ideal interpolation layer, as well as a set of ideal process parameters, is sought for both configurations. These optimal configurations for the single- and dual-layer IPL configuration are then compared in order to evaluate the effectiveness of the dual layer approach.
7.1 Objective

The VAMM system is intended for creating freeform components with a high surface quality. Therefore, it is desirable to achieve a maximum part complexity while maintaining a maximum surface quality.

For a given pin array, the complexity of the freeform surfaces is limited by the thickness of the interpolation layer $t_{IPL}$. Assuming that a certain pin array resolution leads to a certain minimum permissible radius of the component [Wang et al. 2010], the interpolation layer acts as an offset on this permissible radius. An increase in thickness therefore reduces the possible curvature of the component or its complexity. A minimal IPL thickness is therefore preferable.

The vacuum pressure $\Delta p$ also influences part complexity. As shown in chapter 5.1, concave geometries benefit from higher vacuum pressure because it can result in the IPL better converging to the pin array. This increases the possible contour depth and curvature of convex sections of a component. It is therefore desirable, to apply as high a pressure as possible, without compromising the surface quality.

The surface quality of the VAMM manufactured parts in turn is quantified by the dimpling parameters $D_i$ (compare chapter 6.7). Hence, the dimpling response of the VAMM system must be minimised.

A general multi-objective optimisation problem can be formulated as

$$f_m(x) \rightarrow \text{min}, \quad m = 1 \ldots M$$

with $x$ being the vector of design variables and $m$ being the dimensions of the objective space. For the given problem, $m$ represents the optimisation parameters. The IPL thickness $t_{IPL}$ and the dimpling $D_i$ are to be minimised, while the process pressure $\Delta p$ is to be maximised. This lead to the following formulation of the optimisation problem:

$$t_{IPL}(x) \rightarrow \text{min},$$

$$D_i(x) \rightarrow \text{min}$$

$$\Delta p(x) \rightarrow \text{max}$$

For the parameter $D_i(x)$, it must be ensured that at least the general tolerances according to DIN 16742 [DIN Deutsches Institut für Normung e. V. 2013] for cast plastic parts are met. The size of the VAMM tool under consideration falls within the size range of 120 mm to 160 mm as defined in the standard. The finest tolerance group possible for this range is TG2, which defines a minimum symmetrical dimensional limit of $\pm 0.13$ mm and a cylindrical tolerance zone of $\varnothing 0.37$ mm for the position tolerance.
7.2 Experimental Set Up and Procedure

In an optimisation process, between a few hundred and several thousand designs have to be evaluated. For this purpose, the VAMM manufacturing model, with a runtime of a couple of hours per design (compare chapter 6.4), is too computationally expensive. Instead, a meta-model is used, to reduce the computation time significantly. This model only captures the relationship between the significant input parameters and the system outputs without modelling any underlying physical process. To create such a model, first a variance based sensitivity analysis is conducted on the virtual manufacturing model, in order to identify these relevant input parameters. Therefore, all system parameters are defined and their boundaries are delimited. DoE is used to scan the parameter space. Regression methods are then used on the experimental data to approximate the system responses and understand the systems’ behaviour. The influence of individual variables is then quantified using the coefficient of prognosis (CoP). A reduced set of important parameters is subsequently used to create a Metamodel of Optimal Prognosis. On this MOP, a multi-objective optimisation is executed in order to find Pareto optimal solutions. In order to obtain a single optimal solution, the conflicting objectives of the multi-objective optimisation are then reduced to a single objective optimisation problem. This optimisation then results in a final solution that is in turn verified on the VAMM manufacturing model. This workflow is performed in the software OptiSlang\textsuperscript{49}, separately for both the single layer IPL and the dual layer IPL configuration. Subsequently, the results of both configurations are compared against each other.

7.2.1 Sensitivity Analysis and Design of Experiment

Vacuum Assisted Multipoint Moulding is a complex manufacturing process with a number of parameters influencing the resulting part quality and dimpling in particular. Most of these parameters are already known from other multipoint tooling technologies and are introduced in chapter 2.5. In figure 2-28, these parameters are compiled and clustered into four categories: pin array parameters defining the tool hardware, IPL parameters describing materials, as well as the geometry of the interpolation layer, process parameters define the manufacturing process, and part parameters describing the component that is manufactured.

Each combination of specific values for these parameters, called a design, lead to a specific system response. In the VAMM optimisation process, the dimpling parameters introduced in chapter 6.7.4 are defined as these relevant system responses.

The sensitivity analysis identifies the parameters that predominantly influence these system responses. These parameters can then be used to create a reliable MOP.

\textsuperscript{49} OptiSlang 6.2. Dynardo GmbH, Weimar, Germany.
which adequately describes the behaviour of the physical system. For the use in an optimisation process, a MOP can be considered reliable, when its CoP is at least 90 % [Dietmar et al. 2015; Wartzack 2017]. In these cases, very useful results can be expected, when optimisation algorithms are applied to the MOP.

In order to conduct a global sensitivity analysis on the VAMM system, first the design space has to be explored comprehensively. Due to the relatively high number of parameters, Advanced Latin Hypercube Sampling is used to create a set of independent designs [Dynardo GmbH 2014]. All parameters of the model, their default values, and their range for sensitivity analysis are presented below and compiled in table 7-1. The reference values are then used in the base FE model described in chapter 6.

**Pin array parameters**

The pin cross section is hexagonal, the pin diameter is 24 mm, and the pin head radius is 13.86 mm, as defined in chapter 4.4. In this optimisation, these parameters are set constant.

**IPL parameters**

The IPL total thickness $t_{ipl}$ ranges from 5 mm to 40 mm. The materials used for the VAMM tool are available in sheets with a thickness of 5 mm, which defines the lower limit. Initial experiments on the other hand show that seemingly acceptable part quality can be achieved with a thickness of 20 mm (see chapter 5.1). The upper limit is set to twice that value in order to cover all possibilities.

The number of layers of the IPL can be one or more. This defines whether the model represents a single-layer or multi-layer IPL configuration. In the model, only the single- and the dual-layer configurations, with two IPL layers, are evaluated. Both configurations are evaluated individually (chapters 7.3 and 7.4). The model is theoretically capable of handling more layers, but this will not be investigated further due to resource restrictions.

The IPL layer thickness depends on the number of layers. It is equal to the total thickness in case of a single layer configuration. In dual layer configuration, the thickness of layer one and two add up to the total IPL thickness. They can be combined in ratios from 1/9 to 9/1 (e.g. $t_{ipl1} = 0.1 \times t_{total}$ and $t_{ipl2} = 0.9 \times t_{total}$).

The four silicone rubber materials, introduced in chapter 6.4.2, are used as IPL layer materials for layer one and two. In the model, they are defined using the corresponding Mooney Rivlin parameters C01, C10, C11 and D (see chapter 6.4.2).

The IPL diameter defines the size of the interpolation layer. It is equal to the inner diameter of the tenter frame (shown in figure 4-17). Since the pin array is fixed in size for this optimisation, the diameter defines the circumferential area between the pin array
and the tenter frame. The lower limit results from the dimensions of the wedge clamping system (see chapter 4.5). With an IPL diameter of at least 240 mm, the tenter frame does not collide with the clamping system. The upper limit of 300 mm on the other hand, equals the dimension of the test bench hardware.

**Process parameters**

The process temperature describes the temperature during the curing process of the component. Within the FE model, it is variable and can be adjusted as required, in order to achieve optimum curing. However, as stated in chapter 6, due to limited material testing capabilities, the IPL materials are only characterised at ambient temperature. Hence changing the process temperature cannot be modelled correctly with the currently available material data. The value is therefore fixed to ambient temperature at 24°C.

The process pressure $\Delta p$ defines the vacuum underneath the interpolation layer, which forces the IPL on the pin array, in order to create concave geometries. In the real system, this parameter can be set from 0.0 bar (vacuum pump off) to 0.99 bar (vacuum pump at full power). Experiments show that 300 mBar is sufficient to deform a thin interpolation layer to form a concave 3D curved component (see chapter 5.1). However, a noticeable effect can already be observed starting at 0.1 bar. Hence, the range is defined from 0.1 bar (0.01 MPa) to 0.99 bar (0.099 MPa).

The friction parameter between the machine components and IPL, describes the coefficient of friction between the IPL and the pins, the base plate and the tenter frame. The reference value is measured to be 0.32, as described in appendix A-5. It could however be modified using lubricants or adhesives. For rubbers in general, it can go down to 0.2 [Muhs et al. 2007], and lubricated material pairings in general go down to 0.1 [Kuchling 2014] which is set as the lower limit. The upper limit is set to 0.75, corresponding to approximately the friction between two silicones (see below).

Friction between the IPL layers is measured at 0.73, as described in appendix A-5. The range is defined equal to the friction between the machine components and IPL to 0.1 to 0.75.

Since the pin array can be adjusted freely, the component specific configuration can be offset from the base plane. This pin array offset can increase the tension in the IPL and could thereby influence the part quality. As shown in chapter 6.3, equation (37) and (38), the maximum permitted angle between a pin and the IPL is 60°. Above that, the contact point is at the edge of the pin tip, increasing the risk of damage to the IPL. At the edge of the pin array, it is expected that the IPL will not be completely attached to the pin array. Instead, it might be stretched to create a hollow cavity between the base and the pin array. This overstretched area must not exceed 30 mm in
order to maintain the function of the clamping system. Combined with the permissible contact angle, this results in a maximum permissible offset of 52 mm.

Table 7-1 - Input parameters and ranges for optimisation process

<table>
<thead>
<tr>
<th>type</th>
<th>parameter</th>
<th>min</th>
<th>max</th>
<th>referenc e value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>pin array parameters</strong></td>
<td>pin cross section</td>
<td></td>
<td></td>
<td>hexagonal</td>
<td></td>
</tr>
<tr>
<td></td>
<td>pin diameter</td>
<td>-</td>
<td>-</td>
<td>24</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>pin head radius</td>
<td>-</td>
<td>-</td>
<td></td>
<td>mm</td>
</tr>
</tbody>
</table>

**IPL parameters**

|                  | IPL total thickness         | 5   | 40  | 15               | mm   |
|                  | number of layers            | 1   | 2   | 2                | -    |
|                  | layer thickness layer 1-2   | 0   | 40  | 10/5             | mm   |
|                  | layer material layer 1-2    | see materials compiled in table 6-2  |      |                  |      |
|                  | IPL diameter                | 240 | 300 |                  | mm   |

**process parameters**

|                  | temperature                | 24  |     |                  | °C   |
|                  | pressure                   | 0.1 | 0.99| 0.9              | bar  |
|                  | friction (machine/IPL)     | 0.1 | 0.75| 0.33             | -    |
|                  | friction (between IPL layers) | 0.1 | 0.75| 0.73             | -    |
|                  | pin array offset           | 0   | 52  | 0                | mm   |

**part parameters**

|                  | radius**                   | 100 | 300 | 150              | mm   |
|                  | radius sign**              | -1  | 1   | 1                | -    |
|                  | chord length               | 80  | 144.5| 100             | mm   |

*modelled as IPL diameter = pin array diameter + circumferential area (range: 240 mm-300 mm)

**positive sign makes convex part, negative sign makes concave part;
radius not defined between -120 mm and 120 mm

**Part parameters**

The parts, produced in the VAMM manufacturing model, are hemispherical segments, open to the top (concave, negative sign) or bottom (convex, positive sign). The radius of these segments is defined to be between 100 mm and 300 mm. The lower limit creates parts with contact angles at the circumference slightly exceeding the allowed 45°. The upper limit is chosen, since the parts created are only slightly curved, and nearly resemble a plane. Further increasing the radius brings no significant change in geometry. The side of the opening is defined via the radius sign, which can be either -1 or 1, creating a convex or concave component respectively.
The actual size of the part is defined using the **chord length**. The lower limit is set to 80 mm. This value ensures that the centre axis of each pin, in the pin array, is inside of the parts boundary. The upper limit is defined by the array's width A/F of 144.5 mm (compare chapter 4.5). To ensure comparability of the parts however, for this optimisation process, the value is set constant to 100 mm, equal to the minimum part radius, to ensure that all components are mathematically possible.
7.2.2 Optimisation System

The objective of this optimisation is to find an ideal interpolation layer and setting for the VAMM system. This in turn means that the optimal solution has to be independent from the part that is manufactured and the corresponding part parameters. Instead, it should be able to produce sufficient surface quality for all possible parts. The optimisation system, as shown in figure 7-1, considers this circumstance. It does not consider the part parameters as an integral part of a VAMM design. Instead, an optimisation design consists of pin array parameters, process parameters and IPL parameters only (compiled in the figure as system parameters). In order to incorporate the part properties, a DoE is conducted to evaluate the influence of the part parameters on each particular design. The part radius and radius sign parameters are varied, using three level full factorial sampling. This leads to six parts being evaluated in the analysis: both concave and convex hemispherical segments with small, medium, and large radii (depending on the predefined range). In order to reduce computation time, these designs are solved not on the VAMM manufacturing model itself, but on the MOP. Subsequently, the dimpling response with the highest value (worst dimpling) is selected as a response for the design. This ensures that a component manufactured, with the corresponding set of parameters, always has a surface quality equal to, or better than, the response determined. For an optimised design, this ensures that all components meet the surface quality requirements.

![Optimisation System Diagram](image)

*Figure 7-1 - Optimisation system*
7.2.3 Solution Process

The three objectives of the optimisation are in conflict with each other. As a result, it is not possible to find a single best solution, but only a set of Pareto optimal designs. A scalarisation approach [Branke 2008] however reduces the order of the optimisation problem, making it possible to find a single optimal solution. This means, that the initial multi-objective problem is reduced to a single objective problem with additional constraints. In a first step, as shown in figure 7-2, a multi-objective optimisation obtains a set of Pareto optimal solutions. By visualising the resulting Pareto front, threshold values for all but one parameters can be identified. These thresholds are then defined as constraints for the subsequent single objective optimisation, which in turn results in a final optimal design.

Both the multi objective optimisation and the subsequent single objective optimisation use an Evolutionary Algorithm (EA). This is chosen due to its capability to handle discrete parameters like the Mooney-Rivlin parameters describing the IPL materials. The following parameters defining the EA are described in detail in Dynardo GmbH [2014]. The algorithm uses a start population size of 1,000 and an archive size of 20. Together with the offspring, the archived individuals form the set of individuals, from which the next generation is selected. The selection of parents for future generations uses the Pareto method for ranking individuals. A hundred parents are selected for reproduction, using the tournament method, with two individuals selected for each tournament. The offspring is then created, using a multipoint crossover operator, with three points to recombine two parents. Mutation introduces random
variation to the genes of the offspring’s chromosomes. The mutation operator is defined to be self-adaptive with a probability of 28% for a gene to mutate.

After the initial multipoint optimisation, the reduced single objective optimisation problem with inequality constraints can generally be written as

\[ f(x) \to \min, \]

with

\[ g_i(x) \geq 0 \quad i = 1, 2 \]

with \( x \) being the vector of design variables and \( g_i(x) \) being the constraints of inequality. For the given problem, the minimisation of the thickness \( t_{iPL} \) is defined as the remaining optimisation objective. The process pressure and dimpling are set as constraints.

\[ t_{iPL}(x) \to \min, \]

with

\[ \Delta p(x) \geq \Delta p_t \]

\[ D_i(x) \leq D_t \]

The actual thresholds \( \Delta p_t \) and \( D_t \) for these constraints are defined based on the results of the Pareto analysis.

The results of the single objective optimisation are validated on the VAMM manufacturing model. The process is similar to the optimisation system, as shown in figure 7-1. The optimised design is subjected to a DoE in order to exclude the influence of the component geometry. New designs are generated, using a three-level full factorial sampling, and solved on the VAMM model. The sample with the highest dimpling values is considered as the system response. This response is then compared to the optimised results from the MOP.
7.3 Single Layer IPL Configuration

The single layer IPL configuration is the basis configuration of the VAMM tool. A single sheet of elastomer is placed on top of the pin array in order to create the desired smooth tooling surface. It is defined in the VAMM manufacturing model by setting the number of IPL layers to one.

7.3.1 Sensitivity Analysis

Advanced Latin Hypercube sampling is used to create a set of 300 designs. From this set, 258 designs are evaluated successful, while 42 failed\textsuperscript{50}. The simulations took approximately 1,150 hours on an Intel Xeon CPU E5-2630@2.40 GHz (6 cores) with 32 GB of RAM running Windows 10. Of the evaluated designs, 231 are solved correctly while 27 did not converge in the FEA process due to incompatibilities of geometric parameter combinations. Some of the solved designs do not fulfil the convergence criteria for the shape controller defined in chapter 6.6 making them non-feasible for further evaluation. The number of feasible designs is 159 while 109 are not feasible and are deselected. These designs either have no contact between at least one pin and the IPL (94 designs), or have a non-sufficient $e_{AM}$ or $e_{RMS}$ (compare chapter 6.6) after the maximum number of iterations. This means, that the designs exceed the production limits of the VAMM tool.

The developed dimpling evaluation process requires a good quality geometry file, coming from the FE analysis. In some cases, however, the FE analysis fails locally (for instance at a collapsed contact element), leading to a deformed geometry and a flawed dimpling evaluation, with dimpling values multiple times higher than expected. Hence, all dimpling values 20% higher than the average are checked manually to identify falsely evaluated designs. For the single layer IPL concept, two such failed designs are found. This leads to 157 designs that can be used for further evaluation.

In a first sensitivity analysis, considering all parameters, the influence of single parameters is determined using their CoP (see figure 7-3 (a)). The individual indices of the input variables describe their contribution to the variance of the particular model and thus show how strongly each input influences the respective output. The total CoP at the end of each line quantifies the quality of the approximation model. It shows that the prediction quality of the created models varies between 46.7% and 52.7%. This is not sufficient for use in an optimisation process. It also shows that some parameters do not influence the results of the model at all. By successive deselecting these

\textsuperscript{50} Designs can fail due to hardware problems (e.g. computer crashes or power outages), or software problems (e.g. licence server communication errors)
unimportant parameters, a reduced set of parameters with increased prediction quality can be obtained (see figure 7-3 (b)).

The parameters IPL diameter and process friction influence the results by 1% or less. These parameters are therefore considered to have no significant influence on the VAMM manufacturing process, and can be eliminated from the model. The resulting temporary models identify the influence of the parameters pin array offset (process offset z) to be less than 2%. Removing it further improves the CoP of the final models.

*(a)*

![CoP matrix of the single layer IPL MOPs, before (a) and after (b) parameter reduction](image)

Additionally, the material parameters $C_{01}$, $C_{10}$, and $C_{11}$ are physically related to each other. This results in high input correlations, which in turn reduces the model quality
and can lead to an overestimation of the material influence. For the optimised model, each of these three parameters is tested individually, in order to avoid these input correlations. It shows that using only $C_{11}$ results in the most physically meaningful models, with the highest prognosis quality.

With the remaining parameters, MOPs with CoP values >90 % can be created for the dimpling parameters $D_{vol}$, $D_{vert}$ and $D_{min}$. This means that the corresponding fraction of variance is explained by the metamodel, and that only a relatively small share of the system behaviour cannot be completely replicated.

The reduced MOPs are created for all four dimpling parameters using an isotropic Kriging formulation. Figure 7-4 shows the response surfaces for the dimpling parameters depending on IPL thickness and IPL material.

Figure 7-4 - Response surfaces for the dimpling parameters depending on IPL thickness and IPL material (defined in the model by the material constant $C_{11}$);

$D_{min}$ with a CoP of 93 % (top, left), $D_{orth}$ with a CoP of 55 % (top, right),
$D_{vert}$ with a CoP of 92 % (bottom, left), and $D_{vol}$ with a CoP of 93 % (bottom, right)
The models for $D_{vol}$, $D_{vert}$, and $D_{min}$ all show very similar behaviour. This correlates with the very similar CoPs of ~92%. In contrast, $D_{orth}$ shows a slightly different behaviour in the figure. The behaviour of the response surface is less steep in areas of lower thickness, and the influence of the material parameter is less pronounced. This however can be expected due to the significantly lower CoP of 55%. In conclusion, the MOP for $D_{orth}$ replicates the system behaviour far less accurately compared to the other three MOPs. It is therefore excluded in subsequent analysis.

### 7.3.2 Optimisation

The optimisation is ultimately conducted on the MOP for $D_{vol}$. With a CoP of 93%, it best describes the system behaviour of the VAMM process. In the multi-objective optimisation, 89 generations with a total of 9,900 designs are evaluated using an EA. The resulting Pareto front is shown in Figure 7-5 with Pareto designs shown in orange. The Pareto front shows a strong decrease in dimpling for increased IPL thicknesses. The process pressure on the other hand causes a slight increase in dimpling with increasing values.

\[
\begin{align*}
\text{Figure 7-5 - Pareto front of possible best designs for the single layer IPL configuration}
\end{align*}
\]

In order to find a single optimal solution, the multi-objective optimisation task is transformed into a single objective optimisation with additional constraints. Minimising the thickness of the IPL remains the optimisation task for this single objective optimisation. Based on the Pareto front the process pressure and dimpling are defined as constraints. The constraint for dimpling is defined to include 5% of the designs calculated in the multi objective optimisation. This results in a threshold level
of \( D_{vol} \leq 0.1 \text{ mm} \). This is well within the GD&T defined in DIN 16742 [DIN Deutsches Institut für Normung e. V. 2013] (see chapter 7.1).

The process pressure threshold is defined based on the failed designs. For each design, the minimum contact pressure between the pins and the IPL is evaluated. If this value is zero, at least one pin does not touch the IPL. When, at the same time, the shape error is above the allowed threshold, the design cannot be produced, since the IPL does not conform fully to the pin array. A value of \( \Delta p \geq 0.8 \text{ bar} \) is identified as the threshold, at which higher pressure differences do not significantly improve this shape convergence.

![Figure 7-6 - Single objective optimisation history of the IPL thickness (a) and dimpling (b) for single layer IPL configuration](image)
The single objective optimisation also uses an EA. 23 generations, with a total 3300 designs, are evaluated to solve the optimisation problem. Figure 7-6 shows the convergence history of the algorithm for the IPL thickness (a) and dimpling (b). It shows that in the first generation (designs 0-1000) has a high level of jitter in both parameters, as is expected for an EA. Within the next 10 generations (designs 1,000 to 2,000), most of the dimpling oscillates to values $< 0.5$ mm, while the IPL thickness also adjusts to a value of $\sim 30$ mm, while scattering strongly. In the magnification (see in figure 7-6 (a)) it becomes clear, that only very few of the optimisation designs actually comply with the defined threshold values (indicated by green diamonds). The limit values can therefore be considered very strict. Within the last 12 generations, dimpling does no longer change significantly. Concerning the thickness, there is no visible improvement in this stage of the optimisation. The best design no. 2322 is indicated by the orange cross.

### 7.3.3 Results and Discussion

The optimisation algorithm converged to the final design no. 2,322. The parameters of this design are shown in table 7-2. It uses a process pressure of 0.80 bar. The IPL is made of a single layer of red silicone rubber, with a shore hardness of 60 ShA (corresponding to the C11 value of 0.00205) and a thickness of 28.9 mm. According to the MOP, this configuration results in a dimpling $D_{vol}$ of 0.10 mm.

<table>
<thead>
<tr>
<th>parameter</th>
<th>optimised value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process pressure</td>
<td>0.8002 bar</td>
</tr>
<tr>
<td>IPL thickness</td>
<td>28.94 mm</td>
</tr>
<tr>
<td>IPL C11</td>
<td>0.00205</td>
</tr>
<tr>
<td>IPL material</td>
<td>silicone rubber red 60 ShA (C11 = 0.00205)</td>
</tr>
<tr>
<td>response</td>
<td></td>
</tr>
<tr>
<td>$D_{vol}$</td>
<td>0.10 mm</td>
</tr>
</tbody>
</table>

The final design is validated using the virtual VAMM manufacturing model. Six different components are evaluated, and the highest dimpling values are used as the response of the mode, similar to the optimisation system. The hemispherical convex segment with part radius of 120 mm produces the highest volumetric dimpling value $D_{vol}$ of 0.13 mm. Figure 7-7 shows the result of this evaluation. The colour gradient on the component shows no typical dimpling pattern. Instead, the centre of the
component is well represented with a tolerance of less than 0.1 mm. At the edges, however, the deviation increases to up to 0.7 mm.

![Graph showing volumetric dimpling evaluation](image)

*Figure 7-7 - Volumetric dimpling evaluation of the final design for the single layer configuration with the part producing the highest dimpling value (part radius 120 mm)*

All dimpling results of the optimisation (dark green), as well as the validation (light green) are shown in figure 7-8. The bar sizes are displayed relative to the range of all responses of the optimisation. Except for the excluded orthogonal dimpling, all validation values are higher than the values predicted by the MOP. These deviations result from the inaccuracy in the modelling of the MOP. A CoP of 93 % for $D_{vol}$ in turn implies that 7 % of the variance of the system is not explained by the model. Considering this, it can be concluded that the validated results are in good agreement with the results created on the MOP.

![Response Data Graph](image)

*Figure 7-8 - Validated results for the final solution for the single layer IPL configuration; results predicted by the Evolutionary Algorithm on the MOP (dark green) and validated using the VAMM manufacturing model (light green)*
Under the defined preconditions, it can therefore be assumed that the final best design in fact represents an optimum for the single layer IPL configuration of the VAMM.
7.4 Dual Layer IPL Configuration

The dual layer IPL configuration uses two layers of elastomer, with different mechanical properties, stacked on top of each other. This stack is placed on top of the pin array in order to create the desired smooth tooling surface. It is defined, in the VAMM manufacturing model, by setting the number of IPL layers to two.

7.4.1 Sensitivity Analysis

The evaluation of the dual layer IPL model is more time consuming than the single layer model and fewer designs can be evaluated in a similar timeframe. Advanced Latin Hypercube sampling is used to create a set of 200 designs. From this set, 165 designs are evaluated while 35 failed. The evaluation of these designs had a runtime of approximately 1,300 hours on an Intel Xeon CPU E5-2630@2.40 GHz (6 cores) with 32 GB of RAM running Windows 10. Four of the evaluated designs, did not converge in the FEA process, while 161 are solved correctly. Of these, 54 do not fulfil the convergence criteria for the shape controller, as defined in chapter 6.6. The remaining 107 designs are feasible for further evaluation. Similar to the single layer sensitivity analysis, these designs are checked manually for falsely evaluated designs. However, for the dual layer IPL concept, no such designs are identified. This means that all 107 feasible designs can be used for modelling the system.

The initial sensitivity analysis (Figure 7-9 (a)) considers all parameters in the VAMM manufacturing model. It shows that the CoPs of all four models are well below the 90% threshold. The values for $D_{orth}$ and $D_{vert}$ are particularly low, with 54.5% and 61% respectively. This indicates that the MOPs are not sufficient for the use in an optimisation process. In order to improve the model accuracy, similar to the single layer IPL models, parameters are removed from the model systematically. The parameters process offset (CoP 2.2% - 5.8%) and process friction (CoP 1.3% - 7.3%) contribute least to the total results and are therefore deselected first. In a second step, physically dependent parameters are removed from the model to prevent overestimation of their physical effects. The total IPL thickness is the sum of the thicknesses of the first and second layer. Having the total and first layer thickness in the model is sufficient to fully describe the thickness distribution of the IPL. Thus, the second layer thickness is not required in the model. The material parameters $C_{01}$, $C_{10}$, and $C_{11}$ also have to be reduced to a single parameter defining the material of each of the IPL layers. Each of the three parameters is tested individually. Unlike in the single layer IPL model, here the parameter $C_{01}$ produces the best results. The resulting final MOPs are shown in figure 7-9 (b). The model $D_{vert}$ reproduces the process worst, with a CoP of 67.7%. The other models are close to each other in terms of their quality of prediction. $D_{orth}$ has a CoP of 87.8%, while $D_{min}$ predicts the system behaviour slightly
better with 88.6%. The model $D_{vol}$ again is superior with a CoP of 90.2%, making it the only CoP above the 90% threshold for optimisation.

![CoP matrix of the MOP before (a) and after (b) parameter reduction and variable sensitivities obtained by the MOP (dual layer IPL model)](image)

Each of the models is created with the approximation method giving the best results. Isotropic Kriging is used to model $D_{vert}$, while $D_{orth}$, $D_{min}$, and $D_{vol}$ are modelled using anisotropic Kriging. Figure 7-10 shows the response surfaces for the dimpling parameters, depending on the thickness of the IPL layers one and two. Even though, $D_{orth}$, $D_{min}$, and $D_{vol}$ are similarly modelled and have similar CoPs, the
behaviour of $D_{orth}$ is clearly different from the other two. The dent in this MOP (marked with red ellipse in figure 7-10 (top, right)) cannot be explained physically. In the dented area, specifically around $t_{IPL2} \in [0 \ldots 10]$, the local CoP is between 55% and 44%. Therefore, the model is not used in in subsequent steps.

$D_{min}$ with a CoP of 89% (top, left), $D_{orth}$ with a CoP of 88% (top, right), $D_{vert}$ with a CoP of 88% (bottom, left), and $D_{vol}$ with a CoP of 90%.

$D_{vert}$ with the relatively low CoP of 68% also shows a slightly different behaviour compared to $D_{min}$, and $D_{vol}$. The response surface is less steep in areas of lower thicknesses. Due to the low CoP, this model is also excluded from further evaluations.

The remaining two models exhibit a similar behaviour in the figure: A decrease of each IPL thickness results in increased dimpling. The influence of both thicknesses is similar.
### 7.4.2 Optimisation

The MOP for $D_{vol}$, with a CoP of 90 %, ultimately best describes the behaviour of the dual layer IPL configuration. For this reason, it is used in the optimisation system. In the initial multi-objective optimisation, 89 generations with a total of 9,900 designs are assessed. Figure 7-11 shows the resulting Pareto front. It behaves similar to the single layer IPL configuration. An increase in IPL thicknesses causes a strong decrease in dimpling. The process pressure $\Delta p$ on the other hand causes a slight increase in dimpling with increasing values. The lowest values for dimpling on the Pareto front range from 0.044 mm to 0.067 mm, at IPL thicknesses of 26.44 mm to 31.62 mm (the axis values in the image are 10 mm).

![Figure 7-11 - Pareto front of possible best designs for the dual layer IPL configuration](image)

As previously defined, minimising the thickness of the IPL remains the optimisation task for this single objective optimisation, while the process pressure and dimpling are defined as constraints. In the optimisation of the single layer configuration, the threshold for dimpling is defined to include 5 % of the multi objective optimisation. In the dual layer configuration, this would result in a threshold value of $D_{vol} = 0.14 \text{ mm}$. This threshold value would not meet the dimensional limit of $\pm 0.13 \text{ mm}$ as defined in DIN 16742 [DIN Deutsches Institut für Normung e. V. 2013]. Therefore, and in order to ensure comparability of the optimisation results, the constraint for dimpling is defined as $D_{vol} \leq 0.1 \text{ mm}$, equal to the optimisation of the single layer configuration. The threshold value of $\Delta p \geq 0.8 \text{ bar}$ for the process pressure parameter is defined in the same way.
Optimisation of the VAMM System

The single objective optimisation evaluates 89 generations, with a total of 9,900 designs, to solve the optimisation problem. Figure 7-12 shows the convergence of the optimisation algorithm for the IPL thickness and dimpling. The thickness parameter shows a trend towards its optimal value. It jitters strongly in the first generation (designs 1 - 1,000) and stabilises somewhat within the next 15 generations (1,001 – 2,500) to a mean value of ~27.5 mm. From there, the remaining generations show a slight trend towards 26.5 mm with occasional outliers below. The orange cross indicates the best design no. 6,268.

Figure 7-12 - Single objective optimisation history of the IPL thickness (a) and dimpling (b) for dual layer IPL configuration
7.4.3 Results and Discussion

The optimisation algorithm converged to the final best design no. 6,268. The design parameters are shown in table 7-3. It uses a process pressure of 0.99 bar. This is the upper limit for the process pressure as defined in chapter 7.2.1. The IPL is made of a two layer with a total thickness of 26.47 mm. The top layer is made from translucent silicone rubber with a Shore hardness of 40 ShA (corresponding to the C01 value of 0.156), and a thickness of 5.7 mm. The bottom layer is made from red silicone rubber with a Shore hardness of 60 ShA (corresponding to the C01 value of 0.204). It has a thickness of 20.76 mm. The IPL diameter is 299.6 mm, which is at the top end of the range. This indicates that a reduction of the circumferential area around the pin array has no positive effect. According to the MOP, this configuration results in a dimpling \( D_{vol} \) of 0.10 mm.

Table 7-3 - Optimised parameters of the final design for the VAMM dual layer configuration

<table>
<thead>
<tr>
<th>parameter</th>
<th>optimised value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process pressure</td>
<td>0.99 bar</td>
</tr>
<tr>
<td>IPL thickness total</td>
<td>26.47 mm</td>
</tr>
<tr>
<td>IPL layer 1 thickness</td>
<td>5.7 mm</td>
</tr>
<tr>
<td>IPL layer 1 material</td>
<td>silicone rubber translucent 40 ShA ( C_{11} = 0.156 )</td>
</tr>
<tr>
<td>IPL layer 2 thickness</td>
<td>20.76 mm</td>
</tr>
<tr>
<td>IPL layer 2 material</td>
<td>silicone rubber red 60ShA ( C_{11} = 0.204 )</td>
</tr>
<tr>
<td>IPL diameter</td>
<td>299.6 mm</td>
</tr>
<tr>
<td>response</td>
<td></td>
</tr>
<tr>
<td>( D_{vol} )</td>
<td>0.10 mm</td>
</tr>
</tbody>
</table>

The final design is validated using the VAMM manufacturing model. Similar to the optimisation system, six parts with different radii are created on the model. The highest dimpling values then are used as responses.

As for the single layer IPL configuration, the hemispherical convex segment, with part radius of 120 mm, produces the highest volumetric dimpling value \( D_{vol} \) of 0.079 mm. Figure 7-13 shows the volumetric dimpling evaluation of this part. The dimpling error distribution, across the parts surface, is relatively uniform. In the centre of the component, the deviations are 0.04 mm, at most. At the edges, they are
correspondingly higher, at up to 0.18 mm. However, there is no visible golf ball pattern typical for dimpling. This indicates, that the interpolation layer is sufficient.

All dimpling results of the optimisation (dark green), as well as the validation (light green), relative to the range of all responses of the optimisation, are shown in Figure 7-14.
The values for $D_{\text{orth}}$ and $D_{\text{vert}}$ are excluded from the evaluation as previously discussed. The remaining minimal dimpling and volumetric dimpling are in good agreement with the results created on the MOP. In summary, the final solution found can be assumed to represent an optimum for VAMM.
7.5 Comparison of Single and Dual Layer IPL configurations

The dual layer IPL is a new approach, introduced in this thesis. It is therefore interesting to see how this new solution compares to the established single-layer IPL. Table 7-4 shows the maximum allowable pressure and the minimum allowable IPL thickness from the final solutions of both, the single- and dual layer IPL configurations. The corresponding dimpling values $D_{vol}$, evaluated with the VAMM manufacturing model, are shown in Figure 7-15 for different part radii.

<table>
<thead>
<tr>
<th>parameter</th>
<th>single layer IPL</th>
<th>dual layer IPL</th>
<th>improvement dual to single layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>max. process pressure</td>
<td>0.8002 bar</td>
<td>0.99 bar</td>
<td>+ 24 %</td>
</tr>
<tr>
<td>min. IPL thickness</td>
<td>28.94 mm</td>
<td>26.47 mm</td>
<td>- 9 %</td>
</tr>
<tr>
<td>IPL material</td>
<td>silicone rubber red, ShA60</td>
<td>silicone rubber red 60/ translucent 40</td>
<td>n.a.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>response</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{vol}$ (MOP)</td>
<td>0.10 mm</td>
<td>0.10 mm</td>
<td>± 0 %</td>
</tr>
<tr>
<td>$D_{vol}$ (simulation)</td>
<td>0.13 mm</td>
<td>0.074 mm</td>
<td>- 43 %</td>
</tr>
</tbody>
</table>

It shows that both configurations are able to produce similarly high surface quality according to the MOP. However, looking at the validation simulation the results are different. Here the single layer IPL configuration only produces acceptable results for large concave and convex radii ($\pm 210$ mm and $\pm 300$ mm). For the small radius of $\pm 120$ mm however, dimpling exceeds the accepted threshold value. This makes the configuration technically non-feasible, according to the predefined quality criteria. Figure 7-8 shows the convex of these critical parts with a radius of $\pm 120$ mm. It becomes clear, that the dimpling value does not in fact show a golf ball like dimpling defect, but results from an artefact at the edge of the evaluated area. Therefore, the interpolation still can be considered adequate for smaller geometries. However, the sharp increase between 210 mm and 120 mm also indicates that the solution found is not robust. Instead, there might be situations in which the interpolation is actually not sufficient.

In contrast, the dual layer IPL configuration produces uniformly good values with a further improvement in large convex radii ($210$ mm to $300$ mm). The dimpling values for small radii and convex geometries are even better than the single layer IPL.
configuration. Only for larger concave geometries (-210 mm and -300 mm) the dimpling values are not superior. It has to be considered that these results are achieved using a 24% higher maximum process pressure and a 9% reduced minimum IPL thickness compared to the single layer IPL configuration. The increased maximum pressure improves the conformation of the IPL to the pin array. This in turn enables the creation of more pronounced concave geometries and reduces the risk of undesired edge effects. The reduced minimum IPL thickness on the other hand reduces the loss in resolution and increases the possible complexity of components.

In summary, the dual layer configuration provides a more robust solution towards surface quality at higher process pressures and requires a thinner interpolation layer.
7.6 Summary

In this chapter, the VAMM system with two IPL configurations was analysed and the IPL and process parameters optimised. In order to identify the relevant parameters of the VAMM system, sensitivity studies were carried out for the single-layer and dual-layer IPL configuration. In a first step, the known system parameters were identified and their value ranges defined. The machine itself is defined by three parameters, which in this evaluation were assumed constant. Depending on the configuration, the interpolation layer is defined by seven (single layer) or eleven (dual layer) parameters. The manufacturing process is controlled via five parameters, with the process temperature being set as constant. The components, to be manufactured, are ultimately defined via three parameters, the radius, the radius sign and the chord length. However, the chord length was also set constant for the optimisation process. The design space, resulting from these parameters, was scanned using DoE. Five hundred designs were calculated on the VAMM manufacturing model and the dimpling was evaluated, for both configurations. A Metamodel of Optimal Prognosis was then generated from these results and the influence of the individual parameters on the model was evaluated. The quality of the models was successively improved, by iteratively removing the least influential parameters. For the single layer IPL, only five parameters turned out to be relevant to describe the whole VAMM system. The part radius and sign, the IPL thickness and material (described by the Mooney-Rivlin parameter C11), as well as the process pressure, are sufficient to describe the manufacturing process. For the dual layer IPL configuration, the IPL diameter, as well as the thickness of the individual IPL layers, was found as additional critical parameters. This leads to eight parameters to describe the system sufficiently. In contrast to the single layer model though, the IPL materials are defined using the Mooney-Rivlin parameter C01 to obtain models with the highest possible quality of prediction. This answers the research question Q4.2, which parameters influence dimpling in the VAMM system and to what extent, for the single as well as the dual layer IPL configuration.

Based on these reduced order MOPs, the VAMM system was optimised. For this purpose, optimisation objectives were defined:

- dimpling should be minimised,
- IPL thickness should also be minimised and
- process pressure should be maximised.

Using a scalarisation approach, this multi-objective optimisation problem was reduced to a single objective optimisation problem with additional constraints. Therefore, an acceptable dimpling threshold is defined as \( D_{\text{vol}} \leq 0.1 \, \text{mm} \) which ensures that the shape and position tolerances for plastic components according to DIN 16742 [DIN Deutsches Institut für Normung e. V. 2013] are met. A sufficient vacuum pressure threshold is defined as \( \Delta p \geq 0.8 \, \text{bar} \). For the single layer configuration approximately
5% of the calculated design meet these limits. This means that there are multiple solutions for the single layer IPL configuration that lead to acceptable dimpling which in turn answers the research question Q4.3: Dimpling can well be minimised with a single layer IPL.

Using this optimisation approach, for both single- and dual-layer IPL configurations, optimal designs were obtained. The results were validated on the virtual VAMM manufacturing model and proved to be in good agreement with the predicted solutions. This answers the questions Q4.4 and Q4.6 respectively:

- The ideal single layer IPL for the considered VAMM system is specified according to the parameters in table 7-2.
- The ideal dual layer IPL for the considered VAMM system is specified according to the parameters in table 7-3.

Comparison of the two optimal solutions shows the dual layer IPL configuration to be superior to the single layer IPL configuration. With this setup, it is possible to increase the process pressure by 24%, thereby increasing the conformation of the IPL to the pin array. Meanwhile the IPL thickness can be reduced by 9%, reducing the loss in pin array resolution and in turn increasing the possible part complexity. At the same time, this setup leads to more constant dimpling values for different parts, indicating a more robust solution in general operation. This means, that the dual layer IPL is well capable of decreasing dimpling at the same IPL thickness or that the thickness can be reduced while maintaining similar dimpling, both compared to a single layer IPL, ultimately answering Q4.5.
Chapter 8  Conclusion and Guideline for Future Work

This work was initially motivated by the increasing global demand for fibre composites and the resulting need for more moulds. This need is further amplified by the growing trend of mass customisation and the resulting reduction in production volumes of individual components. Consequently, the aim of this work was to develop the novel Vacuum Assisted Multipoint Tooling technology as a contribution for enabling this paradigm shift in industrial production. The technology should be specifically tailored for the manufacturing of fibre-reinforced plastic composites. In addition, it should be capable of manufacturing high quality parts competitive to parts made on traditional tooling. These objectives were pursued in a three-stage process. The first step was to develop the hardware for the VAMM system. For this purpose, specific development goals were defined, an overall concept and system architecture were developed, and components were optimised. Subsequently, two VAMM tools were constructed. A test bench was built to carry out testing and conceptually validate the hardware design. A fully automatic full-scale prototype was then realised, which represents a possible industrial implementation. In the second stage, the manufacturing process was virtualised in order to predict the system behaviour and the expected part quality. A shape control algorithm was implemented in order to improve the dimensional accuracy of the process and a dimpling evaluation method was developed. The virtual model was used in the third step to conduct sensitivity analysis on the VAMM system, and identify the IPL and process parameters that critically influence dimpling. Parametric optimisation was then used to find optimal interpolation layers, which suppress dimpling sufficiently and ensure high geometric quality in the manufacturing process.
8.1 Summary of Results

At the beginning of this thesis several research questions around Vacuum Assisted Multipoint Moulding were formulated. These questions were answered in the course of the work as follows:

Q1. How can established FRP manufacturing technologies be enabled in the Vacuum Assisted Multipoint Moulding technology?

In order to answer this, first a number of partial questions had to be answered. The requirements of such a VAMM system had to be specified in order to address the following research question:

Q1.1 What are the specific requirements of established FRP processes?

In the design and development of the Vacuum Assisted Multipoint Moulding technology, it was crucial, to first clarify, how the specific characteristics of established FRP manufacturing technologies could be considered in the Vacuum Assisted Multipoint Moulding system. Analysis of established manufacturing processes in chapter 2.1 showed that they generally utilise open mould configurations to manufacture multiply curved freeform geometries with convex and concave sections, as well as inflection points. On these open moulds, a fibre layup and liquid resin is placed and consolidated either manually, or using a vacuum. Then, the resin is hardened at high temperatures for minutes up to hours. For the VAMM tool, this results in specific requirements compiled in chapter 4.2, that include the following key points:

- the need for the interpolation layer to be airtight in order to consolidate the fibre layup with a vacuum,
- the need for a high chemical resistance of the tooling surface to withstand the thermoset resins and release agents,
- the need for an even heat application in order to enable consistent hardening of the thermoset resin.

The lack of an upper mould in the VAMM concept also resulted in the following question:

Q1.2 How can components with convex and concave sections as well as inflection points be created without an upper mould?

In order to address this requirement, the eponymous vacuum was introduced between the pin array and the interpolation layer to forces the IPL on the pin array and create these desired geometries. This concept was implemented in a system architecture that takes all requirements compiled for Q1.1 into account (see chapter 4.3). It divides the system into five interchangeable modules that form a scalable solution, which in the future can also be scaled and adapted to different potential applications:
Conclusion and Guideline for Future Work

- The **pin array** which uses pins with a hexagonal cross-section with hemispherical pin heads,
- the cost-efficient **SPS pin actuation** concept is introduced which uses a passive, low complexity pin design and an array of actuators for adjustment,
- a single- and a dual-layer **interpolation layer** concept which use either one or two functional layers of different silicon rubber sheets, with a distinct thickness, to create a smooth tooling surface,
- a **radiation heater** with individually controllable radiators to heat the freeform surfaces evenly, and
- A modular **control system** to control all machine functions of the VAMM system.

In order to prove, that this concept enables the use of established FRP manufacturing technologies on a multipoint tool, as stated in Q1, and to demonstrated and verified the modularity of the approach, two versions of VAMM, the VAMM test setup, and the VAMM full-scale prototype, were subsequently designed and built:

- The test setup is a proof-of-concept machine with 35 pins and a manually adjusted actuator. It proved the general functionality of the VAMM concept and the capability to create concave and convex tooling geometries on an open mould multipoint tool. On this tool, the validity of the defined requirements with regards to Q1.1 and Q1.2 was proven by successfully manufacturing a concave component (see chapter 5.1) on the tool with a conventional vacuum bagging process.
- The VAMM full-scale prototype, on the other hand, is a prototype of an industrial installation. It has a working area of ~0.25 m², using a pin array with 572 pins, which are adjusted fully automatic. The pin and actuator design in particular were developed from scratch. This led to a cost reduction of nearly 40% for a tool the size of the VAMM prototype, compared to established concepts, without compromising functionality or precision. This shows, that the developed tooling concept is superior for an industrial application than previous installations of MPT. On this tool, parts were manufactured using a conventional vacuum bagging process (see chapters 4.6 and 5.2), further proving the validity of the previously defined requirements.

Summarizing, the developed tooling system meets all the requirements defined and is capable of enabling the desired manufacturing processes without unexpected restrictions, hence answering research question Q1.

Subsequently, the impact of this novel manufacturing technology on the mechanical properties of components had to be evaluated in order to answer the following question:
Q2 How do the mechanical properties of VAAM manufactured parts compare to traditionally manufactured ones?

In FRP manufacturing the tooling can also influence the mechanical properties of the parts. Tensile tests, bending tests and thermogravimetry tests were conducted on specimens cut out of three CFRP panes made on the VAMM full-scale prototype at 15 mm, 20 mm and 25 mm IPL thickness, respectively. Reference values were gathered from specimens cut out of a panel manufactured on an aluminium tooling (see chapter 5.2.2). As discussed in chapter 5.2.3, the experiments show, that at an IPL thickness of 20 mm or more, the mechanical properties are close to, or corresponding to the reference values. The laminate quality even appears to benefit from the rubber tooling. The void fraction of all VAMM made panels is lower than in the reference panel and decreases with increasing IPL thickness.

This investigation did not consider the system immanent shape error that results from the elastic deformation of the rubber tooling surface. For material testing flat panels were manufactured on the VAMM tool, making this error negligible. For freeform components however, it has to be considered. Hence, in order to address this effect, the following question had to be answered:

Q3 How can components be created with sufficient shape accuracy in VAMM?

Minimising the shape error and maximising the shape accuracy in VAMM is achieved by readjusting the pins to compensate the IPL elasticity. To do this, a virtual manufacturing model was developed in chapter 6. As described in detail chapter 6.1, this fully automated virtual process chain implements the whole product creation process, from part design, over production to quality control, to predicting, quantifying and optimising the expected part quality. It includes the following modules:

- The part design module creates geometric primitives based on a set of parameters.
- The initial configuration module calculates the pin configuration for the created primitives from the part design module or for general 3D CAD data.
- The forming process module evaluates the forming process using finite element analysis and predicts the tools behaviour.
- The shape error evaluation module calculates the deviations between the actual tooling surface and the target geometry.
- The shape control module compensates the shape error by creating new pin configurations in an iterative process.
- The dimpling evaluation module assesses the expected dimpling severity using one of four newly established dimpling parameters.

This virtual process chain, or parts of it, can subsequently be used as a preprocessing tool to pre-optimise the pin configuration for a part before manufacturing and for virtual parameter studies and optimisation.
However, in order to adequately implement the *shape error evaluation* and *shape control module*, the following preliminary questions had to be addressed first:

**Q3.1 How can the shape error be measured adequately?**

The shape error $\Delta z$ is based on the deviation of the tooling surface to the target geometry in vertical direction. It is defined as a scalar value for each individual pin. This way, the values can be used directly for subsequent shape error compensation. In order to compare the shape error of different parts, the global shape error parameters root mean square error $e_{RMS}$ and absolute maximum error $e_{AM}$ are defined in chapter 6.5. These three parameters enable both the local and the global evaluation of the shape error and thus represent an adequate solution for question Q3.1. With this interim conclusion, the research question Q3.2 can be addressed:

**Q3.2 How can shape error be compensated sufficiently in VAMM?**

A shape controller, that can compensate the local shape error at each pin, is implemented in the VAMM process and adequate threshold values for the local shape error are defined (see chapter 6.6). The control algorithm can create new pin configurations in an iterative process and proved to be capable to effectively minimize shape error within two to four iterations (see chapter 6.7.5).

With Q3.1 and Q3.2 being answered, the shape error evaluation and shape control module were implemented in virtual manufacturing model. Now, this tool enables the preprocessing of arbitrary parts for VAMM manufacturing and the creation of pin configurations that no longer show any significant shape error. This addresses the question on how components can be created with sufficient shape accuracy in VAMM as stated in Q3.

With the capability to manufacturing parts with no significant shape error, the second system immanent surface defect, dimpling, could be addressed. Thereby it was of utmost interest how this effect can be reduced to a minimum:

**Q4 How can dimpling be minimised sufficiently in VAMM?**

For the shape-error compensated tooling surface the dimpling can be minimised by ideal configuring the IPL and the manufacturing process. Therefore, the following questions were answered first:

**Q4.1 How can dimpling be measured?**

Four different dimpling parameters were proposed describing the severity of dimpling. These parameters use different definitions of distance to measure the deviation between a target geometry and the actual tooling geometry (see chapter 6.7). Specifically, these definitions are based on the vertical distance, orthogonal distance, minimal distance, and the volume between surfaces. Evaluations in chapter 6.7.5 showed that the proposed dimpling parameters are linear dependent, making each of them equally suitable to give a meaningful impression of the severity of dimpling.
With these values defined, the influence of the different system parameters compiled in Figure 2-28 (see chapter 2.6) could be investigated to answer the following question:

Q4.2 Which parameters influence dimpling in VAMM and to what extent?

The relevant parameters of the VAMM system were identified using sensitivity analysis for both the single-layer and dual-layer IPL configuration as described in chapters 7.3.1 and 7.4.1 respectively. For that, all system parameters and their respective value ranges were defined. DoE created designs were evaluated on the virtual manufacturing model in order to scan the resulting design space. The results were used for creating a Metamodel of Optimal Prognosis to then evaluate the influence of the individual parameters on the model. The quality of these models was then successively improved, by iteratively removing the least influential parameters. The influence of the individual parameters thereby was measured via their CoP. This resulted in the following findings:

- The single layer IPL configuration can be described using five relevant parameters: The part radius and sign, the IPL thickness and material (described by the Mooney Rivlin parameter C11), as well as the process pressure, are sufficient to best describe the manufacturing process.
- The dual layer IPL configuration, can be described using eight relevant parameters: The part radius and sign, the IPL diameter, the thickness of the individual IPL layers and their materials (described by the Mooney Rivlin parameter C01), as well as the process pressure are sufficient to obtain a model with the highest possible quality of prediction.

The CoPs of the individual parameters are found in chapters 7.3.1 and 7.4.1 respectively.

In the course of the sensitivity analysis for the single layer configuration, a large number of components were virtually produced on the VAMM tool. On the basis of the data obtained the following question could be answered:

Q4.3 Can dimpling be minimised sufficiently in VAMM using a single layer rubber IPL?

For answering this question, a dimpling threshold was defined as \( D_{vol} \leq 0.1 \, mm \), which is well within the established norms for moulded plastic components. When this threshold is met, the dimpling is considered insignificant. Within the designs evaluated for the sensitivity analysis, \(~5\%\) of designs meet this criterion. This means, that a single layer IPL can well be used to sufficiently minimise dimpling in VAMM.

However, from these 5% of designs some perform better than others in supressing dimpling, which led to the following question:
Q4.4 What is an ideal single layer IPL for VAMM?

This question was approached using optimization techniques. The optimisation objectives said that the dimpling value and the IPL thickness should be minimised, while the process pressure should be maximised (see chapter 7.1). Using an evolutionary algorithm on the on the previously created MOP, an optimal design was found that is capable of sufficiently supressing dimpling for the single layer IPL configurations on the given VAMM tool as shown in chapter 7.2.2. This configuration uses a process pressure of 0.80 bar, and an IPL made of a single layer of red silicone rubber (see appendix C - 1) with a shore hardness of 60 ShA and a thickness of 28.9 mm. According to the MOP, this configuration results in a dimpling $D_{vol}$ of 0.10 mm.

The multilayer IPL was proposed in this thesis as a possibility to reduce dimpling without increasing the thickness of an interpolation layer. This led to the formulation of the following question:

Q4.5 Can a multilayer IPL decrease dimpling and increase shape fidelity?

Preliminary tests in chapter 4.4.3 showed that different layers of elastomer stacked on top of each other can reduce dimpling better than an equally thick single layer. To quantify this effect the research question Q4.6 had to be answered first. It turned out, that the optimised dual layer IPL configuration is superior to the optimised single layer IPL configuration. With this setup, it is possible to increase the process pressure by 24 %, increasing the conformation of the IPL to the pin array. Meanwhile the IPL thickness can be reduced by 9 %, reducing the loss in pin array resolution and in turn increasing the possible part complexity. The results were validated on the VAMM manufacturing model and proved to be in good agreement with the predicted solutions.

Q4.6 What is an ideal dual layer IPL for VAMM?

The ideal configuration for the dual layer IPL on the given VAMM test bench was evaluated similar to the optimised single layer IPL configuration (see chapter 7.4.2). It uses a process pressure of 0.99 bar. The IPL has a diameter is 299.6 mm, is made of a two layer with a total thickness of 26.47 mm, with the top layer being made from translucent silicone rubber with a Shore hardness of 40 ShA and a thickness of 5.7 mm, and the bottom layer being made from red silicone rubber with a Shore hardness of 60 ShA (see appendix C - 1) and a thickness of 20.76 mm. As for the single layer, this configuration results in a dimpling $D_{vol}$ of 0.10 mm, according to the MOP.

Since all partial questions of research question Q4 have been answered, the answer to the question itself can be summarized as follows: Dimpling can be minimised sufficiently in VAMM with a single, as well as, dual layer IPL configuration. Best results can be obtained for the single layer using the configuration in table 7.3.3. The shape fidelity of the VAMM tool can be improved however, by using the dual layer IPL configuration in table 7.4.3.
Overall, the results of this thesis show that the VAMM technology is capable of producing high quality, doubly curved, fibre-reinforced plastic composite parts. That is why it has a high potential to drastically reduce the time and cost involved in manufacturing small batch sizes and especially one-offs.
8.2 Limitations and Prospects for Future Work

In the course of this work, all the research questions raised were addressed and all the defined goals were achieved. In some areas, however, there are limitations, which should be mentioned as well. But these restrictions could also represent potential in the future. For this reason, further measures and future activities are outlined, which could lead to converting the high technological potential of the VAMM technology into a commercial success.

**Operational reliability of the actuator system**

The VAMM technology itself and all its critical components were developed, built and demonstrated successfully. Especially the pin and actuator design were developed from scratch. Compared to established concepts, the new design resulted in a cost reduction of nearly 40 % for a tool the size of the VAMM prototype. However, further development is still necessary in order for VAMM to work in an industrial setup. Especially the reliability of the actuators and the coupling mechanism in particular, need to be improved. The optimisation measures carried out in chapter 4.7 lead to the tool being well suited for an academic laboratory demonstrator, but the remaining coupling error rate of 6 % would still result in the system being to error-prone for a real industrial application.

![Figure 8-1 - Detailed view of a coupling error](image)

To improve the design of the coupling mechanism and and prevent interlocking between the clutch claw and the torque bar, it would be desirable to minimise the contact area between the two that could potentially interlock. Figure 8-1 shows the detailed view of a coupling error. There, the torque bar rests on the sloping flank of the clutch. By increasing the size of the torque bar or decreasing the diameter of the clutch, this type of contact would no longer be possible. Instead, only the tips of the clutch could get into contact with the bar. This should potentially prevent most coupling errors.
Validation of additional manufacturing processes

In this thesis, all CFRP components were manufactured on the VAMM tool using the vacuum bagging process. Due to the similarity in regards to the moulds, other manufacturing processes like VI or VARTM are expected to be usable as well. However, this is not validated in the course of this work. Hence, further investigations regarding the suitability of the VAMM tool for these and other manufacturing processes are recommended.

Geometric complexity of parts

The geometric complexity of VAMM manufactured parts remains limited. Even though, the application of a vacuum, the introduction of multiple IPL layers and the minimisation of IPL layer thickness do increase the capabilities to produce smaller curvatures and parts with inflection points, the manufacturing of edges or beadings is still not possible.

In the course of the FlexForCFK project the component portfolio of Airbus Helicopter was examined. In the course of the investigation, components were sought which only have radii greater than 100 mm and no edges or corners. This radius corresponds to the minimum value used in the VAMM manufacturing model. Furthermore, the components could not be larger than the production area of the VAMM full-scale prototype. Out of all components evaluated, some 20 parts (<1%) met these requirements and could therefore in all probability be produced on the developed system (see chapter 1.2). Most of these components are flaps, lids or small cladding parts of commercial helicopters. However, if a larger production area were available, significantly more parts could be produced from the company’s portfolio. The limitation of not being able to reproduce corners, edges and beads also severely restricts the range of possible applications. With VAMM, these geometric features are limited by the resolution of the multi-point tool. However, this cannot be increased at will for technical and cost reasons.

In order to be able to produce components with filigree structures on the tool anyhow, attachments are needed, which could be produced using additive manufacturing (AM). Within the FlexForCFK project (see chapter 1.2) the University of Applied Sciences Nurnberg investigated the possibility to enable such geometric features by using 3D printed attachments that could be applied to the IPL [Lušić et al. 2016a]. They used 3D printed miniature attachments to create edges, corners and ribs on a VAMM manufactured parts [Lušić et al. 2015]. Different designs for such attachments were evaluated [Lušić et al. 2016a], printed in advance and then placed on the VAMM. The investigations carried out here showed promising results: The geometric limitations of MPT could be significantly reduced and the range of components that could be manufactured significantly expanded. In addition, the fundamental disadvantage of additive manufacturing, the high costs and construction
times for large, flat components, could be avoided [Lušić et al. 2015]. However, the actual implementation of the concept was not part of the Flex4CFK project.

Hence, based on these results, a current project at the Munich University of Applied Sciences tries to integrate the additive manufacturing process directly in the VAMM process. The miniature attachments are therefore no longer printed in advance and placed on the tool by hand. Instead, they are printed directly on the already adjusted VAMM tool using an industrial robot arm, adapted for 3D printing using fused filament fabrication (FFF) or fibre-deposition modelling (FDM).

**Adjustable radiation heating in other applications**

The radiation heating system, developed as a part of the VAMM system could theoretically be used in other applications as well. Traditionally, ovens or autoclaves are used for the curing of fibre composite components. There, the heat is introduced into the component via (forced) convection. This heating process is often very inefficient. Nele et al. [2016] found, that heating in an autoclave can take much longer then theoretically necessary. Fehler! Verweisquelle konnte nicht gefunden werden. (a) shows an exemplary heating cycle for a high-performance CFRP prepreg with an epoxy resin matrix. The actual temperature curve of several components processed in an autoclave, are shown in Fehler! Verweisquelle konnte nicht gefunden werden. (b). It can be seen that the last component only reaches the minimum temperature after approx. 170 minutes, instead of 80 minutes as specified. From this point on, the actual curing cycle of 120 minutes begins. The entire cycle therefore lasts almost twice as long as the optimum cycle. This process time could be reduced by up to 50 % through ideal temperature control in the component. In addition to enormous energy savings, this would also lead to higher utilisation and productivity of the heating system.

![Figure 8-2](image)

*Figure 8-2 - Optimal heating and pressurizing cycle for a high-performance CFRP prepreg (a) and the actual temperature curves on the surface of composites in an autoclave (b) [Nele et al. 2016]*

By using infrared radiation for heat transfer in an autoclave, the surface of the components can be heated directly. In addition, compared to convection, a significantly higher heat flow can be transferred. This could be achieved by converting
the open loop controller for the radiation proposed by Gruber [2017] (see chapter 4.4.4) to a closed loop controller. This would increase the versatility of the system, as well as the heating performance. To this end, the following objectives are to be achieved:

- The surface or geometry to be heated should be automatically recognised.
- The current surface temperature of the target should be measured two-dimensionally.
- A system internal digital twin should use the metrological and temperature data to optimise the temperature distribution.

This way, the adaptive radiation heating system could be a real alternative to convection heating for composite hardening jobs.

**Validation of mechanical properties**

When looking at the experimental evaluation of the mechanical properties of VAMM manufactured parts, it can be concluded that VAMM technology is capable of manufacturing components of high mechanical quality. However, it has to be mentioned that the data collected is not statistically satisfying in all cases. This is due to the high variance in the manufacturing quality and the small sample size, which limit the reliability of the results significantly. However, the manufacturing quality could not be improved further with the laboratory setup used and with the staff available. Qualified FRP manufacturing technicians should be able to improve the part quality and reduce the variance of the measured values, for both the VAMM-made and the reference panels. However, with the available tests, it can be concluded that VAMM technology is capable of manufacturing components of high mechanical quality as well. If the interpolation of the tool surface is sufficient to produce dimpling free components, the mechanical properties are presumably not negatively affected by the manufacturing process.

**Physical effects in the VAMM manufacturing model**

The virtual VAMM manufacturing model can reliably predict the system behaviour. However, it is currently limited to ambient temperature applications. The FE component of the model is not yet capable of taking temperature depending effects into account. These effects could not be modelled in this thesis, since the measuring equipment necessary to conduct material testing at elevated temperatures was not available. With the availability of corresponding material properties for the interpolation layer, it should be possible to extend the model to include thermal effects. Increasing temperature in the model effectively leads to changed material properties, but the rest of the model remains unaffected. An adaptation should therefore not cause any problems.
The Mullins effect, which occurs in the interpolation layer, is a more complex issue. As described in chapter 3.3, rubber materials soften within the first couple of load cycles. In this thesis, this effect has been addressed by exclusively using preconditioned rubbers, which have been loaded at least five times. For an industrial application however, this would mean that the interpolation layer has to be stretched and relaxed over the pin array five times in order to get a consistent material behaviour. This would increase the work preparation for each part considerably, which does not seem feasible. Instead, the influence of the load sequence could be taken into account in the virtual model. In ANSYS, the Ogden–Roxburgh pseudo-elastic model [Ogden and Roxburgh 1999] can be used to model the Mullins effect. However, including this model in the material formulation would increase the complexity and runtime of the FE analysis significantly. Additionally, extensive material testing would be necessary to create the data needed for modelling this effect. For this work, the associated effort was not considered essential. For an industrial application, however, this assessment would at least have to be reviewed.

Modelling the full-scale prototype

In this thesis, the feasibility the virtual VAMM manufacturing model as a pre-processor was successfully demonstrated for the small-scale VAMM prototype. For an industrial application however, this application is insufficient. There, the actual manufacturing process on a full-scale VAMM tool has to be replicated. For that, a FE model of the full-scale VAMM tool needs to be implemented in the existing process chain. In this work however, this was not done, due to the associated dramatic increase in computing time. With the quarter model of the VAMM test-bench (which contains 37 pins), the sensitivity analysis took 1,150 hours and 1,300 hours for the single- and dual-layer IPL configurations, respectively. For a model of the full-scale prototype with its 572 pins and no applicable symmetry, the same calculations are expected to take approximately 71,000 hours and 80,600 hours respectively, assuming linear scaling. This would add up to 17.3 years in total, with the available computer hardware (see chapter 6.4). Even for a single shape error compensation, the full-scale model would probably need around 500 hours for four iterations. This is by far not quick enough and needs to be improved. One way of doing this could be improving the convergence of the shape control algorithm. This could be achieved by optimising the correction coefficient matrix \( c \) in equation (53).

Most likely however, this will still not be sufficient to reduce the calculation time to an acceptable amount. Hence, a new way of estimating the shape error has to be developed. One possibility would be the use of a reduced order model approach. This could, for example, be implemented based on an elementary cell model: A model of one single pin with a small area of interpolation layer and boundary conditions correlating to the position of this elementary cell in a full IPL could be designed. This model would then be used for exploratory data analysis and the creation of a MOP.
This MOP could then be used to estimate the IPL behaviour around each pin in the full-scale machine. The parameters for this estimation could be extracted from the CAD data of the part. This could be achieved using an algorithm similar to a kinematic draping algorithm as proposed by Tschebyschow [1878] or Biswas [1996].

**Generalization of the sensitivity analysis and optimization**

The results of the optimisation process are absolute and only valid for the physical VAMM tool at hand. Other tools e.g. with other pin shapes or sizes will need to be optimised individually. The VAMM manufacturing model includes all parameters that can be varied in the physical system. For the analysis and optimisation of VAMM in this work however, some of the parameters were fixed either to reduce computation time or because they were not relevant for the given system. The pin size, pin head radius and part chord length were not varied in the analysis. Additional parameter studies could be conducted on the developed model including these parameters. This could potentially lead to a more generalized understanding of the VAMM process, the identification of generalised dependencies between the parameters, or even the discovery of a generalized equation for dimensioning of IPLs.
8.3 Personal Outlook and Assessment

In 2017, Prof. Christoph Maurer and the author himself initiated the project Flex4Concrete at the Munich University of Applied Sciences, aiming to develop a reconfigurable shuttering element for concrete construction. Together with the Technical University of Nuremberg, they developed a process for the realisation of three-dimensionally curved structural precast concrete elements in a simpler, faster and more cost-effective way. For architects, such a technology would open up greater creative possibilities and creative scope. The solution principle is also based on the multipoint tooling technology, which make it possible to form a multitude of different geometries quickly and without additional material expenditure. The rigid form is replaced by a multitude of adjustable pins, which can be flexibly adjusted from CAD data. The resulting stepped representation of the desired freeform surface is smoothed with an elastic interpolation layer, which also represents the mould surface. As part of the project, a first mock-up of the tool has already been developed, based on which the final shuttering element will be constructed. In addition, reference components (thin textile concrete shells and thick-walled fibre-reinforced concrete components) were created with a conventional shuttering, serving as a reference geometry for the project. The next step is to develop the interpolation layer against which the component will later be concreted. Furthermore, various reinforcement options and the use of adapted concrete formulations for the application are tested.

In 2018, Adapa\textsuperscript{51}, a young Danish company, supplied 85 of their Adaptive Moulds\textsuperscript{TM}, which is their own adaptation of a multipoint tool, to Kuwait. There the moulds are going to be used to build 40,000 interior wall and ceiling panel elements for a new passenger terminal at Kuwait international Airport (KWI), as shown in figure 8-3.

\includegraphics[width=\textwidth]{figure8_3}

Figure has been removed due to Copyright restrictions

Together with the successful use of MPT technology in the building of the Dongdaemun Design Park in Seoul, Korea and components for the Olympic Stadium in Beijing, China, this indicates, that the area of civil engineering is the most promising

\textsuperscript{51} Adapa, Aalborg Denmark
for the MPT technology. The reason for this might be in the cost structure of such huge building projects. MPT tools can very well be described as expensive. For a manufacturing contractor this makes it difficult to invest in such a tool, since several contracts are required to amortise this investment. Changes in demand could easily lead to the MPT no longer being capable to produce the required parts. This would make it easier and less risky, to rely on individual tools, which are completely assignable to an individual order. In large construction projects, however, many similar components are required. Furthermore, at the time of purchase of a tool, the parts to be produced on it are already known. Hence, purchase costs can be fully passed on to the construction project and the risk of amortisation is therefore minimal. This makes the construction industry the ideal target group for MPT tools and civil engineering the ideal research area for future MPT research.
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Appendix A

Studies
## Appendix A - Interpolation layer materials

### Table 8-1 - Interpolation layer materials

<table>
<thead>
<tr>
<th>Interpolator material</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>[Nakajima 1969], [Hardt and Gossard 1980], [Pham et al. 2011],</td>
</tr>
<tr>
<td></td>
<td>Unspecified [Nakajima 1969], [Finckenstein and Kleiner 1991]</td>
</tr>
<tr>
<td>Natural rubber</td>
<td>[Wolak et al. 1973], [Zhang et al. 2008]</td>
</tr>
<tr>
<td>Silicon rubber</td>
<td>[Walczyk et al. 2003], [Simon et al. 2013]</td>
</tr>
<tr>
<td>Nitril rubber</td>
<td>[Walczyk et al. 2003], [Simon et al. 2013]</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>[Eigen 1992], [Walczyk et al. 2003], [Munro et al. 2004], [Wang et al. 2005], [Zhang et al. 2008], [Su et al. 2012],</td>
</tr>
<tr>
<td>Neoprene®</td>
<td>[Eigen 1992]</td>
</tr>
<tr>
<td>Elvax®</td>
<td>[Eigen 1992], [Paunoiu et al. 2008], [Walczyk et al. 2003]</td>
</tr>
<tr>
<td>Polyether</td>
<td>[Pedersen and Lenau 2010], [Walczyk et al. 2003], [Walczyk and Munro 2009]</td>
</tr>
<tr>
<td>Plaster</td>
<td></td>
</tr>
<tr>
<td>Wood filler</td>
<td>[Wang 2009]</td>
</tr>
<tr>
<td>Plastilicin®</td>
<td>[Nakajima 1969],</td>
</tr>
<tr>
<td>Aluminium</td>
<td>[Paunoiu et al. 2015b]</td>
</tr>
<tr>
<td>Steel</td>
<td>[Nakajima 1969], [Selmi and Belhadjsalah 2013]</td>
</tr>
<tr>
<td>Other</td>
<td></td>
</tr>
<tr>
<td>Specifically designed layers with added functionality</td>
<td>[Simon et al. 2013], [Hundt et al. 2014]</td>
</tr>
<tr>
<td>Blends</td>
<td></td>
</tr>
<tr>
<td>Sandwich structures</td>
<td>[Yuan et al. 2004], [Liu et al. 2016], [Munro et al. 2004], [Walczyk and Munro 2009]</td>
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</tbody>
</table>
## A - 2 Cost for different actuator concepts

<table>
<thead>
<tr>
<th>Actuator Concepts</th>
<th>Cost (€)</th>
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</thead>
<tbody>
<tr>
<td><strong>High Actuator</strong></td>
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</tr>
<tr>
<td>Die Frame</td>
<td>30,000.00</td>
</tr>
<tr>
<td>Controls &amp; Wiring</td>
<td>12,000.00</td>
</tr>
<tr>
<td>Actuators</td>
<td>4,700.00</td>
</tr>
<tr>
<td>Electric Components</td>
<td>6,000.00</td>
</tr>
<tr>
<td>Total</td>
<td>77,000.00</td>
</tr>
<tr>
<td><strong>Medium Actuator</strong></td>
<td></td>
</tr>
<tr>
<td>Die Frame</td>
<td>25,000.00</td>
</tr>
<tr>
<td>Controls &amp; Wiring</td>
<td>12,000.00</td>
</tr>
<tr>
<td>Actuators</td>
<td>4,200.00</td>
</tr>
<tr>
<td>Electric Components</td>
<td>5,000.00</td>
</tr>
<tr>
<td>Total</td>
<td>46,500.00</td>
</tr>
<tr>
<td><strong>Low Actuator</strong></td>
<td></td>
</tr>
<tr>
<td>Die Frame</td>
<td>20,000.00</td>
</tr>
<tr>
<td>Controls &amp; Wiring</td>
<td>12,000.00</td>
</tr>
<tr>
<td>Actuators</td>
<td>4,000.00</td>
</tr>
<tr>
<td>Electric Components</td>
<td>4,000.00</td>
</tr>
<tr>
<td>Total</td>
<td>30,000.00</td>
</tr>
</tbody>
</table>

*Note: Costs are listed in €.*
A - 3  Evaluation of O-ring seals

The pin concept uses O-rings to seal off the vacuum in the vacuum chamber. Since 2,000 pins/m² (or 572 for the prototype) are fed through the baseplate, sufficient sealing is crucial. In order to validate the tightness of the O-rings in use, an experiment was carried out. The O-rings were stressed with three load cycles with 14,000 revolutions each, making 36,000 revolutions in total. This would account for approximately 500 setup processes or 500 individual part geometries created on the tool.

The base plate, bearing and seal of a single pin were replicated for the test. The leadscrew was shortened just above the base plate. A vacuum pump with pressure gauge and a suction cup were used to create a vacuum on the top of the base plate. The pressure drop through the seal was measured at zero revolutions, as a reference and then in three cycles with 14000 revolutions each. For each cycle, the direction of rotation was reversed to prevent one-sided wear of the O-ring. The velocity during the load cycles was set to 240 revolutions per minute.

The O-rings used are 6x2.0 mm (Art. No OR2000600-N7003) and 6 x 2.2 mm (Art. No OR2200600-N7003) NBR70 O-rings manufactured by Sahlberg\textsuperscript{52}. They are lubricated using LGMT 3 mineral oil based, lithium soap thickened grease.

The relative pressure drop is the measured drop in pressure minus the leakage of the measuring system. This was evaluated by doing the same test not on the test setup but on a solid block of aluminium.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure_A-1_Leakage_of_6x2.0_mm_NBR70_O-ring.png}
\caption{Leakage of 6x2.0 mm NBR70 O-ring}
\end{figure}

\textsuperscript{52} Sahlberg GmbH, Feldkirchen, Germany
Figure A-1 shows the relative drop in pressure at the seal with a 6x2.0 mm NBR70 O-ring. It shows that the seal works steadily directly after assembly, and after the first load cycle, with a leakage of \( \sim 0.38 \text{ mbar/s} \). Even though this value is too high for an application in the VAMM prototype \((572 \times 0.38 \frac{\text{mbar}}{s} = 217.37 \text{ mbar/s})\), afterwards leakage drastically increases. After the second load cycle, it increases ten times to \( \sim4.56 \text{ mbar/s} \) to fall to \( \sim3.31 \text{ mbar/s} \) after the last load cycle. This variable behaviour suggests that the O-ring is too small and cannot reliably seal the gap between the baseplate and the pin. Instead, the grease sometimes closes and seals the gap. This however is not a reliable solution.

Figure A-2 shows the relative drop in pressure at the seal with a 6 x 2.2 mm NBR70 O-ring. This ring seals the pin bearing much more sufficiently. Even though, the leakage is even higher after assembly, than with the 2.0 mm ring, with an average of \( \sim0.47 \text{ mbar/s} \) it drops significantly afterwards. After the first second and third load cycle, the leakage is approximately \( \pm0.05 \text{ mbar/s} \). This is within the accuracy of measurement with the used equipment. This solution is therefore considered sufficient and used in the VAMM prototype.

![Figure A-2 - Leakage of 6x2.2 mm NBR70 O-ring](image)
## A - 4 Properties of Different Elastomers

The following table compiles the material properties of different available elastomers, which could potentially be used as an interpolation layer. [Mycin Inc. 2016]

<table>
<thead>
<tr>
<th>Elastomer</th>
<th>Buna-N (Nitrile)</th>
<th>Butadiene, Styrene Butadiene</th>
<th>Butyl</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Brief Summary</strong></td>
<td>Nitrile has good mechanical properties and high wear resistance relative to other elastomers. Unless they are specially compounded, nitrile is not resistant to weathering, sunlight and ozone.</td>
<td>SBR is similar to natural rubber. SBR is mostly used in tires and seals for non-mineral oil based applications.</td>
<td>Butyl has a very low permeability rate making it a great seal under vacuum. Butyl also has good electrical, shock dampening properties.</td>
</tr>
<tr>
<td><strong>Economy (Cost)</strong></td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td><strong>Tensile Strength</strong></td>
<td>1,5</td>
<td>1,5</td>
<td>2</td>
</tr>
<tr>
<td><strong>Maximum Elongation (%)</strong></td>
<td>600</td>
<td>600</td>
<td>800</td>
</tr>
<tr>
<td><strong>Min Hardness (Shore A)</strong></td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td><strong>Max Hardness (Shore A)</strong></td>
<td>90</td>
<td>90</td>
<td>80</td>
</tr>
<tr>
<td><strong>Resilience/Rebound</strong></td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td><strong>Compression Set</strong></td>
<td>1,5</td>
<td>1,5</td>
<td>2,5</td>
</tr>
<tr>
<td><strong>Tear Resistance</strong></td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td><strong>Gas Impermeability</strong></td>
<td>1,5</td>
<td>2,5</td>
<td>1</td>
</tr>
</tbody>
</table>
Chloroprene (Neoprene®) exhibits good oil, ozone, weather, aging, refrigeration and chemical resistance. It also has good mechanical properties over a wide temperature range.

<table>
<thead>
<tr>
<th>Neoprene®</th>
<th>Ethylene Propylene</th>
<th>Fluorocarbon (Viton®)</th>
<th>Fluorosilicone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Copolymer has excellent resistance to phosphate ester fluids, brake fluids (glycol base), steam, weather, and ozone.</td>
<td>Responds very well with resistance to ozone, high temperatures, oxygen, mineral oil, synthetic hydraulic fluids, fuels, aromatics and many organic solvents and chemicals. The universal O-ring.</td>
<td>Has excellent resistance to petroleum oils and fuels. Fluorosilicone has limited strength and abrasion resistance so it is generally recommended for static applications only.</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>1,5</td>
<td>2</td>
<td>1,5</td>
<td>3,5</td>
</tr>
<tr>
<td>600</td>
<td>1,5</td>
<td>300</td>
<td>600</td>
</tr>
<tr>
<td>40</td>
<td>40</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>90</td>
<td>90</td>
<td>95</td>
<td>80</td>
</tr>
<tr>
<td>1,5</td>
<td>2</td>
<td>2,5</td>
<td>2</td>
</tr>
<tr>
<td>2,5</td>
<td>1,5</td>
<td>1,5</td>
<td>1,5</td>
</tr>
<tr>
<td>2</td>
<td>1,5</td>
<td>2,5</td>
<td>4</td>
</tr>
<tr>
<td>1,5</td>
<td>2</td>
<td>1,5</td>
<td>4</td>
</tr>
</tbody>
</table>
### Brief Summary

**Elastomer**

- **Silicone**
  - Silicon exhibits great temperature range capabilities.
  - Silicones also have good resistance to ozone, weather, and is also a good insulator. However, it has low tensile, tear, and wear resistance.

- **Hydrogenated Nitrile**
  - HNBR has excellent abrasion, compression set, tensile, and tear properties. Unlike standard nitriles, HNBR resists ozone, sunlight, and other atmospheric environments.

- **Natural Rubber / Isoprene**
  - Natural Rubber / Isoprene has excellent dynamic properties. However, it does not do well with petroleum oils, sunlight, and ozone.

<table>
<thead>
<tr>
<th>Property</th>
<th>Economy (Cost)</th>
<th>Tensile Strength</th>
<th>Maximum Elongation (%)</th>
<th>Min Hardness (Shore A)</th>
<th>Max Hardness (Shore A)</th>
<th>Resilience/Rebound</th>
<th>Compression Set</th>
<th>Tear Resistance</th>
<th>Gas Impermeability</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Silicone</strong></td>
<td>3</td>
<td>4</td>
<td>800</td>
<td>25</td>
<td>80</td>
<td>2,5</td>
<td>1,5</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td><strong>Hydrogenated Nitrile</strong></td>
<td>4</td>
<td>1</td>
<td>340</td>
<td>50</td>
<td>90</td>
<td>-</td>
<td>1,5</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td><strong>Natural Rubber / Isoprene</strong></td>
<td>2</td>
<td>1</td>
<td>700</td>
<td>40</td>
<td>90</td>
<td>1</td>
<td>2</td>
<td>1,5</td>
<td>3</td>
</tr>
</tbody>
</table>
Polyacrylate

Polyacrylate is used in applications such as transmissions or anything where there is petroleum oils and high temperature. Highly resistant to ozone and weathering.
A - 5 Friction Coefficients

The contacts both between the IPS layers and between punch head and IPS are subject to friction. Both these frictional contact conditions are defined in the simulation model. The coefficients of friction are determined according to DIN EN ISO 8295 [DIN Deutsches Institut für Normung e. V. 2004]. This standard describes the evaluation of the coefficients of static and sliding friction. It is intended especially for plastic films and sheets sliding over themselves or over other materials. The standard is limited to non-sticky plastics with material thicknesses up to max. 0.50 mm. However, the silicone sheets used exhibit sticky material behaviour. The material thicknesses are also clearly above the specified maximum value. Therefore, the tests can only be carried out in approximation to the standard.

The coefficient of friction can be calculated by

\[ \mu_s = \frac{F_s}{F_n} \]  

(71)

where \( F_s \) is the static friction force (the force needed to overcome friction) and \( F_n \) is the normal force.

The two coefficients of friction are determined using the experimental setup, shown in figure a-3. For the coefficient of friction between two silicone layers, the lower layer ("IPS (fixed)") is attached to the worktable together with the base plate 2. The lower silicone layer ("IPS (fixed)") is not required for the friction between the aluminium plate and the IPS and is therefore removed.

Figure A-3 - Schematic of the friction test setup for evaluating the friction coefficient between two silicon rubber IPL materials

Two ground steel plates (with a surface roughness of \( R_a = 0.3 \mu m \)) are used as base plates. Both test surfaces must be free of dust and grease, which would otherwise alter the friction properties. The actual test is carried out on the right-hand plate. The left serves as the sliding surface for the load cell. Preliminary tests show that the resulting friction can be neglected in good approximation. The silicone pair placed
on the right plate has a standard size of 80.0 mm x 200.0 mm. The material has a nominal hardness of 60.0 HA and is 2.0 mm thick. A screw clamp fixes the lower IPS and the base plate firmly to the table. The upper IPS rests loosely on the lower IPS and can therefore move freely. The normal force is generated by a carriage with a square contact area of 40.0 cm² (edge length 63.0 mm). A uniform pressure distribution is ensured by underlying a piece of felt of the same size. The total mass of the carriage is 199.5 g and is therefore within the required tolerance of 200.0 g ±2.0 g. A thin holding plate with double-sided adhesive tape is glued to the left end of the upper IPS. A thin plastic wire is attached to this plate, which is connected to the load cell. This mounting unit weighs 3.5 g, undershooting the maximum permissible weight of the fastening of 5 g. The tractive force for the test is generated by hand. The forces are measured using a K-25 load cell (max. permissible load 50.0 N) and recorded with the Almemo 2690 data logger from Ahlborn at 0.5 s intervals. Since the friction forces to be expected are in the lower third of the measuring range, large measurement inaccuracies should be expected. Consequently, the load cell was first tested with standard weights of 0.5 kg and 1.0 kg. The results confirmed the load cell as a suitable measuring device. The measured tensile force corresponds to the friction force. The coefficient of friction can then be calculated from the ratio of the measured friction force and the normal force.

For each friction pair, 10 measurements are performed. The arithmetic mean value is then calculated from the sample size:

Friction coefficient IPL – IPL

\[ \mu_{H1} = 0.728 \]

Friction coefficient aluminium – IPL

\[ \mu_{A1} = 0.328 \]

53 Ahlborn Mess- und Regelungstechnik GmbH, Holzkirchen, Germany
Appendix B

Software
B - 1 User Interface Functions

Figure B-1 - Required functions and options for the VAMM user interface
B - 2 VAMM System Control Function Blocks

Figure B-2 - Function block for controlling the power stage and the closed loop mode

Figure B-3 - Function block for referencing the drives, homing methods on block, on switch, on internal reference and on the current position are supported.

Figure B-4 - Function blocks for moving the motor: MoveVelocity sets the motor to speed-controlled mode, MoveAbsolute and MoveRelative move to a position either in reference to the zero point (absolute) or in reference to the current position (relative).

Figure B-5 - Function blocks for reading and writing the I/Os of the Nanotec PD 4 and PD 6 motors

Figure B-6 - Function block for controlling the clutch of the actuator unit
Figure B-7 - Function block for complete setting of a single pin

Figure B-8 - Function block for positioning the linear unit; X positions are approached via the stepper motor of the linear unit and Y positions via the pneumatics of the linear unit.
Appendix B Software

B - 3 MATLAB Geometry Evaluation Toolbox

Figure B-9 - UML class diagram of the GeoComp toolbox
OptiSLang offers the possibility to implement custom optimisation algorithms. The shape control algorithm is implemented in Python 2.6 using the optiSLang Python API in version 6.2.0\textsuperscript{54}. The algorithm works as shown in Figure B-10. At the beginning, the parameters are instantiated and their values checked for validity in InitializeAlgorithm. Afterwards, the first design for the optimiser is created in the function block getNextDesigns. Since no further information is available at the beginning of the optimisation, the initial pin coordinates are used which were previously calculated. This design is passed to Simulation and Evaluation to calculate the remaining shape error at the support points as a system response. The results of this process are retrieved by SetResults and passed to the custom algorithm. In Appraise, the termination criteria for the optimisation algorithm are calculated. IsTerminated then checks whether these termination criteria are fulfilled. If this is not the case, the next design for the optimiser is calculated in Adapt and passed to getNextDesigns. This process is repeated until at least one abort criterion is fulfilled. Then IsConverged checks whether the optimiser was able to reduce the shape error successfully or another termination criterion led to this not being possible.

These functions are compiled in \texttt{MPTShapeController} (see Figure B-11). Rms (root mean square error), \texttt{am} (absolute maximum error) and the \texttt{contact\_force} are computed in Adapt. Based on the results, IsTerminated decides to continue or terminate the optimisation. IsConverged then compares the values to the predefined

\textsuperscript{54} OptiSLang Python API 6.2.0. Dynardo GmbH, Weimar, Germany.
threshold values defined in the settings datatype and evaluates the convergence state.

<table>
<thead>
<tr>
<th>MPTShapeController</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>-parameters: PyParameterManager</td>
<td>-parameters: PyParameterManager</td>
</tr>
<tr>
<td>-start_designs: PyOSDesignContainer</td>
<td>-start_design: PyOSDesignContainer</td>
</tr>
<tr>
<td>-settings: PyOSDesignPoint</td>
<td>-responses: PyOSDesignPoint</td>
</tr>
<tr>
<td>-criteria: PyOSCriterionContainer</td>
<td>-criteria: PyOSCriterianContainer</td>
</tr>
<tr>
<td>-next_designs: PyOSDesignContainer</td>
<td>-seed: int</td>
</tr>
<tr>
<td>-results: PyOSDesignContainer</td>
<td>-settings: PyOSDesignPoint</td>
</tr>
<tr>
<td>-all_violated: Bool</td>
<td></td>
</tr>
<tr>
<td>-rms: float</td>
<td></td>
</tr>
<tr>
<td>-am: float</td>
<td></td>
</tr>
<tr>
<td>-contact_force: float</td>
<td></td>
</tr>
<tr>
<td>+GetSettings(): PyOSDesignPoint</td>
<td>+maximumIterations: int</td>
</tr>
<tr>
<td>+CheckSettings(settings: PyOSDesignPoint): bool</td>
<td>+optimizationFactor: float</td>
</tr>
<tr>
<td>+InitializeAlgorithm(parameter: Parameters): bool</td>
<td>+rmsErrorThreshold: float</td>
</tr>
<tr>
<td>+GetNextDesigns(): bool</td>
<td>+absMaxErrorThreshold: float</td>
</tr>
<tr>
<td>+SetResults(designs: PyOSDesignContainer): bool</td>
<td>+contactStatusThreshold: float</td>
</tr>
<tr>
<td>+Appraise(): bool</td>
<td></td>
</tr>
<tr>
<td>+Adapt(): bool</td>
<td></td>
</tr>
<tr>
<td>+IsTerminated(): bool</td>
<td></td>
</tr>
<tr>
<td>+IsConverged(): bool</td>
<td></td>
</tr>
</tbody>
</table>

Figure B-11 - UML class diagram of the MPT shape control algorithm

The control algorithm ends with either an optimised pin configuration (isConverged = True) or with a failed design. The latter can happen either if the evaluated parameter set that cannot produce a convergent solution (e.g. the IPL cannot conform to the desired geometry) or if the forming simulation fails due to computational problems (e.g. no convergence due to ill conditioned or unsuccessful FEA or licence acquisition problems).
**B - 5  ANSYS Update**

The ANSYS workbench FE model of the VAMM tool is controlled via a custom update script in order to incorporate the specific functionalities needed. The UML class diagram is shown in Figure B-12.

![UML class diagram for the ANSYS VAMMUpdate control script](image)
Appendix C

Data Sheets
C - 1 Silicon Rubber Data Sheet

Silikon – Platten

Rollen – Matten – Streifen – Zuschnitte
Flach – Dichtungen – Ringe – Scheiben – Unterlagen

Stanzen * Wasserstrahlschneiden * Kiss Cut * CAD- Platten
• auch selbstklebend als Montagehilfe möglich
• Freihandfertigung geschäftet / geklebt
• Gummidicken doppelt / verklebt

Bezeichnung: VMQ
Beständigkeit: Sehr gute Beständigkeit gegen Alterung, Laugen, Säuren, auch in Verbindung mit sehr niedrigen und hohen Temperaturen, Öl und Treibstoff nur bedingt einsetzbar.

Verwendung: Allround-Qualität für anspruchsvolle Einsätze, sehr gute mechanische Werte bei hoher Beanspruchung für Dichtungen, Abstreifer, Unterlagen, Einlagen, Membranen.
Die rot und transluzente Qualität ist für den Einsatz in pharmazeutischen und Lebensmittelverarbeitenden Betrieben geeignet.

➢ Auf Anfrage weitere Stärken und Härten z.B. 30°b is 85° ± 5 Shore A

<table>
<thead>
<tr>
<th>Silikon</th>
<th>rot</th>
<th>Silikon</th>
<th>transluzent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Härte:</td>
<td>40 und 60 ± 5 Shore A</td>
<td>40 und 60 ± 5 Shore A</td>
<td></td>
</tr>
<tr>
<td>Farbe:</td>
<td>rot und weiß</td>
<td>transluzent</td>
<td></td>
</tr>
<tr>
<td>Spez. Gewicht:</td>
<td>1.30 g/cm³</td>
<td>1.15 g/cm³</td>
<td></td>
</tr>
<tr>
<td>Reißfestigkeit:</td>
<td>ca. 3.5 MPa</td>
<td>ca. 5 MPa</td>
<td></td>
</tr>
<tr>
<td>Reißdehnung:</td>
<td>ca. 300 %</td>
<td>ca. 350 %</td>
<td></td>
</tr>
<tr>
<td>Temperatur:</td>
<td>ca. -60 bis +250 °C</td>
<td>ca. -60 bis +200 °C</td>
<td></td>
</tr>
</tbody>
</table>

Lieferformat / mm

<table>
<thead>
<tr>
<th>Stärke</th>
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<th>1,5</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>8</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breite</td>
<td>1000 oder 1200</td>
<td>1200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Länge</td>
<td>10.000</td>
<td>5.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Artnr. Rot 40 °Shore A 15342 ..

| 0,5 | 0,1 | 0,51 | 0,02 | 0,03 | 0,04 | 0,05 | 0,06 | 0,08 | 0,10 |

Artnr. Rot 60 °Shore A 15442 ..

| 0,5 | 0,1 | 0,51 | 0,02 | 0,03 | 0,04 | 0,05 | 0,06 | 0,08 | 0,10 |

Artnr. Trans. 40 °Shore A 15352 ..

| 0,5 | 0,1 | 0,51 | 0,02 | 0,03 | 0,04 | 0,05 | 0,06 | 0,08 | 0,10 |

Artnr. Trans. 60 °Shore A 15452 ..

| 0,5 | 0,1 | 0,51 | 0,02 | 0,03 | 0,04 | 0,05 | 0,06 | 0,08 | 0,10 |

Figure C-1 - Data sheet: silicon rubber sheet material (German) [GaFa Tec Handels GmbH 2010]
Appendix C Data Sheets

C - 2 Epoxy Resin Data Sheet

[Image of the page with the text and diagram related to the Epoxy Resin Data Sheet]
### Eigenschaften

<table>
<thead>
<tr>
<th>Eigenschaften</th>
<th>Eigenschaftswerte</th>
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<tbody>
<tr>
<td>Feuchtigkeit</td>
<td>5% gr.</td>
</tr>
<tr>
<td>Flüchtige Bestandteile</td>
<td>1,1%</td>
</tr>
<tr>
<td>Weitere Eigenschaften</td>
<td>DIN EN ISO 527-5, DIN EN ISO 14055, EN 14470</td>
</tr>
</tbody>
</table>

### Sicherheitshinweise

- **Zulässige Umgebungstemperatur:** 0°C bis +40°C
- **Bruchdehnung:** DIN EN ISO 527-5, DIN EN ISO 14470
- **Ausmaß der Sicherheitshinweise:** DIN EN ISO 14470

**Allgemeine Anmerkung:**

Appendix D

Mechanical Testing
Appendix D Mechanical Testing

D - 1 Specimen Preparation

Figure D-1 - Manufacturing of sample plate on the VAMM tool
(a) VAMM tool, (b) adjusted tooling surface with IPL, (c) component manufacturing under vacuum

Figure D-2 - Manufacturing of sample plate reference aluminium tool

Figure D-3 - Specimen cut plan
### Appendix D  Mechanical Testing

#### D - 2  Tension Test

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
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<td>758</td>
<td>1,43</td>
<td>39333,76</td>
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<td>50600</td>
<td>764</td>
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<td>40639,97</td>
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<td>3</td>
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<td>802</td>
<td>1,45</td>
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<tr>
<td>6</td>
<td>52500</td>
<td>751</td>
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<td>7</td>
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<td>766</td>
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<td>8</td>
<td>52900</td>
<td>796</td>
<td>1,51</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>54200</td>
<td>719</td>
<td>1,36</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>52400</td>
<td>736</td>
<td>1,48</td>
<td>38158,47</td>
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</tbody>
</table>

| mean    | 53280,00 | 756,60 | 1,45 | 39377,40 |
| std. dev. | 2336,57 | 26,70 | 0,05 | 1241,33 |
| variance | 4% | 4% | 4% | 3% |
### Zug Platte 2 (15mm)

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Young’s modulus [MPa]</th>
<th>ultimate tensile strength [MPa]</th>
<th>strain [%]</th>
<th>fracture force [N]</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>41200</td>
<td>695</td>
<td>1,56</td>
<td>36907,16</td>
</tr>
<tr>
<td>2</td>
<td>52600</td>
<td>649</td>
<td>1,36</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>48900</td>
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<td>4</td>
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<td>5</td>
<td>45900</td>
<td>629</td>
<td>1,2</td>
<td>34732,73</td>
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<tr>
<td>6</td>
<td>50400</td>
<td>667</td>
<td>1,35</td>
<td></td>
</tr>
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<td>43500</td>
<td>708</td>
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<td>638</td>
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<td></td>
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<td>9</td>
<td>48300</td>
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<td>32657,38</td>
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<tr>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

*Die Erste Platte hatte nicht-linearen Verlauf und wurde deshalb gelöscht (vgl. PDF)*

**mean** 45677,78 641,56 1,36 35888,63  
**std. dev.** 4965,32 42,69 0,10 2837,96  
**variance** 11% 7% 7% 8%
### Tension test (20mm)

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<th>Young’s modulus [MPa]</th>
<th>Ultimate tensile strength [MPa]</th>
<th>Strain [%]</th>
<th>Fracture force [N]</th>
</tr>
</thead>
<tbody>
<tr>
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<td>611</td>
<td>1.3</td>
<td>34116.64</td>
</tr>
<tr>
<td>2</td>
<td>61200</td>
<td>600</td>
<td>1.01</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>60000</td>
<td>583</td>
<td>0.97</td>
<td></td>
</tr>
<tr>
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<td>5</td>
<td>52300</td>
<td>663</td>
<td>1.22</td>
<td>35377.4</td>
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<tr>
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<td>34283.16</td>
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<td>1.36</td>
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<td>690</td>
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<td>36526.79</td>
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<td>10</td>
<td>52300</td>
<td>724</td>
<td>1.43</td>
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</tr>
</tbody>
</table>

**mean**: 54840.00, 648.60, 1.25, 35111.68

**std. dev.**: 4710.08, 42.21, 0.16, 970.83

**Variance**: 9%, 7%, 12%, 3%
### Zug Platte 3 (25mm)

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<tr>
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<th>Young’s modulus [MPa]</th>
<th>ultimate tensile strength [MPa]</th>
<th>strain [%]</th>
<th>fracture force [N]</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>44600</td>
<td>700</td>
<td>1,52</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>53000</td>
<td>718</td>
<td>1,41</td>
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<tr>
<td>3</td>
<td>48800</td>
<td>712</td>
<td>1,36</td>
<td>37380,93</td>
</tr>
<tr>
<td>4</td>
<td>50500</td>
<td>595</td>
<td>1,13</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>49800</td>
<td>559</td>
<td>1,18</td>
<td>30992,37</td>
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<tr>
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<td>56300</td>
<td>668</td>
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<td>35135,73</td>
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<tr>
<td>7</td>
<td>54400</td>
<td>644</td>
<td>1,25</td>
<td>34075,11</td>
</tr>
</tbody>
</table>

**mean**

- Young’s modulus: 51057,14 MPa
- Ultimate tensile strength: 656,57 MPa
- Strain: 1,29%
- Fracture force: 34396,04 N

**std. dev.**

- Young’s modulus: 3896,95 MPa
- Ultimate tensile strength: 61,01 MPa
- Strain: 0,14%
- Fracture force: 2654,85 N

**variance**

- Young’s modulus: 8%
- Ultimate tensile strength: 9%
- Strain: 11%
- Fracture force: 8%
### Figure D-4: Measurement log of the thermogravimetry test

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<th>Dish Weight</th>
<th>Specimen &amp; Dish Weight</th>
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<th>Fibre Weight</th>
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