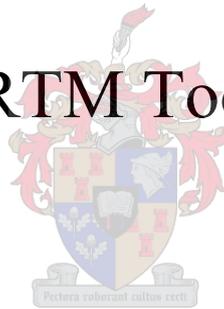




UNIVERSITEIT • STELLENBOSCH • UNIVERSITY
jou kennisvenoot • your knowledge partner

A Technical and Economical Evaluation of RP Technology

for RTM Tooling



D.J. Dippenaar

March 2010



Fakulteit Ingenieurswese
•
Faculty of Engineering



A Technical and Economical
Evaluation of RP Technology
for RTM Tooling

by

D.J. Dippenaar

*Thesis presented at the University of Stellenbosch
in partial fulfilment of the requirements for the
degree of*
Master of Science in Mechanical Engineering

Department of Mechanical and Mechatronic Engineering
University of Stellenbosch
Private Bag X1, 7602 Matieland, South Africa

Supervisor: Prof. K. Schreve

March 2010

DECLARATION

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

Signature: 

D.J. Dippenaar

Date: 28/11/2009

ABSTRACT

This project investigates the use of Rapid Prototyping (RP), with specific focus on Three Dimensional Printing (3DP), in the manufacture of complex shaped advanced composite parts, using variants of the Resin Transfer Moulding (RTM) method of composite manufacture. This study developed design guidelines, cost models and a process chain by studying data obtained by making example parts, from literature and consultation with industry. Advanced composite materials offer some of the best low weight and high specific strength properties for the solution of design problems. A major disadvantage of these processes, however, is the low production rates possible and the need of costly moulds. The 3DP technologies combined with the RTM composite process was found to enable a lowering of costs and increase in productivity if smaller batch sizes are considered. The most meaningful area of application for RP techniques seems to be for smaller and more complex components. The geometrical freedom allowed by RP technologies allowed the manufacture of parts which are challenging to manufacture by conventional technology such as CNC machining. Example part case studies were completed for a simple part utilising the one sided mould Resin Infusion RTM variant as well as for a complex part utilising the closed mould Vacuum Assisted Resin Transfer Moulding (VARTM) process variant. During these two case studies it was clear that proper part infusion with resin is critical for the manufacture of good quality composite parts free of voids and dry spots. It is possible to improve the resin infusion by correct placement of resin inlet and outlet ports as well as resin channels incorporated in the mould. Correct placement of these features for the case studies was obtained through simulations done with RTM-Worx software. Results also indicated that another useful application of RP technology to RTM is the manufacture of disposable cores for parts with thick cross sections. Resin channels were included on the surface of these cores to improve the mould filling with resin and consequently part quality. An early cost estimation model, based on the work of Veldsman (1995), was developed for the combined RP and RTM manufacturing process. This model may help designers to eliminate expensive design features and enables a quick cost comparison with competing processes. Drawbacks of applying RP techniques to RTM include the limited lifetime of moulds produced with 3DP and the size and accuracy limitations of the RP technology.

OPSOMMING

Hierdie projek handel oor die toepassing van die drie-dimensionele druk metode van Snel-Prototipering (Rapid Prototyping) op die vervaardiging van komplekse gevorderde saamgestelde materiaal komponente met die Hars-Inspuit Giet (Resin Transfer Moulding) metode. Die projek behels die opstel van ontwerpsriglyne, koste-modelle en 'n proses-ketting deur data te bestudeer wat bekom is deur middel van die vervaardiging van eksperimentele parte, literatuurstudie asook raadpleging met individue in die industrie. Gevorderde saamgestelde materiale verskaf van die beste sterk, dog ligte oplossings vir sekere ontwerpsprobleme. 'n Ernstige nadeel van hierdie materiale is egter die stadige produksietempo moontlik en die vereiste van duur gietstukke. Die Snel-Prototipering metodes, gekombineerd met 'n saamgestelde materiaal vervaardigingsproses, maak laer kostes met beter produktiwiteit moontlik indien ontwerpers die part grootte- en akkuraatheidsbeperkings in ag neem. Die mees betekenisvolle area van toepassing blyk kleiner en meer komplekse komponente te wees. Die vryheid in geometrie wat moontlik gemaak word deur die Snel-Prototipering tegnologie laat die vervaardiging toe van parte wat uitdagend is om te vervaardig met konvensionele tegnologie soos CNC masjinerie. 'n Gevallestudie is voltooi vir 'n eenvoudige part vervaardig met die enkelkant gietstuk vakuüm-infusie weergawe van die Hars-Inspuit Giet metode asook vir 'n komplekse part wat vervaardig is met die geslote gietstuk Vakuüm Hars-Inspuit Giet weergawe van die basiese metode. Dit het tydens die twee gevallestudies duidelik geword dat deeglike hars infusie van kritieke belang is vir die vervaardiging van goeie kwaliteit parte sonder enige droë kolle of lugruimtes. Dit is moontlik om die hars infusie te verbeter deur hars inlate en uitlate asook hars kanale in die korrekte posisies te plaas. Die korrekte posisies vir hierdie komponente is verkry deur middel van 'n reeks simulaties met die RTM-Worx sagteware. Resultate dui ook daarop dat Snel-Prototipering tegnologie handig te pas kom by die vervaardiging van verbruikbare kerne vir saamgestelde materiaal parte met groter diktes. Hars kanale kan maklik op die kerne se oppervlak geskep word om die hars verspreiding en gevolglik part kwaliteit te verbeter. 'n Vroeë kostevoorspellings model, gebaseer op werk voltooi deur Veldsman (1995), is saamgestel vir die gekombineerde Snel-Prototipering en Hars-Inspuit Giet proses. Hierdie model kan gebruik word om duur ontwerpsbesonderhede op parte te elimineer en om 'n vinnige koste vergelyking met ander vervaardigingsprosesse te toon. Nadele van die toepassing van Snel-Prototipering tegnieke op Hars-Inspuit Giet sluit die beperkte gietstuk-leeftyd en beperkte akkuraatheid in.

ACKNOWLEDGEMENTS

The author wishes to extend his deepest gratitude to the following persons and organisations for their contribution to the success of this study:

To my beloved wife, Jeanne-Mari for her unfailing encouragement and belief that I would succeed in this study.

To my parents, Corné and Rina Dippenaar and my brother, Diederick for all the years of unselfish, unfailing support, encouragement and love. I could not have asked for more.

To my grandmother, Dr. Edna Deudney for sowing the seed of my appreciation for knowledge and written work.

To my study leader, Prof. Kristiaan Schreve for your patience, guidance and advice.

To Philip Hugo, for assisting me with the manufacture of the RP parts and help with the CMM.

To Lawrie Droomer from Aerontec, for providing the composite materials as well as indispensable information regarding the composite manufacture processes.

To Josh Reinecke and Johan Kotze, for the valuable friendship during the past two years as well as the encouragement during all the coffee-breaks.

To Hanno Botha, Frankie Janse van Vuuren, Pieter Greeff, Gerrit de Villiers, Eugene Joubert and all my other post-graduate friends – thank you for all the advice and encouragement, you have been a true blessing!

To AMTS, SANHARP and Zikhona Lose for making this project financially possible; it has been a pleasure working with you!

And finally:

“He who dwells in the secret place of the Most High
Shall abide under the shadow of the Almighty.
I will say of the Lord, *He is my refuge and my fortress;*
My God in Him I will trust.”

Psalm 91:1-2

TABLE OF CONTENTS

	Page
Declaration.....	i
Abstract.....	ii
Opsomming.....	iii
Acknowledgements.....	iv
List of tables.....	viii
List of Figures.....	ix
Nomenclature.....	xi
1. Introduction	1
1.1 Motivation and background	1
1.2 Composite processes	2
1.2.1 Hand layup	3
1.2.2 Filament winding	3
1.2.3 Pultrusion	3
1.2.4 Sheet forming.....	3
1.2.5 Tape/tow placement.....	3
1.2.6 Autoclave processing.....	4
1.2.7 Continuous lamination.....	4
1.2.8 RTM, VARTM and Vacuum infusion.....	4
1.3 Rapid Prototyping	6
1.3.1 RP methods	7
1.3.2 Rapid Manufacturing	10
1.3.3 Rapid Tooling	10
1.3.4 Advantages of RP/RM/RT	11
1.3.5 Limitations	12
1.4 Research Objectives	13
2. Literature Review	14
2.1 RTM process	14
2.1.1 Mould filling	14
2.1.2 Permeability of fibres.....	16
2.1.3 Emissions	17

2.1.4	Practical tips.....	17
2.1.5	Cost estimation	18
2.1.6	Process variations	20
2.2	RT technology.....	21
2.2.1	RT methods.....	21
2.2.2	Build orientation	23
2.3	Use of RT technology in composite manufacture.....	24
2.3.1	General composite manufacturing.....	24
2.3.2	RTM tooling applications	27
2.3.3	Other advantages of RT tooling in composite moulding.....	28
3.	Part manufacture process chain	29
3.1	Process chain description	29
3.1.1	Virtual prototyping	29
3.1.2	Physical prototyping	29
3.2	RTM mould and part design considerations	31
3.3	Case study 1 – One sided mould with resin infusion.....	32
3.4	Case study 2 – Closed mould with inserts and VARTM	36
3.5	Resin flow simulations with RTM-Worx.....	40
3.5.1	Background.....	40
3.5.2	RTM-Worx process steps	41
3.5.3	Case study 1	41
3.5.4	Case study 2.....	44
3.6	Findings and recommendations.....	47
4.	Geometrical qualities.....	48
4.1	Case study 1	48
4.2	Case study 2	51
4.2.1	Unprocessed RP components.....	51
4.2.2	Processed RP components	53
4.2.3	Composite parts	55
4.3	CNC aluminium parts	57
4.4	Surface finish measurements.....	59
4.5	Conclusion and recommendations	60
5.	Early cost estimation models.....	62

5.1	Background	62
5.2	Conventional composite moulds	63
5.3	RP moulds	65
5.3.1	Preliminary work	65
5.3.2	Build time	66
5.3.3	RP mould	67
5.3.4	Part cost.....	69
5.3.5	Results.....	71
5.4	CNC aluminium moulds	72
5.5	Interpretation of results	73
6.	Conclusions	74
6.1	Review of thesis objectives.....	74
6.1.1	Design a process chain for the manufacture of composite parts.....	74
6.1.2	Complete a simple and complex part case study	74
6.1.3	Create a set of part and mould design rules	74
6.1.4	Determine dimensional deviations with the proposed RT-RTM hybrid process.....	74
6.1.5	Develop a cost model for the manufacture of composite parts.....	75
6.2	Applicability of RP technology to RTM.....	75
6.3	Part manufacture process chain.....	76
6.4	Use of cost estimation models.....	77
6.5	Recommendations and future work	78
7.	List of sources.....	80
	Appendix A: RTM design guidelines	86
	Appendix B: RTM-Worx results	98
	Appendix C: Geometrical data	104
	Appendix D: Cost models.....	107

LIST OF TABLES

	Page
Table 1: RP process comparison (Rao & Padmanabhan, 2007).....	9
Table 2: Constants for case study 1 simulation	42
Table 3: Constants for case study 2 simulation	45
Table 4: Standard deviation values for 6 sample parts	57
Table 5: Surface roughness values - case study 1.....	60
Table 6: Surface roughness values - case study 2.....	60
Table 7: Comparison of standard deviations in case study 1.....	61
Table 8: Comparison of standard deviations in case study 2.....	61
Table 9: Cost and times for case studies as predicted by Veldsman (1995).....	63
Table 10: Part manufacture times for case study 1	64
Table 11: Part manufacture times for case study 2.....	65
Table 12: Cost model predictions for RT-RTM process	71
Table 13: Cost model results for case of aluminium mould.....	72
Table 14: Part cost at maximum mould lifetime.....	73
Table 15: Updated material and other prices used in cost models.....	107
Table 16: Mould manufacture times for case study 1	108
Table 17: Mould manufacture times for case study 2.....	109
Table 18: Actual direct cost for case study 2 part.....	109
Table 19: Manufacturing times and costs for aluminium moulds	110

LIST OF FIGURES

	Page
Figure 1: RTM process (JHM Technologies, 2009).....	5
Figure 2: Metal skull patch manufactured on SLS machine.....	12
Figure 3: Cost components in RTM (Veldsman & Basson, 1998a).....	20
Figure 4: Classification of RT techniques (Rosochowski & Matuszak, 2000).....	21
Figure 5: Sand casting tool manufactured with EOS S700 machine.....	22
Figure 6: Staircase effect on RP parts Hugo (2008).....	24
Figure 7: Process chain for the manufacture of composite parts.....	30
Figure 8: Primed and sanded mould.....	33
Figure 9: Fractured mould complete with steel backing plate.....	34
Figure 10: Infusion setup (Govignon et al., 2008).....	34
Figure 11: Complete infusion setup (Engineer's Handbook, 2008).....	34
Figure 12: Fibre preform with spiral tubing for resin ports.....	35
Figure 13: Vacuum bagged mould with Greenflow.....	36
Figure 14: CAD model of blade core.....	37
Figure 15: Mould and core directly from 3D-printer.....	38
Figure 16: Core placed in mould with ports in position.....	39
Figure 17: Mould assembly ready for resin introduction.....	39
Figure 18: Carbon fibre blade.....	40
Figure 19: Completed RTM-Worx model for case study 1.....	42
Figure 20: Fully infused prediction.....	43
Figure 21: Comparison 1 of physical model to simulation.....	44
Figure 22: Comparison 2 of physical model to simulation.....	44
Figure 23: Initial simulation with no resin runners.....	45
Figure 24: Green cylinders represents runner positioning.....	46
Figure 25: Simulation at $t = 10$ s.....	46
Figure 26: Simulation at $t = 20$ s.....	47
Figure 27: Histogram with statistics for case study 1 unfinished tool.....	49
Figure 28: Measured points for case study 1 unfinished tool indicating deviations [mm].....	49
Figure 29: Histogram with statistics for case study 1 finished tool.....	50
Figure 30: Histogram with statistics for case study 1 sample part.....	51
Figure 31: Histogram with statistics for case study 2 unfinished tool bottom.....	52
Figure 32: Measured points for case study 2 unfinished tool bottom indicating deviations [mm].....	53
Figure 33: Histogram with statistics for case study 2 finished tool bottom.....	54
Figure 34: Measured points for case study 2 finished tool bottom indicating deviations [mm].....	54
Figure 35: Histogram with statistics for case study 2 used tool bottom.....	55
Figure 36: Histogram with statistics for case study 2 sample part bottom.....	56
Figure 37: Measured points for case study 2 sample part bottom indicating deviations [mm].....	56

Figure 38: Aluminium part with supports visible	57
Figure 39: Histogram with statistics for case study 2 aluminium part bottom	58
Figure 40: Measured points for case study 2 aluminium part bottom indicating deviations [mm]	59
Figure 41: Filleting of corners (Veldsman, 1995)	87
Figure 42: Chamfering of corners (Veldsman, 1995).....	87
Figure 43: Positioning of ply drop-offs (Veldsman, 1995)	88
Figure 44: Staggering of plies (Veldsman, 1995).....	89
Figure 45: Material transition (Veldsman, 1995)	90
Figure 46: Example for the correct use of inserts (Veldsman, 1995).....	90
Figure 47: Hole placement practice (Veldsman, 1995)	91
Figure 48: Schematic of RTM mould (Veldsman, 1995).....	92
Figure 49: Case study 2 resin distribution for t = 2 s.....	98
Figure 50: Case study 2 resin distribution for t = 52 s.....	99
Figure 51: Case study 2 resin distribution for t = 182 s.....	99
Figure 52: Case study 2 resin distribution for t = 473 s.....	100
Figure 53: Case study 2 resin distribution for t = 567 s.....	100
Figure 54: Case study 2 resin distribution for t = 6 s.....	101
Figure 55: Case study 2 resin distribution for t = 15 s.....	102
Figure 56: Case study 2 resin distribution for t = 26 s.....	102
Figure 57: Case study 2 resin distribution for t = 40 s.....	103
Figure 58: Case study 2 resin distribution for t = 56 s.....	103
Figure 59: Histogram with statistics for case study 2 unfinished tool top.....	104
Figure 60: Histogram with statistics for case study 2 finished tool top.....	105
Figure 61: Histogram with statistics for case study 2 used tool top	105
Figure 62: Histogram with statistics for case study 2 sample part 1 top	106
Figure 63: Histogram with statistics for case study 2 sample part 2 top	106

NOMENCLATURE

Abbreviations

CNC	Computer Numerically Controlled
CMM	Coordinate Measuring Machine
EDF	Error Distribution Function
FDM	Fused Deposition Modelling
HPL	High Permeability Layer
LM	Layered Manufacturing
LOM	Laminated Object Manufacturing
MJM	Multi-Jet Modelling
NC	Numerically Controlled
RIFT	Resin Infusion under Flexible Tooling
RM	Rapid Manufacturing
RP	Rapid Prototyping
RT	Rapid Tooling
RTM	Resin Transfer Moulding
RT-RTM	Rapid Tooling – Resin Transfer Moulding
SLA	Stereolithography
SLS	Selective Laser Sintering
SRIM	Structural Reaction Injection Moulding
VARTM	Vacuum-assisted Resin Transfer Moulding
VOC	Volatile Organic Compound
3DP	Three Dimensional Printing

List of symbols	Description	Unit
A_{ave}	Average area for printed RP sections	cm ²
A_{cost}	Monthly cost due to mould	R
A_f	Total outside surface area of master model	m ²
A_p	Surface area of part	m ²
A_T	Total mould area including area for clamping	m ²

A_{v1}	Additional area for vacuum clamping	m^2
A_{v2}	Additional area for manual clamping devices	m^2
b	Width of top hat section	m
C_P	Total part cost	R
C_1	Cost due to vacuum pump	R
C_2	Cost per part due to mould	R
C_3	Cost per part due to floor space rent	R
D	Diameter of dome	m
d	Fibre diameter of reinforcement	m
G_1	Geometrical constant for rectangular shape	m^2
G_2	Geometrical constant for dome-like shape	m^2
h	Height of top hat section	m
h_{total}	Total height of mould	m
k	Kozeny constant	unitless
$K_{permeability}$	Average permeability of fibre preform	m^2
k_{11}	Permeability in longitudinal fibre direction	m^2
k_{22}	Permeability in transverse fibre direction	m^2
$K_{1,2,3,4,5}$	Constant for reinforcement layer placement	unitless
$K_{6,7}$	Constant for mould filling with resin	unitless
L_{mould}	Length of mould	m
L_{Tophat}	Length of top hat section	m
M	Resin flow constant	s
m_{Binder}	Mass of RP binder for part	kg
$m_{infiltrate}$	Mass of resin to infiltrate RP part	kg
m_{Powder}	Mass of RP powder for part	kg
M_{P1}	Material cost for part using model 1	R
M_{P2}	Material cost for part using model 2	R
M_{P3}	Material cost for part using model 3	R
n	Kozeny constant	unitless
n_{clamp}	Number of manual clamps	unitless
n_{corner}	Number of sharp corners on top hat section	unitless
n_M	Number of moulds drawn from master model	unitless

N_P	Maximum number of parts per mould	unitless
n_P	Number of parts manufactured per day	unitless
n_{port}	Number of inlet plus outlet ports	unitless
n_{print}	Number of RP layers to be printed	unitless
n_R	Total number of part reinforcement layers	unitless
n_{resin}	Number of steps to fill mould backing with resin	unitless
$N_{sections}$	Number of sections to bond for RP mould	unitless
N_I	Number of months to reclaim capital	unitless
P_{binder}	RP binder cost	R/kg
P_{core}	Cost of part core	R
P_{Cost}	Cost price of RP mould	R
P_{fill}	Cost of filling mould backing with resin	R
P_i	Injection Pressure	kPa
$P_{infiltrate}$	Cost of low viscosity epoxy resin	R/kg
P_{labour}	Labour cost per hour for general work	R
P_M	Total mould cost	R
P_{Markup}	Mark-up on cost of RP parts	unitless
$P_{mould_material}$	Total mould material cost	R
P_O	Resin outlet pressure	Pa
$P_{Overheads}$	Overhead cost rate for RP parts	unitless
P_{paint}	Cost of 2 layers spray paint	R/m ²
$P_{painting}$	Cost of mould paint	R
P_{plate}	Cost of backing plate	R
P_{powder}	RP powder cost	R/kg
P_{primer}	Cost of 2 layers MS automotive primer	R/m ²
$P_{priming}$	Cost of mould priming coat	R
P_{resin}	Cost of epoxy resin for mould filling	R/cm ³
P_{Sell}	Selling price for RP mould	R
P_{steel}	Cost of 3 mm mild steel material	R/m ²
Q	Volumetric flow rate	m ³ /s
r_{cure}	Curing rate per layer for 3DP	unitless
r_{max}	Furthest resin path from inlet port	m

R_O	Inlet port radius	m
S	Permeability for Darcy equation	m^2
S_M	Average mould perimeter	m
S_P	Perimeter of part	m
S_{PO}	Outside perimeter of mould	m
T_{bag}	Total labour for vacuum bagging	min
T_{bag_place}	Labour time to cut and place vacuum bag	min
T_{bond}	Labour time to bond mould sections	min
T_{clean}	Time for RP part removal and cleaning	min
T_{clean2}	Labour time to clean mould between parts	min
t_{delay}	Delay time between printing of RP layers	s
T_f	Labour time to surface finish mould	min
T_{fill}	Model prediction for resin filling time	min
t_{fill_C}	Mould filling time for channel flow	min
t_{fill_R}	Mould filling time for radial flow	min
T_{fill2}	RTM-Worx prediction for resin filling time	min
$T_{greenflow}$	Labour time to cut and place greenflow layer	min
$T_{infiltration}$	Infiltration time for 3DP parts	min
T_{lead}	Lead time to complete RP mould	h
T_{L2}	Total part manufacture labour time	min
T_{occr}	Mould opening, closing and release time	min
t_P	Maximum part thickness	mm
T_{paint}	Labour time to paint mould	min
$T_{peelply}$	Labour time to cut and place peelply layer	min
T_{plate}	Labour time to manufacture and fit backing plate	min
T_{prime}	Labour time to prime mould	min
T_{print}	RP printing time	min
T_{print2}	Model prediction for RP printing time	min
T_{port}	Labour time to place piping for ports	min
T_{resin}	Labour time to fill mould backing with resin	min
T_{resin_prep}	Preparation time for infusion resin	min
T_{RL}	Total labour for reinforcement placement	min

T_{RLD}	Labour for reinforcement placement for dome	min
T_{RLP}	Labour for reinforcement placement for flat plate	min
T_{stitch}	Time allowance if preform is stitched or glued	min
T_{tacky_tape}	Labour time to seal vacuum bag with tacky tape	min
T_{total}	Total labour time for RP mould	h
T_{trim}	Part trimming time	min
T_{wax}	Labour time to polish mould with release wax	min
v_F	Fibre volume fraction	unitless
V_{mould}	Printed mould volume	cm ³
V_{resin}	Resin volume to fill mould cavity	cm ³
W_{mould}	Width of mould	m
α	Geometry constant for mould filling	unitless
Φ	Fibre layup angle	degrees
μ	Resin viscosity	kg/m.s

1. INTRODUCTION

This project investigated the use of Rapid Prototyping (RP) technologies in the manufacture of complex shaped advanced composite parts. The question that this study aims to answer is what RP can bring to the manufacture of these parts. This study developed design rules, cost models and a manufacturing process chain. The data was primarily obtained by making example parts (case studies), from literature study and consultation with industry.

Some background to the RP and RTM processes is firstly provided in Chapter 1 before a more focused investigation is completed in the literature review. Information gained during the literature review is then applied to the manufacture of case study parts in the process chain chapter. The geometrical qualities of the manufactured parts are then presented and discussed after which a model for the early cost estimation of these parts is presented. Finally, some conclusions are drawn on the basis of the presented results.

RP and composite material manufacturing methods are developing very fast and knowledge in both these fields will be valuable for any engineer in the manufacturing field. This chapter will now provide some background to these two technologies and the motivation for the work done in this study.

1.1 Motivation and background

The increase in global competition and product mass customisation have placed the manufacturing industry under increasing pressure to look for and implement processes that can provide flexibility and cost savings to cope with small batches and rapid product modifications (Ma et al., 2007). According to many researchers in the field, such as Ma et al. (2007) and Kruth et al. (2007), RP technology has gained good acceptance for the quick fabrication of prototypes. Low cost irrespective of the complexity of the geometry is possible. RP technology was developed to solve design problems using an approach in which the shape of the physical part is created by adding the material layer by layer.

Many RP methods currently in use are unsuitable to produce functional parts with acceptable material properties, and are normally not cost effective for mass producing parts. Even though the technology has greatly improved and there is increasing use of RP for direct rapid manufacturing (RM), it is often impossible to manufacture parts that have good material properties and acceptable accuracy. This creates the desire for a hybrid process, still utilizing the speed and flexibility of RP, but allowing for the manufacture of components from stronger materials and in larger quantities. Rapid tooling (RT), a tooling fabrication method which utilises RP methods, grew out of this need. This entails the manufacturing of tooling on a RP machine, for use in a secondary process. This is ideal, as many components have production quantities insufficient to justify the high cost of conven-

tional steel tooling as manufactured on CNC machines. These rapid tools can also fill a niche in the new product development process where tooling is often needed to manufacture small runs of prototypes for structural or functional testing.

The use of rapid tools in the manufacturing process represents a secondary process, apart from the RP process used for the tooling. These tools are normally used in some sort of a moulding process, typically plastic injection moulding as done by Ma et al. (2007) and Zhang et al. (2001).

Advanced composite materials offer some of the best low weight and high specific strength properties for the solution of design problems. A major disadvantage of these processes, however, is the low production rates possible. A major part of this problem is the manufacturing time of the moulds needed to form the composites. These moulds are usually also very costly. If RT methods can be combined with one of these advanced composite manufacturing methods, time and cost savings might be possible.

The most prominent process that could lower manufacturing costs of advanced composites is believed to be Resin Transfer Moulding (Gutowski, 1997). Resin Transfer Moulding (RTM) is a low pressure (less than 700 kPa) closed moulding process. It is ideal for moderate volume production, filling the gap between the slower hand layup processes and the faster compression moulding processes (Engineer's Handbook, 2008). Due to the flexibility and automation possibilities offered by this process, it was decided to investigate what RP can bring to this process.

1.2 Composite processes

Engineering composite materials enable the manufacture of very light yet strong structures which are not possible with most other materials. A very wide variety of composite manufacturing methods are in use, each with unique advantages and applications. This section will briefly comment on the most prominent processes and then discuss RTM in more detail.

According to Veldsman & Basson (1998a), many designers still see composites only as suitable for a few niche markets, mainly due to material costs. Many studies tend to contradict this notion and indicate that composite components can be very competitive on a price and performance basis especially when produced with newer methods such as RTM (Veldsman & Basson, 1998a).

This research project is specifically focused on so called advanced polymer composites. Advanced polymer composites are made of high-strength fibres and moderately high-temperature resins. Another attribute of advanced composite materials is the very high fibre volume fractions of between 50% and 70% normally achieved (Gutowski, 1997). This generally leads to stiffer and stronger structures.

1.2.1 Hand layup

As the name implies, glass fibre or other reinforcing fibres are positioned manually in an open mould and resin is then brushed on or sprayed over the glass plies. Various modifications of the basic process are in use, many utilising a vacuum bag to remove entrapped air.

This is still the most popular composite manufacture method as it is simple, capital costs are low and large and complex components are possible. It is also the composite process with the lowest productivity and results are very variable and subject to operator differences.

1.2.2 Filament winding

Resin impregnated fibres are wound onto a rotating mandrel in this process. This method is obviously suited to the manufacture of cylindrical hollow parts and provides excellent control over fibre placement and uniformity in the structure. Non-round parts are possible but require greater care during manufacturing and geometry is very limited. The productivity possible with this process is very high, but capital costs are also very high.

1.2.3 Pultrusion

Reinforcement fibres are pulled through a resin bath and then through a heated die with an opening with the desired profile. The resin is cured by heating and the material is cut to length as it exits the die. This method is meant for the continuous manufacture of shapes with uniform cross sections. A wide variety of shapes are possible and in-line weaving and braiding equipment can even be included before the fibres enter the die. This is also the most productive composite process available and running costs are low. The specialised machinery which is necessary is very expensive however.

1.2.4 Sheet forming

Sheet forming is a group of manufacturing processes that transform a flat sheet of composite material into a three dimensional shape. These processes are suited to parts with slowly changing thickness and whose final thickness is close to that of the sheet (Gutowski, 1997). Press forming or compression moulding, diaphragm forming and hydraforming are the most popular methods falling under the sheet forming group. These methods have the capability to produce curved shapes and a good surface finish is possible. The tooling cost is also reasonable and there is potential for automation. The major disadvantage of these processes is the limited part shape and size possible.

1.2.5 Tape/tow placement

Resin pre-impregnated fibres are orientated and placed in a specific direction during tape placement. High strength fibres can be concentrated where needed and

part weight can then be reduced. Automated tow placement is predominantly used for large structures while hand tape placement remains widely used but mostly for smaller parts.

This method is suited to large open continuous components such as aircraft wing skins. As this process has very long start-up and slow-down times it is more practical for such large objects or batch layup for smaller parts.

The machines necessary for this process are very complex and represent a massive capital outlay.

1.2.6 Autoclave processing

Autoclave processing may be considered as a secondary process. Parts that have been moulded or formed by other means are placed in a vacuum bag and placed in the autoclave to enable curing. The parts are cured at pressures of between 350 and 700 kPa and temperatures of between 150 and 400 °C (Gutowski, 1997). This cure cycle produces denser and more void free parts than normally possible.

This process is very flexible and can be used on a wide variety of materials. The autoclave however is very costly and curing cycles are usually very slow.

1.2.7 Continuous lamination

Composite parts in sheet form are manufactured with this process. The fibre reinforcement is mixed with resin and sandwiched between two plastic carrier films. The sheet is then formed under forming rollers and the resin cures to form the final part. After curing, the plastic carrier films are removed. This process is limited to large flat panels.

1.2.8 RTM, VARTM and Vacuum infusion

RTM is a low pressure (less than 700 kPa) closed mould manufacturing process which provides a good surface finish on both sides of the part. The dry fibre reinforcing component is placed inside the mould and then low viscosity catalysed resin is pumped in through ports to displace the air through strategically placed vents (Figure 1).

This process often makes use of intricate three-dimensional fibre preforms which are manufactured by processes such as weaving and braiding or stamping. Resin curing may be initiated by a heated mould wall or by adding a catalyst to the resin. This is a process which lends itself to automation. RTM is ideal for medium volume production of small to medium size parts. The closed tooling required for RTM is unique to advanced composite moulding processes and accounts for the much improved dimensional quality and uniform thickness. The most important factor to ensure success in this process is uniform mould filling with resin.

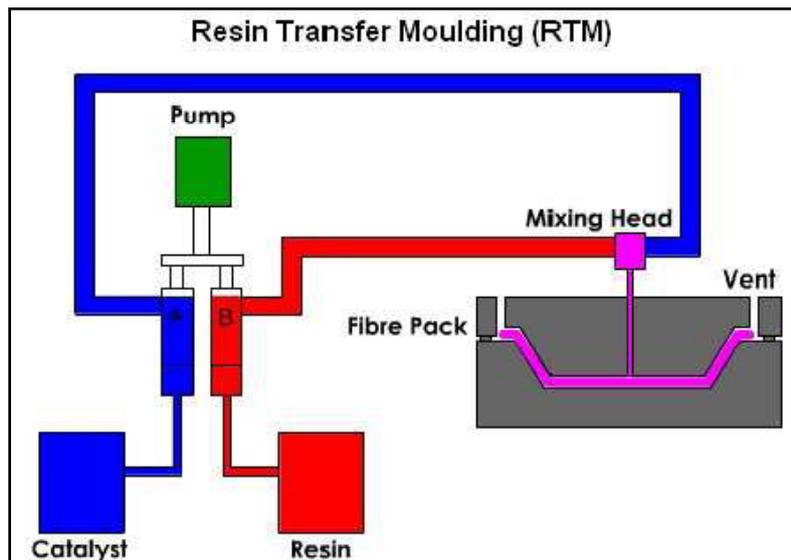


Figure 1: RTM process (JHM Technologies, 2009)

There are a few variations on the standard RTM process that should be noted:

- Vacuum Assisted Resin Transfer Moulding (VARTM) makes use of vacuum instead of pressure from a pump to draw the resin into the fibre preform.
- Structural Reaction Injection Moulding (SRIM) makes use of heated mould walls for resin curing. The moulding times for SRIM are much reduced over RTM and makes this method significant for the automotive industry.
- Vacuum infusion utilises a one sided mould which is vacuum bagged to compress the fibres. The fibres are then wetted out similarly to RTM. This process is effective for large structures like boat hulls and wind turbine blades, but does not have a good surface finish on both sides like RTM. This process is also known as RIFT (Resin Infusion under Flexible Tooling) and a version is patented as SCRIMP (Seeman Composites Resin Infusion Manufacture Process). Tooling costs are also lower than RTM due to using a one sided mould.

Advantages of RTM over other processes

- Excellent dimensional stability
- Closed mould protects workers from exposure to volatile organic compounds (VOC's) such as styrene (Modi et al., 2007)
- Ability to produce very complex parts
- Low energy consumption compared to compression moulding
- Mouldings can be manufactured to close dimensional tolerances

- Components will have good surface finish on both sides
- Selective reinforcement and accurate fibre management is achievable
- Inserts may be incorporated into mouldings
- Tooling costs comparatively low compared to other manufacturing processes
- Ability to produce near net shape mouldings, reducing material wastage
- Process can be automated, resulting in higher production rates with less scrap
- Low resultant voids in moulded components
- Ability to achieve from 0.5 mm to 90 mm laminate thickness (Gutowski, 1997)
- Higher and more consistent fibre volume fraction achievable than with open mould processes (Govignon et al., 2008)
- Room temperature curing increases tool life (Lunn, 2004)
- Unlike prepregs, resins can be stored at room temperature (Lunn, 2004)

Disadvantages

- High tooling costs due to closed moulds (not applicable to vacuum infusion)
- Mould filling needs to be carefully considered

1.3 Rapid Prototyping

This section briefly looks at the history of RP and considers some of the main processes that fall under the RP grouping of manufacturing techniques.

The term Rapid Prototyping (RP) refers to a grouping of manufacturing processes that generate the physical shape of a part from the CAD model using an additive approach. RP processes are also often referred to as layered manufacturing (LM). This is due to the fact that the CAD model is decomposed into a number of thin layers, typically 0.1 mm thick, and each layer is then created separately. The process of creating the part by adding layers sequentially is known as printing, building or growing. The layer thickness is a compromise between accuracy, build speed and strength. The chosen RP method and material also influences the layer thickness. The additive nature of RP is in sharp contrast to traditional machining, where material is removed to shape the final part.

To enable the manufacture of a part with a RP method, a CAD model in STL format is first necessary. STL file formats were developed specifically for the RP industry. The STL version of the CAD file is a model consisting of triangles with normal vectors indicating the material side of the triangular facet. In more recent

colour RP techniques, the colour of the part is also assigned to the triangular facets which approximate a specific area on the surface (Wang et al., 2006). This allows the printing of full colour models.

1.3.1 RP methods

According to many sources, the first successful RP method, Selective Laser Sintering (SLS), was patented in 1987 by Carl Deckard, a researcher from the University of Texas (National Science Foundation, 2009). Deckard printed solid CAD models by employing laser beams to fuse metal powder into solid parts layer by layer. Earlier researchers tinkered with similar ideas, but Deckard was the first to successfully employ these ideas. During the following 22 years, RP methods have expanded into a bewildering number of methods with widely differing applications and material capabilities. The most popular RP methods will now be briefly discussed. There are many more, but most are based on the five that will be discussed.

SLA (Stereolithography)

In this process, a low power UV laser is used to cure a photo sensitive resin. The UV laser cures one layer of the plastic part, then the build platform is lowered and the surface of the part is recoated with resin. The UV laser then cures the second layer and the whole process is then repeated. After the completed part has been removed from the resin bath, it needs to be post-cured in an UV oven to attain full strength.

This is a very accurate RP method which allows intricate detail such as with jewellery. A variety of photo-sensitive resins are available, such as acrylate-based resins, epoxy polymers and vinylethers. The epoxy based materials are usually the strongest. Because of the resin bath in which the part rests, supports are needed for overhanging structures to avoid collapses.

Besides the good accuracy and surface finish of the SLA parts, another advantage over other RP processes is the large build volumes of these machines. Materialise in Belgium makes use of a SLA machine known as the Mammoth which has a build volume of 2100x650x600 mm (Materialise, 2008).

SLS (Selective Laser Sintering)

The SLS RP technique makes use of a laser (usually CO₂) to heat fine particles above melting point and fuse them together. After one layer has been sintered together, the build volume is lowered and the part is recoated with powder particles to enable the sintering of the next layer. The sintering is done in an inert gas environment to prevent oxidation of the powder particles. After the part has been completed, it is removed and can be sintered further if required. In many cases the particles are coated with a binder material to enable bonding. It may then be required that the parts are post processed to enable complete particle bonding.

A wide variety of materials is available for this process, including polyamides, polycarbonates, nylons, ceramics and various metal powders. Some of the newer

SLS machines, like the EOS M270, are capable of sintering very strong materials like titanium metal powders (EOS, 2009).

This RP technology has numerous advantages including the wide variety of materials available, dimensional stability of parts and minimal post-processing necessary. Major disadvantages include the high capital costs and the poor surface finish of the parts.

3DP (Three Dimensional Printing)

This RP technique utilises inkjet printing technology to deposit a binder liquid onto a bed of powder. After the layer of powder has been fused together by the binder, the build platform lowers and another layer of powder is scraped onto the bed of the build volume. This process is then repeated until the entire part has been printed. The completed part is porous and weak and is usually infiltrated with another material to attain full strength.

The use of established inkjet technology enables 3DP to be the most affordable RP technique. A wide range of powder materials can be used, including starch based powder, plaster based powder as well as metal powders. According to Wohlers (2003), major advances in 3DP materials are taking place and new materials have improved strength and shrink less. The metal powders need to be sintered afterwards however. The 3D-printers are also very fast compared to other RP technologies and they are suitable for an office environment. Newer 3D-printers are even capable of printing full colour parts.

The major disadvantages of 3D-printers are the low strength of the parts and the poor surface finish and accuracy. It is possible to improve the surface finish by polishing.

Wohlers (2003) predicts that the bulk of growth in the RP industry will come from 3D-printing. As the low cost 3DP machines improve, it will become increasingly difficult for companies to sell high-end RP machines.

LOM (Laminated Object Manufacturing)

LOM is a RP process where layers of paper are cut to shape and bonded layer by layer to form the complete part. The paper is cut to shape by a CO₂ laser as it is unrolled from the paper supply roll. Excess paper is cut in a hatched pattern to facilitate later removal. The paper is normally backed with glue to facilitate the bonding of successive layers. After the part has been completed, it can be sanded, polished or painted like a wooden part.

Paper is not the only material that can be used and glue also does not necessarily have to be used. Levy et al. (2003) described a variation on the standard LOM technique where metal sheets were cut by laser and welded together by diffusion welding. Another very interesting LOM process was investigated by Klosterman et al. (1998), where layers of fibreglass was bonded with polymer matrix adhesives.

Advantages such as good accuracy compared to other RP techniques and large

build volumes make this process attractive. The waste paper also provides a support for parts with overhanging sections. Some disadvantages of LOM are that the laser needs to be very precisely adjusted to ensure good parts, the removal of waste paper may be difficult and that the laser and paper combination may pose a fire hazard.

FDM (Fused Deposition Modelling)

In FDM, a plastic filament is fed from a supply coil through a heated nozzle. This nozzle moves around in the x-y plane and deposits the semi-molten material onto the partially constructed part. Because of the semi-molten state of the material, it easily bonds to the previously deposited layer. The build platform then lowers down in the z-direction to allow for the deposition of the following layer. A wide range of materials may be used, but ABS plastic is the most popular. Advantages compared to other RP processes include low materials cost, good strength allowing functional testing, low levels of material wastage and ability to quickly change between different materials. The main disadvantages of this process are poor accuracy and slow build time compared to other RP processes.

Comparison of RP methods

The widely differing RP technologies make it difficult for a designer to select the optimal technique for the problem at hand. It is therefore important to have a clear understanding of the advantages, disadvantages and unique capabilities of the available RP technologies. Table 1 below includes some of the results from a study done by Rao & Padmanabhan (2007). This study was done to provide the user with a tool to choose the optimum RP process for a given product or part using graph theory and a matrix approach. It is important to take note that the values in the table are for specific models of RP machines utilising one type of material each. A different make of 3DP for example might have a longer build time. These values however are sufficient to indicate the overall comparison between the different RP technologies. As a rule of thumb, conventional material removal processes like CNC machining are normally more accurate than RP methods, but this will be investigated in more detail in later chapters.

Table 1: RP process comparison (Rao & Padmanabhan, 2007)

RP Process	Accuracy (µm)	Surface roughness (µm)	Tensile strength (MPa)	Elongation (%)	Cost	Build time
SLA	120	6.5	65	5	Very high	Medium
SLS	150	12.5	40	8.5	Very high	Medium
FDM	125	21	30	10	High	Very high
LOM	185	20	25	10	Slightly high	Slightly low
3DP	600	15.5	5	1	Very low	Very low

In the study by Rao & Padmanabhan (2007), it is evident that 3DP RP technology, as used for this project, is less accurate than other types, but the fast build time and low cost makes it desirable for research work.

1.3.2 Rapid Manufacturing

When rapid prototyping machines were still in their infancy, they were used exactly as the name implies, for making prototypes rapidly. The accuracy possible and strength of available materials were deemed as insufficient to make anything more than prototypes with little functionality. RP technology has improved tremendously during the past 20 years however; and the newer RP machines boast better accuracy and improved materials capability. It is now possible to directly manufacture end use products for many applications. This spin-off from the conventional RP processes is known as Rapid Manufacturing (RM). Rudgley (2001), as quoted by Levy et al. (2003) gave the following definition for RM: “the manufacture of end use products using additive manufacturing techniques”. Many current RP machines have been designed almost exclusively with RM in mind.

The possibilities that RM creates are truly impressive. So called mass customisation, where a product can be customised for a specific application, is now possible without lengthy and costly changes to the production process chain. The geometric freedom made possible with RP processes also gives designers the tools to design parts that were not previously economic to manufacture.

1.3.3 Rapid Tooling

While RM techniques have greatly improved, current machines are often incapable of manufacturing parts with certain material qualities and/or in sufficient quantities. In such cases it is still possible to make use of the advantages offered by RP technology. Rapid Tooling (RT) is a natural extension of RP techniques. In RT, the RP machines are used to manufacture the tooling required to produce the part/prototype. The tooling is then used in a secondary process such as plastic injection moulding.

These rapid tools were originally intended only as stopgap tooling to produce a small number of prototype parts, but the tooling that is possible with current RP machines are often durable enough to be directly used in the production environment (Rosochowski & Matuszak, 2000). According to Rosochowski & Matuszak (2000), a major shift from normal prototype tooling practice to RT is underway in the manufacturing environment. This follows from the tendency to increasing product mass-customization. Approximately ten years ago, Radstock (1999) predicted that widespread use will be made of RT techniques if the following material properties have been achieved:

- Strength \geq 500 MPa
- Accuracy \geq 0.01 mm
- Roughness \leq 1 μ m

This target is still beyond the reach of commonly available RP machines, but it is becoming possible.

RT methods will in many cases result in both a time and cost saving in the manufacturing environment. Demand for faster and more affordable tooling solutions has resulted in a large number of RT processes being developed worldwide. These tooling methods can be further classified into groups such as patterns for casting, direct and indirect tooling. These groups will be discussed in more detail in Section 2.2.

1.3.4 Advantages of RP/RM/RT

Most traditional methods of prototyping are labour intensive, slow, expensive and rely heavily on operator skill. This often limits the amount of design iterations and often leads to costly design changes in the production stage. The increasing use of RP techniques gives designers much more freedom to complete more design iterations early in the product design cycle and potentially leads to better engineered products and savings during the later production stages.

The production time reductions possible with RP technology are another major reason for the increasing use thereof. Many RP laboratories provide a service where the part is completed in less than 24 hours after the designer has submitted the CAD model. Materialise in Belgium is probably the most well known provider of such a rapid service (Materialise, 2008). Many local companies in the Cape Town area is able to provide a similar service, e.g. GCC at Stellenbosch University and Protoform and Custom 3D in Cape Town. According to Ding et al. (2004), it is reasonable to expect a 60% decrease in product development lead time over traditional methods when RP techniques are applied. Product life cycles are decreasing and new products are required to reach the market very quickly, making the lead time reduction offered by RP very desirable (Ferreira et al., 2005).

Besides the indirect cost reductions possible with RP, a significant direct cost reduction is also possible. Small batches of parts manufactured with RP techniques are usually less costly than parts manufactured by conventional techniques such as CNC milling. In a study where RP techniques were used to manufacture a wax injection tool for investment casting, Sadegh et al. (2009) found a cost reduction of 60% was possible over conventional production methods.

Another major advantage of RP techniques is the high level of complexity possible. The nature of layered manufacturing makes intricate internal detail possible. This advantage creates some interesting design possibilities. As an example, the author recently witnessed the manufacture of some titanium nozzles with internal cooling channels being grown on an EOS M270 SLS machine owned by the Centre for Rapid Prototyping and Manufacturing in Bloemfontein. This geometrical flexibility has also made RP very popular for certain medical applications (Levy et al., 2003). See Figure 2 showing a surgical implant manufactured on a metal SLS machine at the Centre for Rapid Prototyping and Manufacturing.

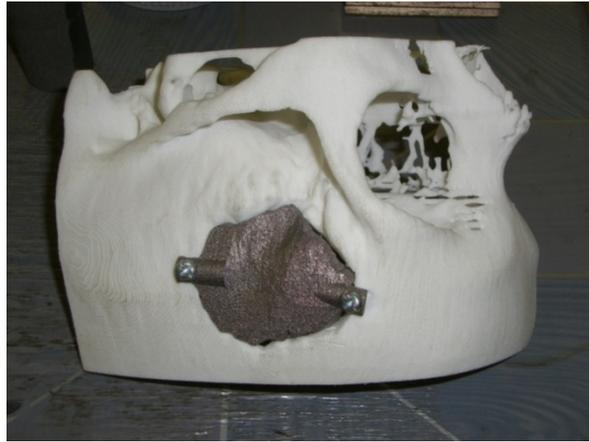


Figure 2: Metal skull patch manufactured on SLS machine

1.3.5 Limitations

Although big advances have been made with RP technology, various limitations still need to be considered.

The allowable size of parts that can be manufactured with current RP machines is still limited. Machines with build volumes as large as 2100x650x600 mm (Mammoth owned by Materialise) is known to exist, but a quick visit to the product catalogue of one of the leading RP machine manufacturers such as EOS (EOS, 2009) indicates that the build volume of average production machines are closer to 450x400x350 mm. It is possible to print parts in sections and assemble them afterwards, but this is time consuming and accuracy may be compromised.

Accuracy and surface finish of many RP processes do not compare favourably to metal removal processes such as milling. RP parts are also often porous, but this can be improved by infiltration with suitable materials.

The better RP machines are very expensive, often costing in excess of a million rand.

Anisotropy of the RP part material needs to be considered. Because of the layered construction of RP components, parts might have anisotropic strength, accuracy and surface finish.

The available materials for RP machines are often limited. Another negative factor is that the specialized materials are usually not interchangeable from machine to machine.

All the above mentioned limitations are being eliminated as RP technology improves, but it is still necessary to take note thereof when processes are compared.

1.4 Research Objectives

At the outset of this project, there were some questions regarding the research field under consideration. These questions included the following:

- Can RP technology be of any advantage in the execution of RTM?
- Will this process be more economical than conventional RTM?
- Will this process be faster than conventional RTM?
- Will this process enable the manufacture of complex parts not possible in any other way?
- Will the accuracy of parts manufactured with this combined process be acceptable?
- What is the ideal part infiltration method and mould release agent?

To enable some of these questions to be answered, certain research objectives had to be formulated:

- Become proficient with the RP and RTM processes
- Complete a simple and complex part case study
- Determine dimensional deviations in these case study parts
- Create a set of design rules giving guidelines on draft angles, wall thickness, etc.
- Determine a cost model, possibly by using a current model and adapting it for this project
- Design a process chain including all the relevant steps necessary to manufacture a composite part
- Initiate contact with other research facilities and possibly collaboration with researchers doing similar work

At the beginning of this project, the expected outcome was that meaningful improvements will only be possible with smaller, more complex parts. Expected problems included the porosity of the 3DP parts (hence the need for infiltration), low strength of these parts and dimensional deviation of the final composite parts.

Requirements for the simple case study part included reasonable depth to check influence of draft angles, constant wall thickness and flat planes to enable accurate measurement of surface finishes. A final decision on the complex case study was only made after the data for the simple case study was reviewed.

2. LITERATURE REVIEW

It was realised early in this project that very little research has been conducted in the implementation of RP methods for composite manufacture, much less in the specific use of 3DP for RTM composite manufacture. It is therefore necessary to look to processes that are as similar as possible and then apply the results obtained to this project. After some personal interviews with individuals working in the fields of composite manufacture and RP, it became clear that some work has been done locally on these methods, but unfortunately not much has been formally written up. The results of these personal interviews will also be discussed in this chapter.

2.1 RTM process

According to JHM Technologies (2009), there are three major driving forces increasing the industrial use of RTM today:

- 1) Environmental agencies are reducing the allowable levels of styrene/VOCs in the workplace to levels that are difficult to meet with open mould processes.
- 2) There is a shortage of labourers with the required skill level to manufacture parts with open mould processes without expensive reworking of poorly manufactured parts.
- 3) Innovation from manufacturers of tooling and equipment for RTM has increased the competitiveness of this process.

It is necessary to be aware of some of the technical issues with RTM and the available technical improvements to ensure the successful manufacture of parts. Some of these issues will now be briefly discussed.

2.1.1 Mould filling

RTM is a process that has the ability to greatly influence the manufacture of composites in the production environment, but there are a few issues which impede the acceptance of this technology. The greatest issue influencing the quality of RTM parts is the issue of mould filling (Luo et al., 2001). The incomplete wetting out of fibre preforms leads to rejected parts and financial loss. Analogous to electricity, the resin tends to follow the path of least resistance. If such a preferential flow path exists it could lead to incomplete mould filling and it will be necessary to allow some resin to bleed through the vent, resulting in wasted resin and longer mould filling times (Modi et al., 2007). The aim of any RTM system is therefore to promote a very uniform resin flow field and to get the resin to its final destination before it starts solidifying.

According to Gutowski (1997), the usual model for the flow of resin through

reinforcements is based on Darcy's law. Darcy's model describes the flow of Newtonian fluids in porous media and can be expressed as follows:

$$Q = S.A.\Delta P/\mu.L \quad (2.1)$$

Where Q is the volumetric flow rate, A the cross-sectional area, ΔP the pressure difference over the sample, L the streamwise length, μ the viscosity and S is the permeability with dimension $(\text{length})^2$. It is clear that the resin flow rate through a fibrous material will be proportional to the pressure gradient and inversely proportional to resin viscosity. The required resin flow distance L also plays an important role. Also note that the higher the required fibre volume fraction, the higher the required resin inlet pressure to ensure complete filling (Veldsman, 1995) and (Govignon et al., 2008). Two very simple ways to improve the issue of mould filling is by using a special low viscosity resin with a viscosity of less than 15 poise (Veldsman, 1995) and by increasing the permeability of the preform. The permeability of the preform can firstly be increased by choosing fibres with higher permeability. This however is not always practical and Tari et al. (1998) and Govignon et al. (2008) advocate the use of a high permeability layer (HPL). A HPL is also known as a distribution medium and is simply a porous layer that promotes resin flow such as the commercially available Greenflow 75. This layer can be placed between the top layer of the reinforcement and the vacuum bag in the case of vacuum infusion or as an inter-laminar layer with one of the closed mould RTM variants (Smaldon, 2004). If peelply is placed between the laminate and the HPL, the HPL can be easily removed after curing. Peelply is a porous layer to which resin does not easily bond. The designer should keep in mind that the use of a HPL may diminish surface finish and dimensional stability (Tari et al., 1998). It is also necessary to plan for the extra thickness of the HPL.

The second method to improve mould filling is to improve mould and part design. Veldsman (1995) proposes a few ways to improve design. This will be elaborated upon in Chapter 3, and includes guidelines such as: sharp corners with small radii should be avoided where possible, simple part geometries are preferable and the mould halves must seal properly.

If core material is utilised in the moulding process, special grooves or channels can be cut to promote the resin flow (Smaldon, 2004). This novel approach was attempted at the North-West University during the manufacture of wind turbine blades. The cores for the blades were CNC milled from high density foam and resin runners were then manually cut onto the surface. These cores were then covered with the fibre reinforcement before being placed in the mould used for the RTM process. Much labour was required and parts exhibited dry spots. (Jonker, 2009)

Placement of injection points are very critical to mould filling and has a significant influence on part quality and process efficiency (Luo et al., 2001). If possible, the injection port should be placed at the lowest point to prevent air being trapped inside the mould. It is also preferable to place the port at the thickest section of the mould so that the resin flows from thick to thin, preventing resin rich

areas. Venting points, on the other hand, should be placed at the highest point, at the thickest section and as far away as possible from the injection points. According to Luo et al. (2001), port and vent location has the single most critical effect on mould filling times and resin flow patterns.

Modern simulation programs have made it possible for designers to predict the influence of each of the abovementioned factors and optimize the RTM setup for a specific part. A great deal of effort has been made to develop packages that can accurately predict resin filling times and flow distributions (Govignon et al., 2008). Tari et al. (1998) used such a simulation package, RTMsim that was developed at UCLA, to successfully predict the resin flow field and determine port locations for optimal mould filling. This package functions by solving Darcy's equation using an alternating direction implicit time integration scheme based on global mass balancing. In a study done by Luo et al. (2001), the RTM process was simulated and a neural network genetic algorithm optimization procedure was then applied to the simulation results to find the optimum process parameters for the part in question. This approach removes all the guesswork from issues such as port placement and if effectively implemented can lead to time and cost reductions. The commercial availability of various simulation packages has greatly improved the ability of designers to correctly design a RTM setup. Another package is RTM-Worx (Polyworx, 2009). This package works well but is costly (Tavenor, 2008). Other available packages include PAM-RTM from ESI, myRTM from IWK in Switzerland (IWK, 2009) and Moldflo (sic) from Autodesk (Autodesk, 2009). The myRTM package is open source software but is very limited in application as only one inlet port and vent can be simulated. The Autodesk package is actually meant for plastic injection moulding but can be adapted to RTM applications. Besides predicting the resin flow distributions and being helpful to determine port locations, these packages are also handy to determine the exact amount of resin needed for full mould filling and required input pressure. On larger parts, resin wastage costs may be significant so it is preferable to only prepare the exact amount calculated by these packages. Different port locations will also result in different volumes of resin through-flow required for complete part infiltration. A resin flow software package can also show the resin volume required for different port locations, indicating the most economical setup (Tari et al., 1998).

Even though simulation removes most of the guesswork from RTM design, fibrous preforms often have inherent heterogeneity in permeability values (Modi et al., 2007). In an automated environment, it might be practical to actively control the infusion process to ensure complete mould filling. In a project conducted by Modi et al. (2007), an active control system capable of monitoring resin flow, identifying flow disturbances and taking corrective action through computer-controlled injection ports was successfully implemented. This system used affordable web cameras to capture images and analyse for flow disturbances.

2.1.2 Permeability of fibres

If any resin flow simulations/calculations are to be made it is important to have

permeability values for the fibre preform. It is not always possible to find permeability values in literature and it is therefore handy to be able to have some means to calculate it. Models for the calculation of fibre permeability are usually based on Darcy's law (Williams et al., 1996). Veldsman (1995) was one researcher who also followed this approach by using equations derived by Boccard et al. (1994) from Darcy's law. This approach implements a constant resin injection pressure and assumes that the flow near the injection port is radial and that the flow becomes channel-like when the boundaries are reached. Full details of the equations used in this method are provided in the cost model in Appendix D.

Another method recommended by Gutowski (1997) is the well known Kozeny-Carman equation. This is based on the hydraulic radius model and considers a bed of parallel cylinders as equivalent to a porous medium. Govignon et al. (2008) made use of a modified Carman-Kozeny equation:

$$S = d^2 \cdot k(1 - V_f)^{n+1} / 16 \cdot V_f^n \quad (2.2)$$

where S is the permeability in m^2 , d the fibre diameter, V_f is the fibre volume fraction and n and k are dimensionless Kozeny constants which can be found experimentally. This equation emphasizes the strong role which the fibre volume fraction, influenced by fibre compaction, plays on permeability.

Weitzenbock et al. (1999) did a great deal of research on permeability measurement in the context of RTM. A method of permeability measurement was developed where the experimental axis does not even have to be aligned with the principal fibre directions of the laminate.

Tari et al. (1998) provides two semi-empirical equations that were used to calculate the permeabilities in the two principal fibre directions in their project, but it is not clear how these equations are implemented.

2.1.3 Emissions

As worldwide laws regarding process emissions become more strict, industries are looking to methods which emit less VOCs than most popular composite manufacturing methods. Styrene is the main VOC that is emitted by composite processes when cross linking of unsaturated polyester or vinyl ester resins takes place (Williams et al., 1996). According to the World Health Organization (2000) the daily styrene exposure level of the average operator in the composite industry is more than 2 gram. This is one of the highest levels, even higher than industries such as paint and adhesives. The RTM family of processes have the advantage that all these emissions can be captured at the source (Modi et al., 2007).

2.1.4 Practical tips

When dry fibres have to be placed on vertical surfaces or complex geometry, specialised spray adhesives such as Airtech's Airtac 2 (Airtech, 2008) is very helpful to hold the fabric in position before resin infusion (Lunn, 2004). 3M's 77

spray-on adhesive is a similar product. To ensure no effect on final laminate qualities, these adhesives should not be used excessively. Excessive application may weaken the bond between resin and fibre. Perhaps a safer option is an adhesive coated mesh also manufactured by Airtech (Lunn, 2004).

Spiral plastic tubing is also very handy when vacuum infusion is performed (Lunn, 2004). The resin supply and venting pipes are connected to the spiral tubing which then serves as a distributed source of resin supply and for venting. These spiral tubes do not collapse under the vacuum pressure inside the vacuum bag and also serves as a means of vacuum distribution through the laminate.

A resin trap/pot is a container placed between the VARTM/infusion setup and vacuum pump to arrest all the excess resin and prevent it from entering the vacuum pump. The resin is separated by gravity. Tari et al. (1998) advocate the use of this device to protect the vacuum pump.

When executing the infusion process, care should be taken to place the resin source at the same height as the mould to prevent pressure losses due to gravitational forces (Tari et al., 1998).

Something to be aware of with RTM is the existence of clearance between the fibre preform and mould edges. This clearance can create a preferential flow path, called edge flow, which may disrupt the flow patterns during the mould filling stage (Yang et al., 2008). According to Yang et al. (2008), presence of this edge effect may lead to incomplete infusion of the fibre preform, dry spot formation and other defects in the part. A mathematical model for this phenomenon was developed by Yang et al. (2008) for flow behaviour involving the interface between an edge clearance and a porous medium. The use of a HPL seems to lessen the effect of the edge clearance (Tari et al., 1998).

2.1.5 Cost estimation

When designers compare the advantages and disadvantages of competing processes, one of the most important considerations to enable decision making is the cost of the proposed process. Cost estimation models are especially helpful to designers with little experience in composites and help them to decide when such materials should be considered. It would therefore be ideal to have access to tools that estimate the cost of making a part with different processes. Barlow et al. (2002) did some research regarding estimation of the recurring labour costs of aircraft composite structures manufactured with RTM and VARTM processes. The methodology developed during this study was based on cost equations developed at MIT. It is interesting to note that Barlow et al. (2002) found that the recurring labour times for the VARTM process were 10% greater than for RTM. This is due to the time required to apply vacuum bagging and distribution media for the VARTM process, despite the shorter times required to prepare the VARTM tooling.

The main problem with the approach taken by Barlow et al. (2002) is that it is difficult to make allowances for the widely differing complexities of composite

parts. Veldsman (1995) completed a cost model that is superior in this sense. This cost model makes allowances for the different geometries of parts and is handy to eliminate unnecessarily expensive design features. In this study, cost models were presented for producing the master model, the mould and the part itself. These cost models will be discussed in greater depth in later chapters.

Veldsman also completed some other similar cost estimation for RTM studies. In Veldsman et al. (1996), the design and cost estimation of the mould needed for RTM manufacturing were discussed and guidelines such as minimum thickness of the mould to withstand moulding pressure was provided. In Veldsman & Basson (1998a), the advantages of using cost estimation models are clearly illustrated. Here are some of the advantages listed:

- “Cost models can be shared by many designers simultaneously.”
- “Cost models enable designers to make good decisions far sooner in their careers, thus speeding up the learning curve.”
- “If suitable cost models are available, a designer can consider more materials and processes.”
- “Cost models can be used by different people to compare different designs and processes.”
- “Cost models help overcome the tendency of human beings to make choices with which they feel comfortable because of previous experience, even though they cannot justify the choice.”

For a typical medium volume (1000 parts/year) RTM production setup, Veldsman & Basson (1998a) found that tooling costs have a significant influence on the final product cost. Refer to Figure 3 on the next page. It is therefore clear that tooling design is very important and any technology able to lower tooling costs, like RT, deserves serious consideration. Veldsman & Basson (1998a) advise that cost models should provide for all the feasible tooling options. This allows the designer to review results of the cost estimation models and make decisions regarding the feasibility of the predicted lowest cost option.

In Veldsman & Basson (1998b), cost comparison is made between RTM tooling manufactured with hand layup and with the fast cast method. Hand layup was discussed in Chapter 1 and fast cast is tooling cast with a resin highly filled with filler material, usually aluminium. It was found that surface area and complexity of the tool was the main cost driver with these two processes. An addition to the previous work completed by Veldsman (1995) was equations to calculate the lead times needed for each process. The hand lay method is preferred for larger and less complex structures. According to this study, RTM tooling can be divided into four main categories, namely hand lay tooling, machined tooling, cast tooling and plated tooling. Note that no mention is made of RP tooling.

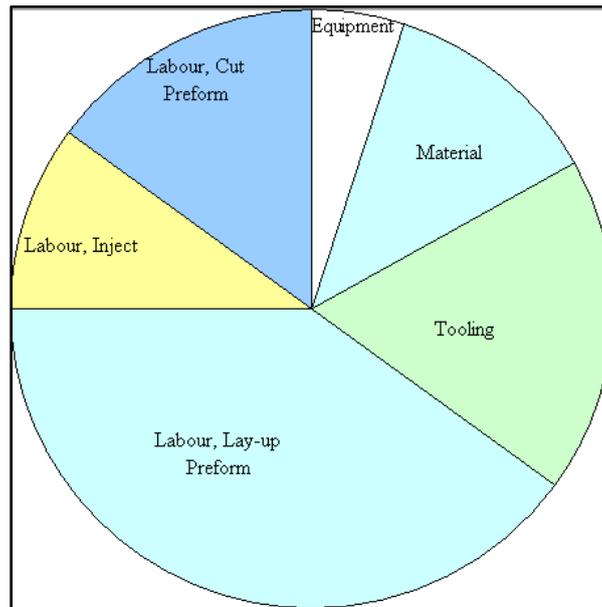


Figure 3: Cost components in RTM (Veldsman & Basson, 1998a)

When the size of the RTM mould increases to more than 100 mm, the number of layers of reinforcement required to provide adequate stiffness becomes economically unviable (Veldsman & Basson, 1999). In Veldsman & Basson (1999), a cost model is provided for the welded support structure for these larger RTM tools.

2.1.6 Process variations

The SRIM process combined with stamped preforms is of special significance to the automotive industry as this enables very high production rates. The low energy consumption, 75% lower than for steel parts, is also very attractive. Mould clamping forces are also only around 2.5% of the forces needed for compression moulded composites. (Gutowski, 1997)

Another technical advance which enables higher productivity is microwave curing of RTM composite parts. Papargyris et al. (2008) achieved a 50% reduction in curing time compared to conventional mould heating when microwave heating was implemented. This type of curing achieved the same flexural strength as in conventionally heated composite parts, but a 9% increase in shear strength was found in the microwave parts. Microwave heating also results in a decrease in process energy requirements and a lowering in operational costs.

Christian et al. (2001) did some research on the RTM manufacture of human bone implants. This process is a good choice for medical application as RTM parts has very good impregnation and therefore resists moisture absorption in the human body. The composite used in this process can also be chosen to closely resemble the mechanical properties of bone.

2.2 RT technology

According to Rosochowski & Matuszak (2000), a major shift from normal tooling practice to RT is taking place. Rapid tooling techniques have expanded dramatically during the last 20 years and it is helpful to be able to classify them into groups. Many of the methods overlap, so Rosochowski & Matuszak (2000) suggests a classification of RT methods based on practical aspects rather than strict definitions. See Figure 4 below for this classification.

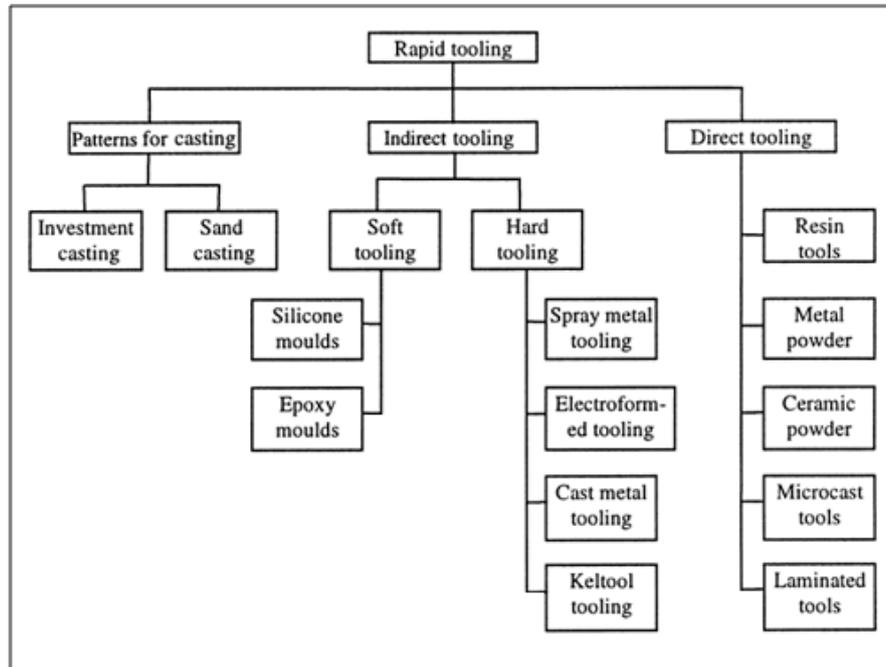


Figure 4: Classification of RT techniques (Rosochowski & Matuszak, 2000)

2.2.1 RT methods

Patterns for casting are a very popular use for RT (Rosochowski & Matuszak, 2000). Modern RP machines are able to manufacture wax patterns for investment casting and sand patterns for sand casting directly. The author witnessed the manufacturing of such tools at the Centre for Rapid Prototyping and Manufacturing in Bloemfontein in 2008. A wax printing machine was employed especially for the investment casting manufacture of fine jewellery and an EOSINT S700 machine was used for printing of sand casting tools. The wax machine operates on the FDM principle and the S700 is a SLS machine. Figure 5 illustrates one of the sand moulds manufactured with the SLS machine.



Figure 5: Sand casting tool manufactured with EOS S700 machine

Good results were also obtained by Rooks (2002) when using the EOS S700 SLS sand machine. During the manufacture of cylinder heads for an UK car manufacturer, a reduction in lead time from 3-6 months to 2-4 weeks was experienced and a break-even point of around 100 castings for prototype castings versus traditional methods was found.

Indirect tooling is typically the printing of a pattern with a low strength plastic material, which is then used to mould a tool with a more durable material like aluminium filled epoxy. Rosochowski & Matuszak (2000) discuss various indirect methods of creating tools, including soft tools such as silicone and epoxy and hard tooling such as metal spray tooling and cast metal tooling. The most frequently encountered indirect tooling method is for the manufacture of injection moulding tools. In the research conducted by Ma et al. (2007), a wax pattern was manufactured and an aluminium oxide epoxy was used to make the mould. Good results were obtained with injection moulding in this project. A similar study was done by Ferreira & Mateus (2003), where soft moulds for plastic injection moulding were cast from RP cores. Widespread use is also made of silicone moulds. The author witnessed silicone moulds manufactured from RP patterns at GCC at Stellenbosch University and the Centre for Rapid Prototyping and Manufacturing in Bloemfontein.

Research on indirect hard tooling was conducted by Zhang et al. (2001), where spray metal tooling was manufactured using RP patterns. This method allows the manufacture of metal moulds without limitation of pattern size. Another similar case study was completed by Ding et al. (2004), where a RP pattern was created using a SLA machine, an intermediate plaster mould was made because of greater heat resistance and finally a metal mould was manufactured by spraying a metal alloy onto the plaster mould.

Direct tooling is the fastest RT method but is very challenging to accomplish in many cases. This method entails directly manufacturing the tooling required on

a RP machine. The only secondary process allowable under this definition is polishing, painting and/or reinforcing. Because of the reduction in steps compared to the indirect approach, dimensional inaccuracy can possibly be reduced (Wohlers, 2003). This is the tooling method of interest to this research project. Rosochowski & Matuszak (2000) again provide numerous examples of this tooling method including SLA resin tools, SLS metal tools and other more specialised techniques. Wohlers (2003) also provides a very handy comparison matrix, listing all the major commercial rapid tooling technologies and comparing the capabilities of these.

Because of the advantages offered by direct rapid tooling, research is being conducted to develop stronger materials for this application. Masood & Song (2004) developed a new metal/polymer composite material for use in FDM machines. This allows the manufacture of strong tools with unmodified FDM machines. Plastic injection moulding experiments, using low density polyethylene (LDPE), have indicated that these tools are sufficiently strong for at least 70 shots.

Another promising technology for direct tooling is LOM metal manufacturing. Levy et al. (2003) described a variation on the standard LOM technique where metal sheets were cut by laser and welded together by diffusion welding.

When the material that will be formed by the tool is soft and temperatures are low, it is much simpler to directly manufacture tools with existing RP technology. Sadegh et al. (2009) completed a project where the mould for a wax injection moulding process was directly manufactured with a SLA machine. Results regarding lifetime and accuracy of the mould compared well to conventional metal tooling.

A project completed by Hugo (2008) is a good indication of the flexibility offered by RP technologies. In this project use was made of SLS and 3DP and Multi-Jet Modelling (MJM) RP techniques to investigate the suitability of layered manufacturing for investment casting tools. The MJM techniques are also part of the 3DP family and works by dispensing thermo-polymer material onto the build surface through multiple jets in a print head. These three technologies were used to manufacture wax patterns, investment casting dies for wax pattern moulding as well as investment casting shells for direct casting. These three components represent direct and indirect manufacture of tools. The surface finish, accuracy and functionality of all the RP parts were evaluated. Very reasonable results were obtained and it seems that RP techniques can have a meaningful impact on tooling manufacture for investment casting.

2.2.2 Build orientation

Designers of rapid tools should remember to keep the anisotropic nature of RP parts in mind. The degree of anisotropy in strength, surface finish and accuracy varies between different RP processes and also with the settings selected or part orientation in the build volume of specific machines (Lee et al., 2007). By carefully selecting the part orientation in the build volume, designers can ensure better accuracy on critical surfaces as well as better strength in required directions. The

greatest cause of surface roughness on RP parts is the so called staircase effect (Xu et al., 2000). The staircase effect is caused by the layered manufacturing process and is greatest on inclined planes. See Figure 6 from Hugo (2008). According to Hugo (2008), build orientation is one of the critical factors to control part cost, quality and use of support structures. He also gives guidelines how to orientate parts in the build volume to minimise the staircase effect.

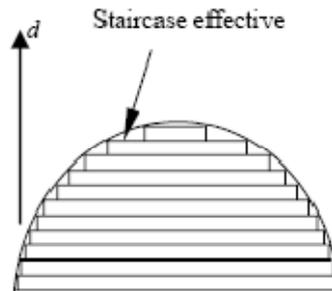


Figure 6: Staircase effect on RP parts (Hugo, 2008)

2.3 Use of RT technology in composite manufacture

Since tooling accounts for a major cost component in any composite manufacturing process, the feasibility of RT techniques in this field is worth thorough investigation. The complex tooling required for most composite processes also results in long lead times and lowered productivity. According to Wohlers (2003), substantial effort is underway in the field of composite manufacture with RP technology. It is therefore surprising to find that very little research has been published regarding the combination of RT and composite moulding technology, much less for the RTM process featured in this research project. The literature found will now be presented and results will be applied to this research project.

2.3.1 General composite manufacturing

Distinction needs to be made between direct manufacturing of composites with RP and indirect manufacturing using moulds from RT processes. This project is focused on the indirect route using the RT technology. It is also necessary to distinguish between long and short fibre composites. Long fibre composites feature continuous fibre filaments running the length of the reinforcement material of the part, improving material properties over short fibre composites. Also note that when reference is made to composites in this study, the materials under consideration is conventional composites consisting of a fibrous reinforcement and a matrix material. Many RP processes implement so called composite materials consisting of two different powder materials such as polymer and ceramic powder, but these are not of specific interest to this project.

Direct composite manufacturing

Direct RP manufacture of composites is very rare. This is because of the difficulties associated with depositing fibrous materials layer by layer with most RP technologies. FDM has been successfully used for the manufacture of particulate and short fibre composites (Masood & Song, 2004) and (Zhong et al., 2001). In a project by Zhong et al. (2001), the normal ABS polymer used in a FDM machine was combined with around 15% by weight of short glass fibres before being deposited onto the build volume. Good results were obtained and tensile strength was increased by more than 500% compared to unmodified ABS material. Masood & Song (2004) combined metal particles, around 70% of the total weight, with a nylon matrix for deposition with FDM. Good quality tooling parts were printed with this composite and proved to work very well in subsequent plastic injection moulding experiments.

According to Christian et al. (2001), no examples could be found where conventional long fibre reinforcement was directly incorporated into a RP process. During the research conducted, however, one example by Klosterman et al. (1998) has been found so far. This project used the LOM RP process to deposit layers of E-glass bonded with polymer matrix. This project also included work on ceramic matrix composites. This project was reasonably successful, but the composite parts could not be fully cured and consolidated by the LOM process alone. Secondary processes were necessary. No moulds are necessary with this process, but it is limited to fibre layers in one plane (horizontal) only and production volumes are very limited.

In the project done by Christian et al. (2001), a modified FDM process was employed to place resin impregnated long fibres on the build surface. A great deal of optimisation of the machine parameters was necessary before parts could be successfully manufactured. This process seems very promising however.

A very unusual direct rapid composite manufacturing process, nanocomposite deposition system (NCDS), was developed in a study by Kim et al. (2007). NCDS is a hybrid system, combining deposition of a photo-curable polymer resin and mechanical micro-machining. The resin matrix contains various nanoparticles like carbon nanotubes, forming a composite material. After deposition of a layer, the matrix is cured by UV light and excess material is then removed by micro-machining. This sequence is repeated for every layer of the part. Predictably, specimens with nanoparticles added were found to have greatly increased tensile strength over pure polymer specimens.

Indirect composite manufacturing

More literature work has been completed on the indirect composite methods than on direct methods. Research that is very applicable to this project was conducted by Ferreira et al. (2005). In this project, a MJM RP machine was used to manufacture a thermo-polymer mould. Dimensional control of the mould was performed by measurement with a FARO arm and comparison with the original CAD model. The bulk (80%) of the measurements fell within 0.0 mm to -0.3 mm of the

CAD model, being deemed acceptable for this project. A carbon fibre composite part was then moulded using the hand layup method. Good results were obtained, but the process was very slow and it took four working days to complete a part. This is a consequence of the low level of automation employed in the hand layup process. The rapid composite manufacturing methodology followed in this research project strongly influenced the methodology followed in the author's project and will be discussed in Chapter 3.

Another good example of indirect composite manufacture was conducted by Lyons (2006) where a ZCorp Z310 3DP, like the one used in this study, was used to print moulds for carbon fibre moulding. After the moulds were printed, they were infiltrated and strengthened with thermoset resins. Lyons (2006) advise the use of an infiltration resin that is incompatible with the composite part's resin to ensure no part removal problems. In this case a polyester resin was used to reinforce the mould and a epoxy resin for the carbon fibre composite. After infiltration, the moulds were sealed, sanded and treated with mould release wax. It was then employed to mould the steering wheel and radiator shroud for a racing car. Good results were obtained, but as with most other mould types many hours of labour was required for the finishing and preparation of the mould. In another application of 3DP by Lyons (2006), the RP parts were used as sacrificial moulds. According to Lyons (2006), green 3DP plaster materials have reasonable stability under high heat and are water soluble. The term "green" used here refers to the fact that the parts are untreated and as directly manufactured with the 3D-printer. These 3DP plaster materials were employed as sacrificial moulds to be dissolved in water. The moulds/cores were firstly printed and coated in mould release wax. They were then coated with composite material in a hand layup process. Once the composite resin has cured, the part can be immersed in a water bath, leaving the final part. A major advantage of this method is that there is no need to compensate for undercuts in the parts.

During a personal interview with Quang-Ut Huynh, a research engineer in RP at the Technical University of Berlin, it was mentioned that this facility has attempted the manufacture of RP tools for use in the manufacturing of automotive composites, but was not at liberty to provide more details. This project was not completely successful and it was not attempted again. (Huynh, 2008)

In an interview with Marinus Potgieter, a researcher at the Centre for Rapid Prototyping and Manufacturing in Bloemfontein, he described the composite RT applications done during his research. The RT technology of choice in his research was SLS combined with polyamide-nylon and nylon-aluminium material. These tools were sanded and sealed with a clear lacquer and were then employed in press moulding processing of pre-impregnated carbon fibre. Good results and reasonable accuracy was obtained, but it was found that sharp edge features deformed under the pressure of moulding and sharp edges became rounded. (Potgieter, 2008)

Another company doing composite prototype manufacture utilising RT is Rapid Prototypes in Cape Town. Use is made of a Zcorporation Z310 3D-printer

to print the moulds for a conventional hand lay method. Mould surface finish is improved by treatment with automotive body filler and sanding thereafter. The main reason this company prefers these moulds over machined moulds is because of greater geometrical freedom. (Alborough, 2009)

RP techniques may also be used to create cores for the manufacture of composite moulds. Custom3D is a company which provides this service. They mainly use the 3DP RP method and emphasize that it is very important to properly finish the core surface with sandpaper before the composite moulds are drawn from the core. The cores should also be adequately treated with mould release agents. (Du Toit, 2009)

2.3.2 RTM tooling applications

It has already been established earlier in Section 2.1 that tooling comprises a major expense in RTM processes, so it comes as no surprise that researchers such as Tari et al. (1998) propose the use of RP techniques for the manufacture of moulds for RTM composite manufacturing. In the research paper by Veldsman & Basson (1998a) it is stated that the cost element introduced by tooling is significant for small production volume environments. This is typically where RT techniques may be advantageous. Tari et al. (1998) also promotes the use of RP moulds for RTM due to the freedom in complexity allowed by both RP and RTM techniques.

The results of the project completed by Tari et al. (1998) are very relevant to the study conducted in this thesis. Use was made of the LOM method of RP manufacture to create a set of moulds for making glass fibre parts with RTM. The LOM mould consists of layers of paper bonded together and can be easily sanded just like a block of wood. After printing, the mould was treated with a surface sealer to fill small voids on the surface, making sanding easier. After sanding, the mould was coated with polyester resin to increase durability. The mould was then sanded with even finer sandpaper, ending with 280 grit paper. The mould then received 5 layers of Moldkote 1906A mould sealing compound as the final barrier against the ingress of moisture or unwanted resin. After treating with mould release wax, the mould was ready for the manufacture of composite parts. Measurements of the mould were made with a Brown & Sharpe CMM (coordinate measuring machine) before and after surface treatment. Although it was found that the mould directly from the LOM machine exhibited geometrical deviations, the effect of the surface treatment was greater. The average deviation caused by surface treatment was -0.25 mm compared to the average deviation of -0.11 mm of the LOM mould from the CAD model. The VARTM variation of the standard RTM process was then employed to mould the composite parts with E-glass fibres and vinylester resin. The mould was fitted with transparent polycarbonate at the top and bottom to enable monitoring of the resin flow front. While monitoring the infusion process, non-uniform flow fronts were witnessed due to the edge effect discussed in Section 2.1. Small dry spots were also initially found in cured parts. A HPL was then incorporated, solving this mould filling issues but having the

unwanted side effect of decreasing the accuracy and surface finish quality of the moulded parts. The final parts indicated an average deviation of 0.564 mm from the CAD model.

In the research project by Christian et al. (2001), a silicone mould for a human jawbone was drawn from a SLA pattern. This silicone mould was then used to manufacture a biodegradable glass fibre composite with the RTM process. The silicone mould tended to absorb some of the resin during the moulding process.

As part of a study done by Lyons (2006), cores/patterns were printed with 3DP and composite moulds were then drawn from the RP patterns. These composite moulds were then employed in a vacuum infusion process to manufacture carbon fibre inlet manifolds for a racing car. This could be referred to as an indirect-indirect method.

Although it is clear that widespread use of RT tools for RTM processes has not been attempted, the results of the few cases found indicate that much potential lies in the combination of these two techniques.

2.3.3 Other advantages of RT tooling in composite moulding

According to Huynh (2008) another advantage of the use of RT moulds for composites is the ability to include complex internal geometry like cooling/heating channels. This advantage is also emphasized by Wohlers (2003). With some resin systems, the exothermic reaction is rather violent and the resin may also expand and crack the mould. It may then be desirable to control the reaction by including cooling channels. The porosity of certain RP parts may also be put to good use for cooling purposes in such cases. Where heated mould walls are required to accelerate the resin curing cycle, the ability of RP to manufacture suitable channels/cavities is also handy.

3. PART MANUFACTURE PROCESS CHAIN

The main challenge of this project was the design of a process chain to enable the successful manufacture of composite parts. It was decided to base the process chain on a modified version of the one proposed by Ferreira et al. (2005). This process chain is illustrated in Figure 7 on the next page and will be briefly discussed. The author will then illustrate how this process chain was applied to the two case studies completed.

3.1 Process chain description

3.1.1 Virtual prototyping

The process chain for this project consists of a virtual and a physical prototyping domain. The virtual prototyping domain begins with the defining of the product specifications. The composite end-product needs to satisfy certain design guidelines, as will be discussed in Section 3.2. The product specifications are incorporated into a CAD model of the mould (rapid tool) required for the RTM process. The mould also needs to satisfy some design guidelines, which are also provided.

The proposed process chain makes use of a resin flow simulation package, RTM-Worx from Polyworx, to predict the resin filling patterns in the designed mould. This serves as a reliable method to improve the mould design and specifically decide on good resin inlet and outlet port placement. This also gives a rough indication of the resin filling times for the RTM setup involved. The CAD model is repeatedly analysed against the design guidelines and RTM-Worx simulation results to ensure good functionality. Improvements to the CAD model are made if necessary and the model is re-analysed until a satisfactory design has been reached.

After the iterative mould design phase has been completed, the CAD model is exported in STL format to the RP machine.

3.1.2 Physical prototyping

The physical stage of the process chain begins with direct RT from the RP machine. The rapid tool may be printed hollow to save material. If the mould has been printed in sections, it needs to be assembled after printing. Raw parts from the 3D-printer are firstly infiltrated with a low viscosity resin and allowed to dry. Dimensional control, using a coordinate measuring machine (CMM), is then performed to compare the geometry of the RT part to the CAD model.

If the mould is found to be within predetermined specifications, the process chain proceeds to the following step. In this step, the mould is reinforced with a 3 mm steel backing plate to provide sufficient stiffness.

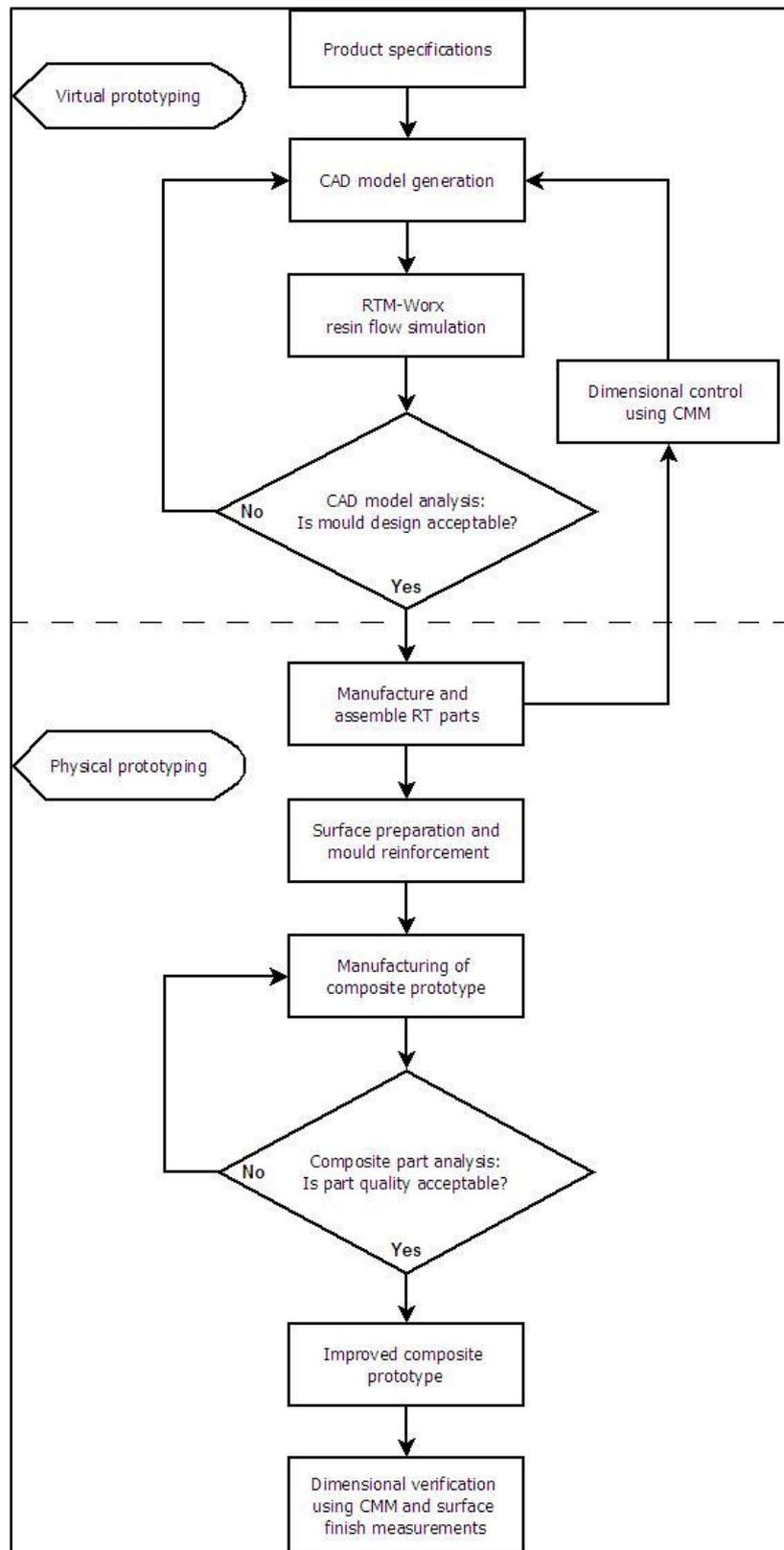


Figure 7: Process chain for the manufacture of composite parts

The mould is painted with an automotive primer to fill small cavities and then sanded with progressively finer sandpaper. When a uniformly smooth surface finish has been attained, the mould is spray painted with a final surface layer in a contrasting colour. The function of the contrasting colour is to indicate when wear/damage occurs on the mould surface.

After application of mould release wax, the mould is ready to be used in the next step which is the moulding of the composite part. The fibre preform is placed in the mould and resin inlet and outlet pipes are positioned correctly. The mould then needs to be carefully sealed and tested for leaks. In this project, vacuum was used to draw the resin into all parts manufactured. A resin trap is placed between the resin outlet and vacuum pump to protect the pump from any resin entering. Resin is then prepared and allowed to fully infiltrate the dry fibre preform. After the composite part has been allowed to cure, it may be removed and inspected. If the analysis of the composite part identifies any flaws, the moulding process is modified accordingly until parts of sufficient quality are possible. Flaws are usually in the form of voids, dry spots and shifting of fibre preforms. This exercise should result in improved composite prototypes, ready for end use or testing purposes.

Before any functional or structural testing of the final composite prototypes take place, the CMM is again employed for dimensional verification purposes. Parts are once again compared with the CAD model and may be rejected if they do not satisfy dimensional tolerances. At this stage a surface tester may also be employed to measure the surface finish of these final parts.

3.2 RTM mould and part design considerations

Proper part and mould design is more critical for the success of RTM than for a typical hand layup process. Guidelines for the design of RTM parts and moulds are provided in Appendix A. Guidelines which are specific to the RT mould also need to be considered and are also provided in Appendix A. A short summary of the major part and mould design principles is provided below:

- Keep part and mould design simple and avoid unnecessary geometrical features.
- Incorporate generous draft angles of at least 5° to simplify part removal.
- Provide generous fillet radii or chamfers where two surfaces meet perpendicularly.
- Take steps to avoid resin-rich areas. This helps prevent part cracking or mould damage due to shrinkage during curing.
- Design for net-shape manufacturing and avoid post-moulding operations.

- Design moulds strong enough to withstand moulding forces.
- Design moulds to enable proper sealing.
- Place resin inlets, outlets and runners in such a way to promote proper mould filling with resin.

After the design guidelines have been applied to a RTM setup, the mould filling needs to be verified with a simulation package before manufacturing commences. The design guidelines provided in Appendix A are meant to serve as general guidelines for a RT-RTM hybrid process which may employ RT processes other than 3DP. The application of these guidelines to the 3DP RT will be evident in Sections 3.3 and 3.4.

3.3 Case study 1 – One sided mould with resin infusion

In this study, the manufacture of a simple part utilising the vacuum infusion process was investigated. A one sided mould, in the shape of a simple boat hull, was designed using the Inventor 2008 CAD package. Draft angles and other tool related features as per the guidelines were included as required. This model was imported into the RTM-Worx simulation package and properties like the viscosity of the chosen epoxy resin and permeability of the fibre preform were incorporated into the model. Simulations indicated that the resin distribution was acceptable with one resin inlet and outlet situated at the diagonally opposed corners of the mould. The results from these simulations are provided in Section 3.5.

After the virtual stage of case study 1 was completed, the CAD model was exported to the Zcorp Z310 3DP for printing. The part was printed hollow with a wall thickness of 5 mm, the recommended minimum as per the design guidelines in Appendix A. The printing was completed in 590 minutes and after the excess powder material was removed, the part was infiltrated with Prime™ 20 LV epoxy resin to increase the strength. Although it was decided to use epoxy resin for the part too, which is contrary to guidelines provided and may cause the part to bond to the mould, it was deemed safe because of the surface treatment planned for the mould. After the resin was allowed to cure, the part geometry was measured with a Mitutoyo CMM. These measurements will be discussed in Chapter 4 and were deemed acceptably close to the CAD model for the purposes of this study.

The hollow backing of the mould was filled with resin and the mould was then judged to be sufficiently strong and stiff for moulding and handling operations. Care should be taken when filling deep components with resin as the high exotherm of the large resin volume and/or expansion/contraction during curing may damage the mould. It is recommended that resin is applied in 30 mm layers. The next step was to sand the mould with progressively finer water paper, beginning with 220 grit and ending with 400 grit. The mould was then painted with Luxor Transline MS automotive primer to fill any remaining irregularities and again sanded smooth.

Figure 8 below indicates the mould after priming and sanding, making it visible where the yellow primer filled surface irregularities.



Figure 8: Primed and sanded mould

As final surface preparation, the mould was given a surface coat of green spray paint, contrasting with the ivory colour of the RP part. This would enable the rapid identification of any wear marks on the surface when the surface layer is damaged. The mould is then treated with Partall high temperature mould release wax followed by a layer of Safelease A150 PTFE-based release agent. The mould was then ready for use.

Before any parts were manufactured by the infusion process, an experimental part was manufactured by hand layup. It was decided to use two layers of 425 g/m^2 $0^\circ/90^\circ$ woven roving as reinforcement. The experimental part indicated that care is necessary to place the fibre reinforcement around the mould. The fibres tended to lift from the mould surface in the vicinity of corners and edges. By carefully shaping the fibre reinforcement and gluing the edges with cyanoacrylate (“superglue”), a fibre preform which negated these problems was created. Cured parts also tended to be difficult to remove, but this was solved by more generous application of mould release agents in subsequent attempts. Another problem which became evident in this experimental part was insufficient mould stiffness. When the cured part was removed, the mould fractured. The mould was then repaired and fitted with a 3 mm mild steel backing plate, solving any further problems. Figure 9 indicates the fractured mould complete with steel backing plate ready for fitment.

Figure 10 indicates the setup used in this infusion process. The function of the vacuum bag and tacky tape is to provide an airtight seal for the vacuum process. The peelply is a porous backing layer which can be easily removed from the cured preform, leaving a uniform surface finish. The distribution media is an optional layer and will be discussed shortly. Figure 11 indicates the complete infusion setup with vacuum pump, resin trap and resin source included.

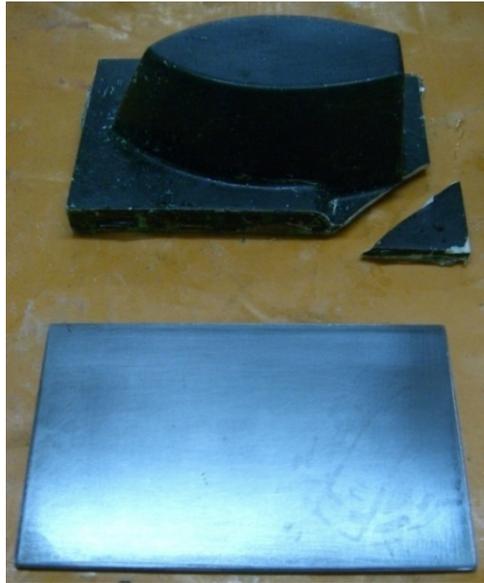


Figure 9: Fractured mould complete with steel backing

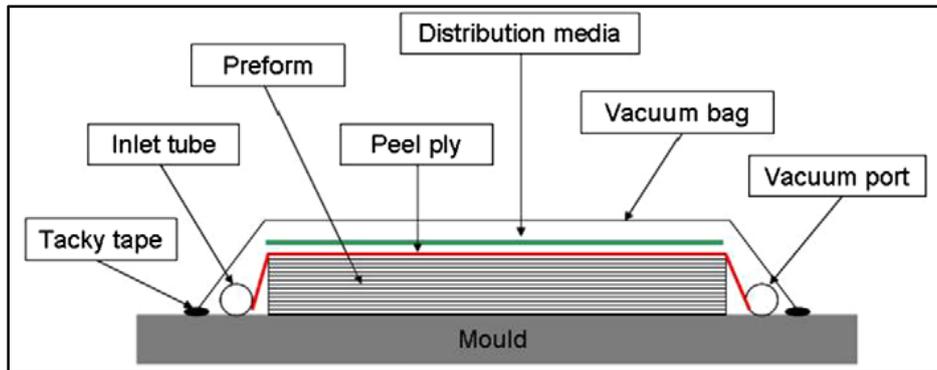


Figure 10: Infusion setup (Govignon et al., 2008)

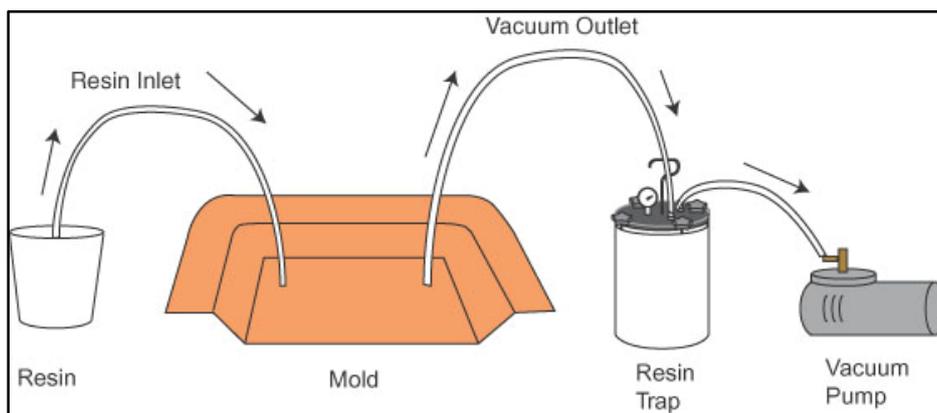


Figure 11: Complete infusion setup (Engineer's Handbook, 2008)

Spiral tubing is used for the inlet and outlet ports (Figure 12). This provides a distributed resin source which stays open even under vacuum pressure and can also be used as a means of vacuum distribution through the laminate (Lunn, 2004).

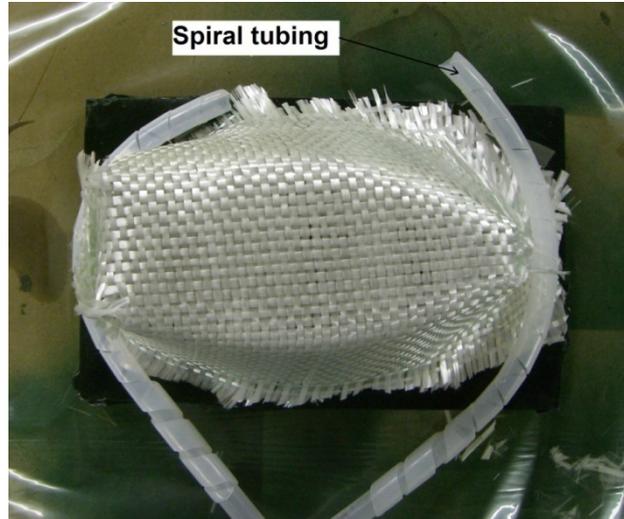


Figure 12: Fibre preform with spiral tubing for resin ports

The vacuum pump was adjusted to 75 kPa and part manufacture was commenced by allowing resin to infuse the fibre preform. After partial curing at room temperature, the layup is subjected to a post-curing cycle of 60 °C for two hours.

Some problems were initially experienced with incomplete mould filling and dry spots were found in the first few parts. This was solved by improving mould sealing, using a special low viscosity resin (Ivory 340/5LV) and fitting distribution media, also known as a HPL, over the fibre preform. The HPL allows the resin to immediately cover the top surface of the preform and only then infiltrates through the thickness. One drawback of this is that resin is allowed to flow all the way to the venting port before the entire preform has been wetted out. This may lead to partial blocking of the venting port and dry spots after infusion. During this project use was made of the commercially available Greenflow 75 HPL.

These corrective steps resulted in the production of good quality, fully infused parts. The use of Greenflow also decreased resin consumption, probably due to the more uniform resin flow patterns. Figure 13 on the next page indicates the vacuum bagged mould with Greenflow 75 (the green mesh) visible.

Lessons learned from this study included the importance of mould sealing, the value of low viscosity resins, HPLs and proper application of part release agents. The importance of sufficiently reinforcing potentially weak RT parts became evident. The total number of parts manufactured was 8 and no signs of mould wear could be detected. An average fibre volume fraction of 51% was accomplished. A gel coat was also incorporated to improve the surface finish of some parts.



Figure 13: Vacuum bagged mould with Greenflow

3.4 Case study 2 – Closed mould with inserts and VARTM

The function of the second case study was to investigate the applicability of the RT-RTM process to more complex parts and closed moulds. The VARTM variant of the RTM process was employed in this case study. It was decided to manufacture a model of an ocean current turbine blade. The motivation for the choice of this part was due to a few reasons which will be briefly explained. The chosen ocean current turbine's blade profile was designed in a project completed by Reinecke (2007) and CAD models were available. A set of these blades had already been manufactured from aluminium on a CNC machine and these blades and CNC manufacturing data were also available for comparison with the VARTM process. The geometry of the turbine blades was ideal for the second case study as it was of manageable size for the 3D-printer, the complex curves were suitable to test the capabilities of the new process and the blades required a good surface finish on both sides, as made possible with a VARTM manufacturing process.

The composite materials employed in the VARTM process also have very desirable material properties for use in aqueous environments. According to Marsh (2009), epoxy matrix composites are usually selected over steel for underwater applications as they are very resistant to moisture absorption and corrosion. As noted in Section 2.1, RTM parts have very good resin impregnation and therefore resist moisture absorption. Composites also have buoyancy advantages over metal. Marsh (2009) goes on to describe carbon fibre epoxy ocean current blades being successfully employed by numerous commercial manufacturers. To date, standard hand layup over a male mould has been the manufacturing method of choice, but resin infusion/VARTM is mentioned as a future technique to increase production efficiency.

Guidelines as provided in Appendix A were once again considered during the mould design stage. The mating surfaces of the mould were designed to be flat instead of following the curved plane where the split-line of the blade is situated, enabling easy cleaning and simplifying sealing. It was decided to rather clamp the mould with bolts than with vacuum to prevent the vacuum pump from operating constantly until the part is cured. The mould requires locating pins to positively locate the two sides of the mould in the correct relative position. These were incorporated as features in the CAD model. To prevent thick resin rich areas, a disposable RP core was also designed for this part. The core was designed with an offset equal to the thickness of the planned fibre layers to create sufficient space for the fibre reinforcement to fit between the core and inside surfaces of the mould. As resin distribution is difficult to control due to the complex blade shape, it was decided to use a core with predetermined resin paths/runners printed on the surface. A similar method, utilising cores machined from hard foam, was previously attempted at the North-West University (Jonker, 2009).

An iterative method of placing the resin runners on the core surface was followed during which various layouts were simulated in RTM-Worx until results indicated a very uniform resin distribution pattern. If the flow front is not uniform, it will be necessary to allow some resin to bleed through the vent, resulting in wasted resin and longer mould filling times (Modi et al., 2007). Figure 14 illustrates the final position of the resin runners on the core surface.

The closed mould was provided with one 12 mm inlet port and one 12 mm outlet port, allowing resin flow from the thick to the thin sections of the blade. The diameter of the ports also allowed the use of commercially available resin piping. RTM-Worx simulations indicated favourable resin patterns for the mould-and-core assembly. Details of the RTM-Worx simulations are provided in Section 3.5. The mould halves were provided with 6 holes for clamping with M10 bolts.

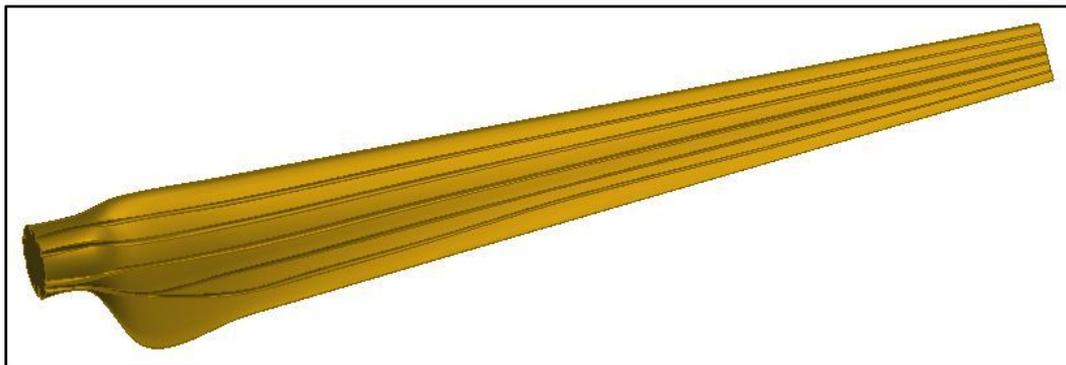


Figure 14: CAD model of blade core

After the virtual modelling phase was completed, the CAD model was exported to the 3D-printer. Because of the length (410 mm) of the mould, it was sliced into two parts to enable fitting into the 3D-printer's build volume and again printed

hollow to save material. Figure 15 illustrates one mould half and blade core directly from the RP machine. Notice the locating pins to positively position the mould halves.



Figure 15: Mould and core directly from 3D-printer

The same steps as in case study 1 were once again followed during the preparation of the mould. The only additional step taken was the bonding of the two sections of each mould half. Care was taken to remove the joining line by polishing.

The steps taken during part manufacture differed somewhat to the one sided mould process in case study 1. It is firstly necessary to cover the blade core with fibre reinforcement. Cyanoacrylate adhesive was initially used to glue the edges in place, but use was later made of the more effective 3M Scotch-Weld 77 spray-on adhesive. This adhesive, as well as the similar Airtac 2, is specifically formulated to be used in RTM processes while having a minimal effect on the final composite quality. The use of these adhesives make accurate fibre placement possible. Initially use was made of two layers of 195 g/m^2 $0^\circ/90^\circ$ woven roving E-glass as reinforcement, but this was soon changed to 185 g/m^2 $0^\circ/90^\circ$ woven roving carbon fibre due to poor stiffness of the E-glass parts.

After covering the core with fibre reinforcement it is placed inside the mould, resin inlet and outlet pipes are positioned and the mould is sealed with silicone sealant (Figure 16). Resin can then be prepared and allowed to infuse the part. Figure 17 on the next page indicates the closed mould ready to be infused with resin. This closed mould is connected to the vacuum source via the resin trap and to the resin source on the other side.



Figure 16: Core placed in mould with ports in position

The first parts exhibited incomplete resin wetting as well as some voids. Investigation indicated that poor mould sealing, caused by porosity and inaccuracies in the rapid tool, was mostly to blame. These problems were solved by vacuum bagging the mould, refining core design and also increasing vacuum pressure on the resin being drawn in from 75 kPa to 85 kPa. It is interesting to note that Tari et al. (1998) and Veldsman (1995) also experienced problems with dry spots on the parts and this was similarly traced to small leaks.



Figure 17: Mould assembly ready for resin introduction

After the corrective steps were taken, parts of very good quality were manufactured. Witness the carbon fibre blade in Figure 18. If a hollow blade is required,

the cores may be dissolved in water if soluble RP materials are used (Lyons, 2006) or melted out in the case of wax cores. Altogether 15 blades were manufactured with the RT moulds and it seems reasonable to expect a mould lifetime of 40 parts without serious degradation.



Figure 18: Carbon fibre blade

3.5 Resin flow simulations with RTM-Worx

As indicated in Figure 7, the resin flow simulation process is one of the steps used to verify/improve the mould design before the physical prototyping stage is attempted. This section will give some background to the resin flow simulations and the results for both case studies will then be discussed. More results from the RTM-Worx models are presented in Appendix B.

3.5.1 Background

RTM-Worx is a simulation code that uses the Finite Element and Control Volume methods to solve the governing equations for resin flow through porous mediums (Polyworx, 2009). It may be used to optimise part injection by location of runners, inlet- and outlet ports as well as assessing the impact of changes in resin and fabric properties.

As motivated in Section 2.1, the aim of any RTM/VARTM/infusion setup is to promote the most uniform resin flow front, leading to better quality parts and less resin wastage. The most important factors influencing the resin flow pattern is the location of runners and ports. Luo et al. (2001) states that the inlet/outlet port locations can be decoupled from other parameters such as resin viscosity and fibre permeability as the resin flow pattern is mainly dependant on the location of these ports. Small inaccuracies in permeability or viscosity values will only influence the filling time, not the flow pattern.

When reviewing the predicted mould filling times, it is necessary to consider the resin manufacturer's recommended pot life. The pot life refers to the amount of time after the resin has been mixed with activators before it starts to set. The composite part in question needs to be fully infused before the pot life of the resin expires. This time is typically 20 to 30 minutes for epoxy resin.

It was decided to follow an iterative procedure to improve mould design during the simulations for this project. The ports and runners were initially placed according to the guidelines provided in Appendix A. If the resulting resin flow pattern was deemed insufficiently uniform, changes were made to port and runner placement until simulations indicated a reasonably uniform flow pattern. Tari et al. (1998) used a similar iterative procedure to find acceptable port locations by comparing alternatives on the base of filling time and resin wastage.

3.5.2 RTM-Worx process steps

The Inventor CAD model of the mould is firstly saved in a DXF format and imported into RTM-Worx. The geometry of the CAD model is then converted into a number of keypoints and the keypoints are connected with lines known as curves. Part geometry may also be defined directly in RTM-Worx, but it is time consuming and takes more effort when complex geometry is involved. Surfaces are then created at regions defined by a closed loop of curves.

The next step is the defining of all model properties. The inlet and outlet ports can now be defined at any existing keypoint location simply by changing the keypoint properties. Properties of curves may also be modified to create runners with specified diameters. By assigning thicknesses to the surfaces, volumes which may be filled with resin are created. Other properties which are assigned to the surfaces are fibre volume fraction, lay-up angle, major and minor permeability as well as a reference direction. The reference direction is a unit vector defining the principal fibre direction for each fibre layer.

After defining all the model properties, a mesh consisting of triangular shell elements are generated on all surfaces. Mesh parameter are refined until all the elements are found to be of good quality. Before the simulation can be commenced, some calculation parameters need to be entered into the Simulator Control panel. The first parameter is the increment between filling time steps which are saved, in other words a value of 1% would result in 101 snapshots during the filling process. The second parameter is the termination criterion for iterative calculation steps. Finally, the resin viscosity is entered and the simulation is started. A variety of results can be plotted, including the following: Filling time, pressure distribution, element quality (how near triangular elements are to an equilateral ideal), average permeability and fibre volume fraction.

3.5.3 Case study 1

Before any simulations are attempted, it is first necessary to know values of certain constants. The values used for case study 1 are presented in Table 2 on the next page. The only constant that warrants further explanation is the permeability values. The layup used in this project has the same amount of fibres in the longitudinal and transverse directions, and therefore $k_{11} = k_{22}$. As discussed in Section 2.1, various methods exist to calculate permeability. It was decided to follow the method used by Veldsman (1995) as it is also part of the cost model used in this

project. This method is based on Darcy's equation. The equations used are presented as part of the cost model in Appendix D. Values obtained with this method seemed reasonable when compared to permeability values experimentally obtained for similar fibres in a project by Tavenor (2008).

Table 2: Constants for case study 1 simulation

Description	Symbol	Unit	Value
Resin viscosity	μ	Pa.s	2
Permeability in principal fibre direction	k_{11}	m ²	1x10 ⁻⁹
Permeability perpendicular to principal direction	k_{22}	m ²	1x10 ⁻⁹
Thickness of fibre reinforcement	H	m	0.00084
Fibre volume fraction	V_f	%	50
Injection pressure	P_i	Pa	75000
Layup angle of reinforcement fibers	Φ	°	0
Runner diameter	D	m	0.012

All the process steps mentioned earlier in this chapter were completed and the model, complete with inlet port (red dot), outlet port (blue dot), resin runners (green cylinders) and surface mesh, is illustrated in Figure 19 below.

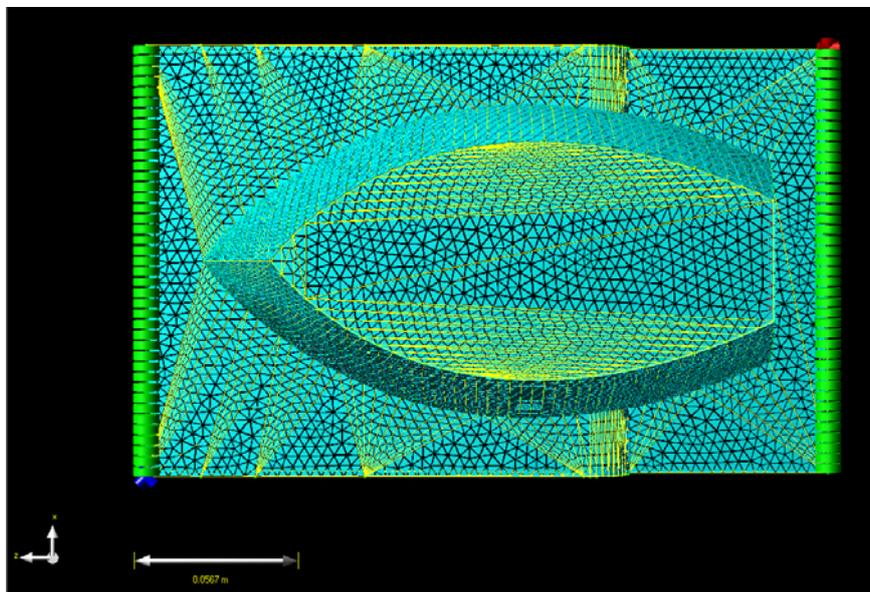


Figure 19: Completed RTM-Worx model for case study 1

After some simulations were completed and grid-dependency tests were done by varying the number of elements, the results were reviewed. The results seemed reasonable and a mould filling time of approximately 22 minutes was predicted. More importantly, the resin flow front shape was very uniform; indicating that good quality fully infused parts could be manufactured with this setup. Figure 20 below indicates a plot of the fully infused part with a time scale indicating the filling times on the left-hand side.

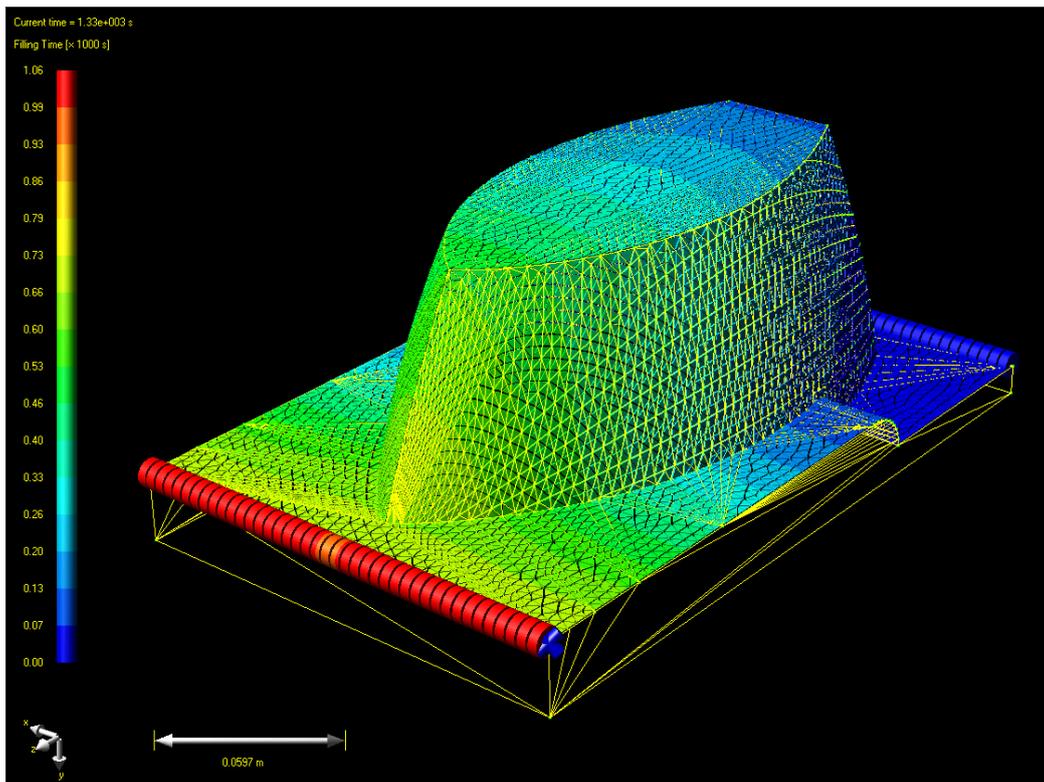


Figure 20: Fully infused prediction

When the physical parts were manufactured as described in Section 3.3, the observed resin filling patterns compared well to the RTM-Worx prediction. This can be confirmed by viewing Figures 21 and 22 where the photographs of the physical part are compared to the simulation at similar filling stages. The darker areas in the photographs are the areas already infused with resin.

A major discrepancy in the mould filling times between the RTM-Worx model and physical part was observed. Actual mould filling times were longer than the predicted time of 22 minutes. The average actual filling time when Greenflow was omitted was measured to be 43 min. According to Polyworx, the supplier of RTM-Worx, this is mainly due to the use of a constant resin viscosity in the program, whereas the viscosity actually increases over time (Koorevaar, 2008). A non-isothermal reactive extension for the RTM-Worx package has been created to

make allowance for this phenomenon, but was not available for this project. Other researchers like Tavenor (2008) reported the same under-prediction. This was of little consequence to this research project as the resin filling pattern is of more importance.

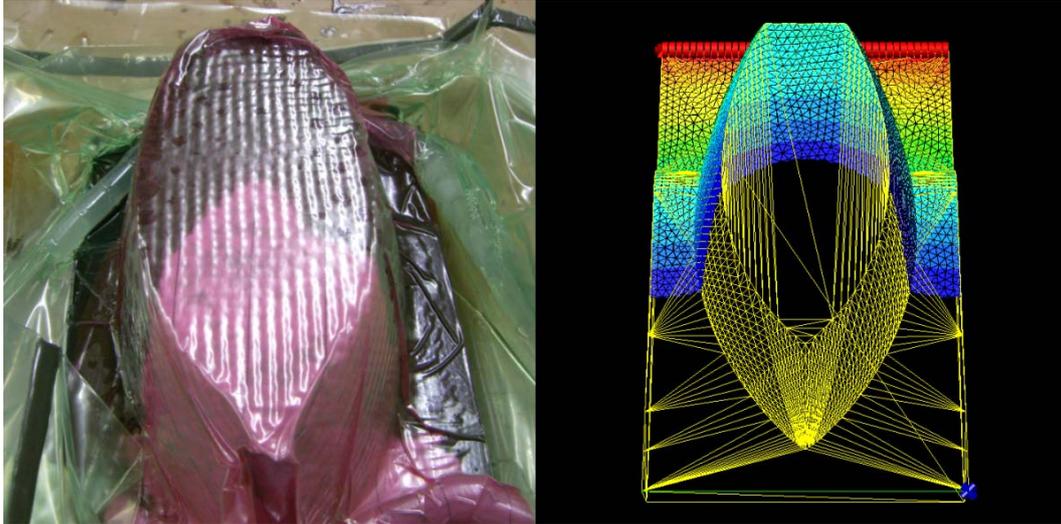


Figure 21: Comparison 1 of physical model to simulation

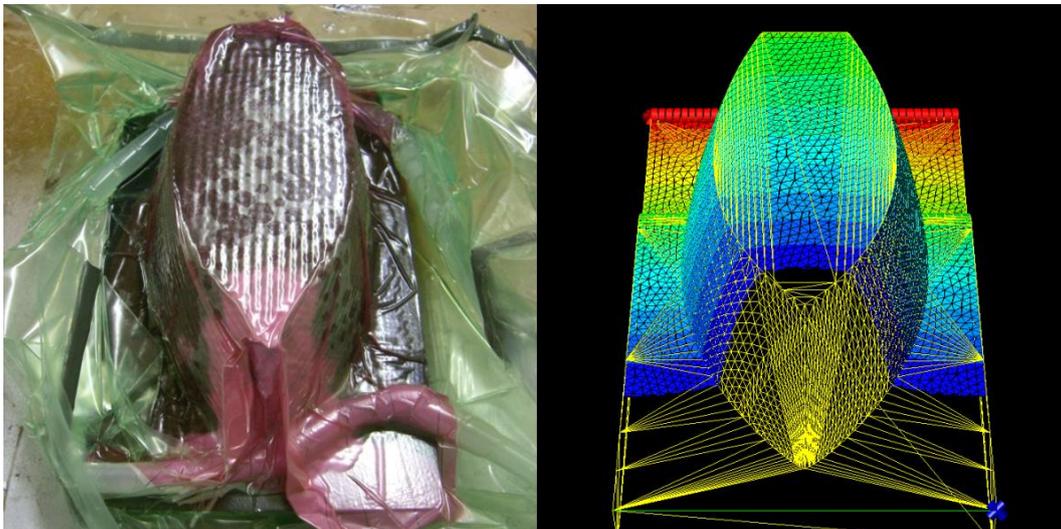


Figure 22: Comparison 2 of physical model to simulation

3.5.4 Case study 2

In this case study similar process steps were taken as for case study 1, but the constants in Table 3 are somewhat different due to the different type of fibres used

in this study.

Table 3: Constants for case study 2 simulation

Description	Symbol	Unit	Value
Resin viscosity	μ	Pa.s	2
Permeability in principal fibre direction	k_{11}	m ²	0.8×10^{-10}
Permeability perpendicular to principal direction	k_{22}	m ²	0.8×10^{-10}
Thickness of fibre reinforcement	H	m	0.0008
Fibre volume fraction	V_f	%	50
Injection pressure	P_i	Pa	75000
Layup angle of reinforcement fibres	Φ	°	0
Runner diameter	D	m	0.002

Preliminary simulations with only a resin inlet and outlet port and no runners on the surface of the core indicated very unbalanced flow. This seems to be due to the implemented edge flow effect, as described by Yang et al. (2008). This is caused by clearance between the fibre preform and mould edges creating a type of channel. In this case, such a clearance existed at the trailing edge. Figure 23 below indicates this phenomenon as found in the initial simulations. Predicted filling time in this case was 9 minutes and 30 seconds.

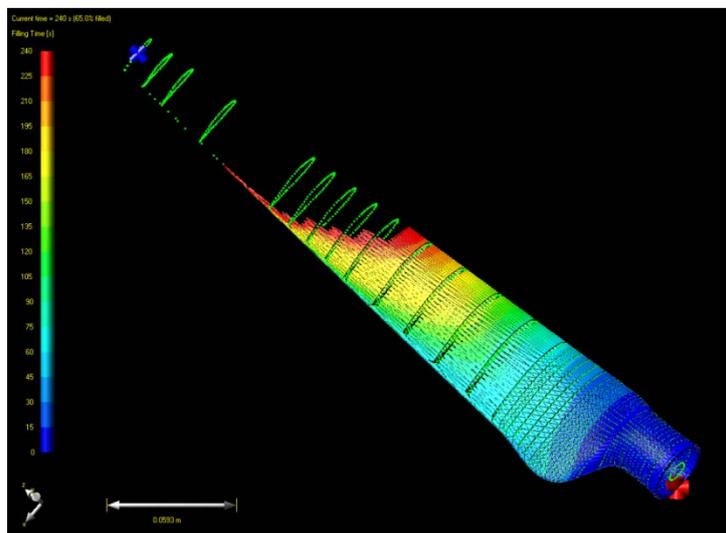


Figure 23: Initial simulation with no resin runners

It was decided to attempt smoothing of the resin flow pattern by adding surface runners/channels to the core as recommended by Smaldon (2004) and also at-

tempted at the North West University (Jonker, 2009). Longitudinal runners were now added to the top and bottom surfaces one at a time until the resin flow pattern was found to be sufficiently uniform. At the stage where 5 uniformly spaced runners with a 2 mm diameter were placed on each side, the resin flow shape was found to be sufficiently uniform. Results from the intermediate simulations may be viewed in Appendix B. Figures 24 to 26 indicate the resultant flow shape for the final design. The predicted filling time was found to be 1 minute. This represents a tenfold decrease compared to the simulation with no runners. The actual average filling times of 1.9 min (refer to Table 11 in Chapter 5) indicates a similar under-prediction as was experienced with case study 1.

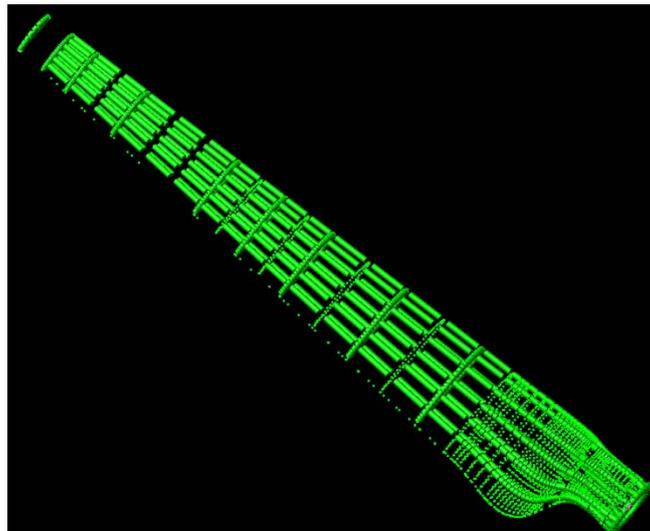


Figure 24: Green cylinders represents runner positioning

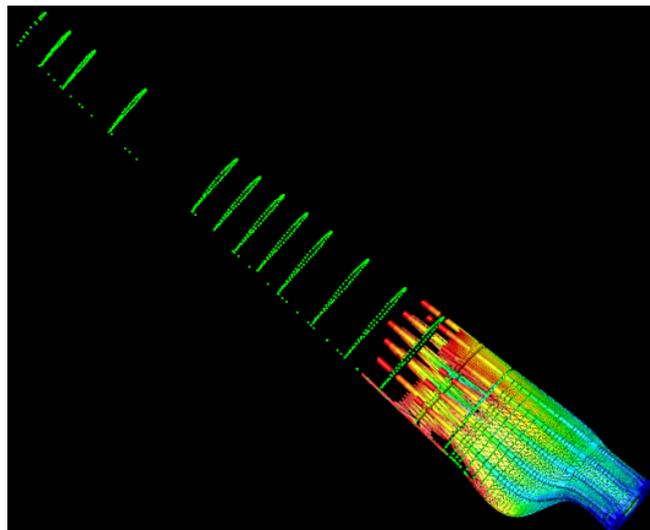


Figure 25: Simulation at t = 10 s

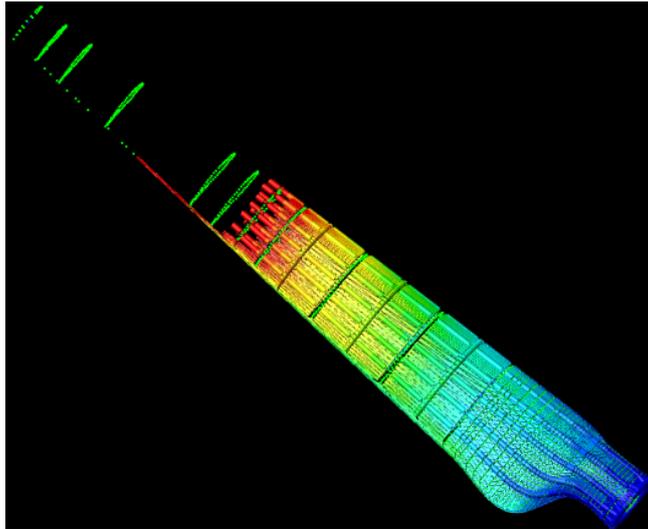


Figure 26: Simulation at $t = 20$ s

3.6 Findings and recommendations

Although only relatively small parts were manufactured during the case studies, the radically different geometries of the two case studies served as a handy platform to test the part design guidelines. As an example, the depth of the sides of the first case study served as a good verification for the minimum draft angle design guideline and the thickness of the second case study part served the same purpose with the guidelines pertaining to cores.

Correct application of the design guidelines resulted in moulds which could be cleaned easily, minimal post-moulding operations to the part were necessary and the resin port and runner placement gave good mould filling results.

Future work should include investigation into the application of other RT techniques to the designed process chain.

4. GEOMETRICAL QUALITIES

When components are needed in an engineering environment, there is always a set of minimum criteria for the accuracy of the part. It is necessary to be aware of the accuracy capabilities of a process before a decision is made regarding applicability to a specific component.

Dimensional measurements were conducted with a Mitutoyo Bright 710 CMM with a calibrated accuracy of 5 μm and a volumetric accuracy of 6.1 μm . The user programs a number of measurements to be made in specific part areas and these measurements are then compared with the CAD model. A short summary of statistical values are provided for each measurement. A Mitutoyo SurfTest 211 was employed to measure the surface finish of all samples. This surface tester uses a stylus which is drawn over the surface to measure the R_a (Arithmetic Average Roughness) values of the object. This machine was used in ISO (μm) mode with a sample length of 0.8 mm.

4.1 Case study 1

The accuracy obtainable with the Zcorp Z310 3D-printer used in this project is well known and has been investigated by many researchers for example Hugo (2008), De Beer (2004) and Louw (2004). The purpose of the geometrical measurement of the RP components was therefore not aimed at obtaining capability profiles of the 3D-printer, but to enable the determination of accuracy loss that occurs with sanding/treating of the mould and the accuracy loss when a part is manufactured with the mould. These measurements will determine the accuracy loss at each of these steps in the process chain and will also give designers a better idea of the final composite part accuracy that can be expected if the 3DP process is substituted with a different RT process.

The Error Distribution Function (EDF) is a histogram which is useful to provide a rapid visual summary of all the geometrical deviations of the part. This histogram of the measurements for the as printed and infiltrated tool is provided below together with a summary of the descriptive statistics (Figure 27). The reasonably small median value indicates the central tendency of the part and that errors are generally random and not systematic. The skewness value is slightly positive and indicates the distribution is hanging to the left of the histogram and that the part is slightly smaller than the CAD model. Figure 28 indicates all the measured points with a key indicating deviation values. If Figure 28 is observed, it becomes clear that large deviations occurred on the top flat surface. These values were smaller than the CAD values, indicating possible sagging in the middle during printing and explaining the positive skewness value. The poor accuracy on the sides of the tool might be due to the stair-stepping effect of the 3DP process being more evident on such inclined surfaces.

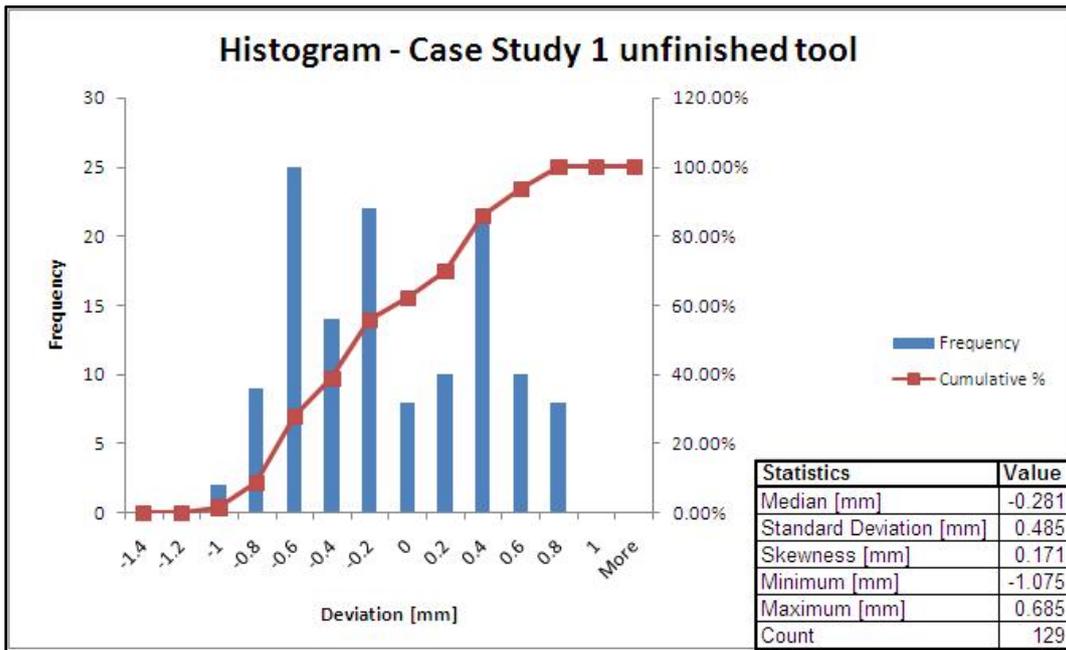


Figure 27: Histogram with statistics for case study 1 unfinished tool

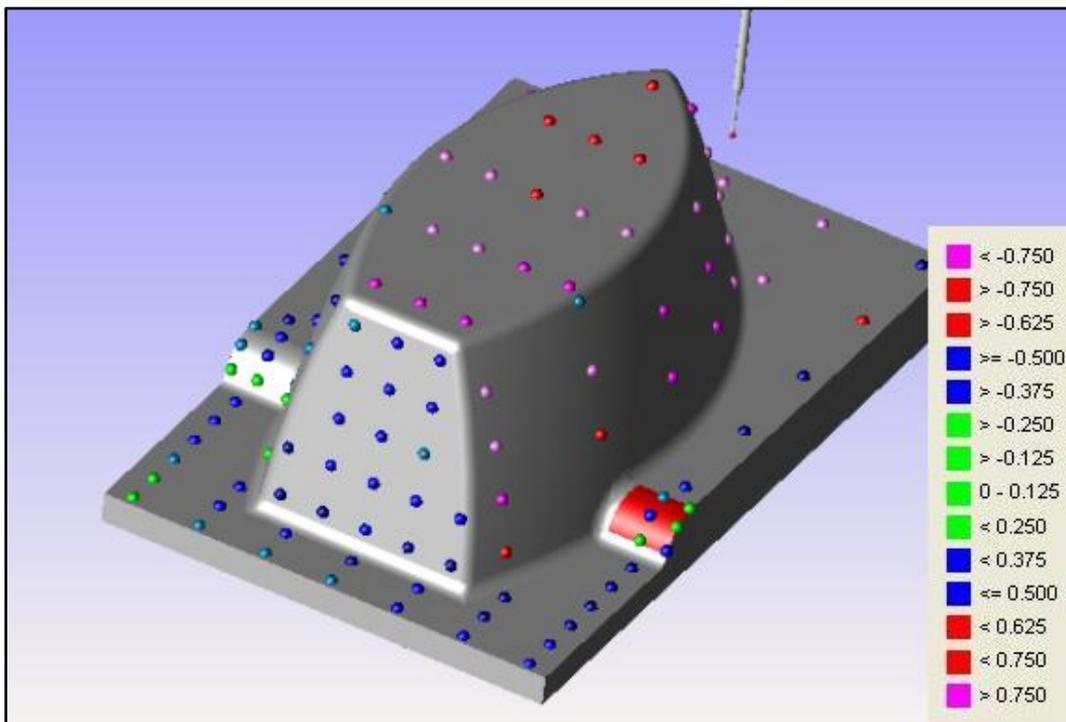


Figure 28: Measured points for case study 1 unfinished tool indicating deviations [mm]

Figure 29 below indicates the statistical results for the tool after sanding and surface treatment. The general tendency of the deviations are the same as for the unfinished part, but the surface treatment process resulted in slight accuracy loss as indicated by the increased standard deviation value of 0.509 mm compared to 0.485 mm for the green part. This reduction in accuracy is minimal and indicates that the impact of the sanding process is not very significant. If the minimum and maximum values of the green and unfinished part are compared, this observation is confirmed.

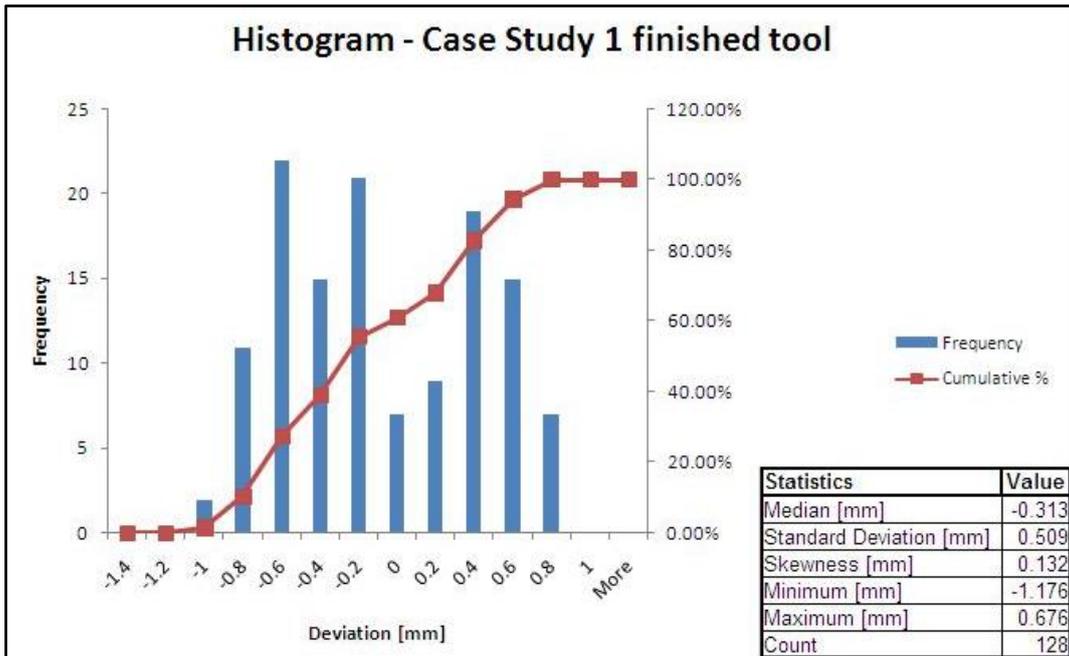


Figure 29: Histogram with statistics for case study 1 finished tool

The summary of geometrical results of one of the composite parts manufactured during case study 1 is provided in Figure 30. The histogram indicates a similar shape to the histograms of the tools. The small median value indicates the central tendency of the part and that errors are generally random and not systematic. As expected, additional accuracy loss occurred during the moulding process, leading to an increased standard deviation value of 0.566 mm compared to the sanded mould's value of 0.509 mm. As was to be expected, the largest deviations occurred in the same areas as found with the tool – the top surface and sides.

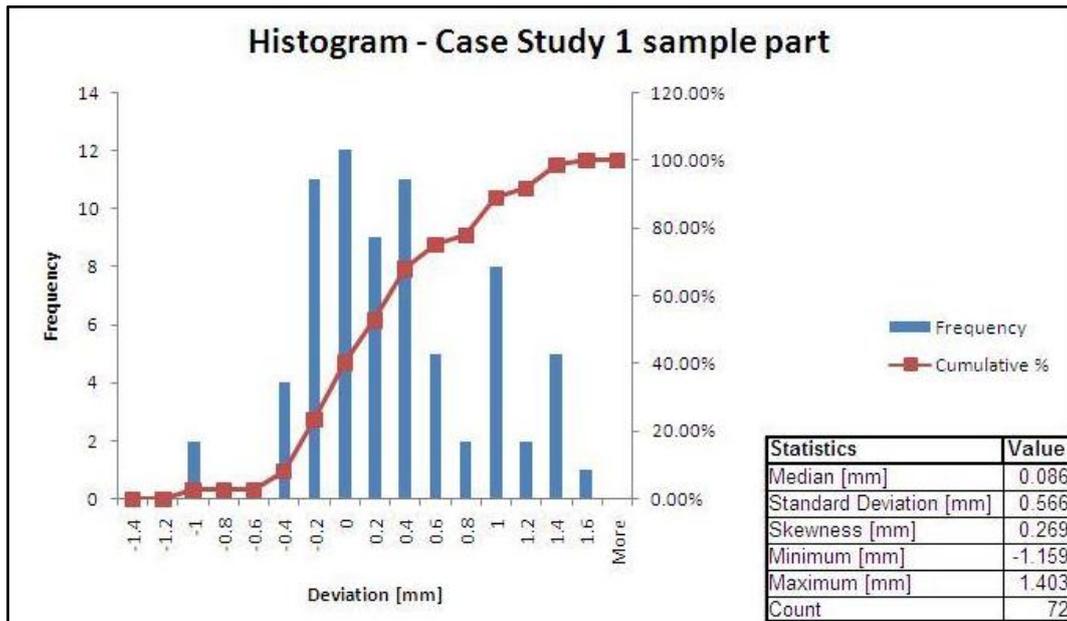


Figure 30: Histogram with statistics for case study 1 sample part

4.2 Case study 2

The geometrical data for the bottom mould halve and corresponding composite part face is provided and discussed in this section. The top half of the mould and parts indicated similar geometrical trends and results can be viewed in Appendix C.

4.2.1 Unprocessed RP components

Suffice to say, the accuracy obtained during these measurements are comparable with results obtained with the same 3D-printer by Louw (2004), De Beer (2004) and Hugo (2008). It is also clear that the rapid tool from case study 2 is significantly more accurate than the tool from case study 1. This might indicate that the operator has an influence on the part quality. As an example, it was observed that very inaccurate parts are printed when the powder material is compressed in the build volume's reservoir. This improvement with case study 2 might also be due to better orientation in the build volume during printing, a lower and stiffer tool design and smaller inclined surfaces. Accuracy influencing factors which can be controlled include materials used, nominal dimensions, build orientation in relation to the different machine axes, infiltrating agent used, geometric features and wall thickness (De Beer, 2004). Louw (2004) developed capability profiles and equations for the Z310 printer, making it possible for users to determine beforehand what the effect of many of the above mentioned factors are on part accuracy.

It was expected that the second case study tools would be less accurate than tools from the first case study due to being printed in two sections. This result is therefore very surprising and might indicate that parts which are printed in sections and carefully located during bonding may not necessarily be less accurate than parts printed in one piece.

The summary of geometrical results of the unfinished tool bottom from case study 2 is provided in Figures 31 and 32 below. The median value and histogram distributions are centred around zero, indicating that errors are random and no systematic trend is present. As mentioned, the standard deviation value of 0.148 mm is much more accurate than found with case study 1. Figure 32 indicates that the largest deviations are in the middle and at the tip of the mould. When the two halves of the mould was bonded after printing, it was noticed that there was some slight misalignment present, accounting for the larger deviations measured in that area. The small positive skewness value indicates that the tool is slightly smaller than the CAD model.

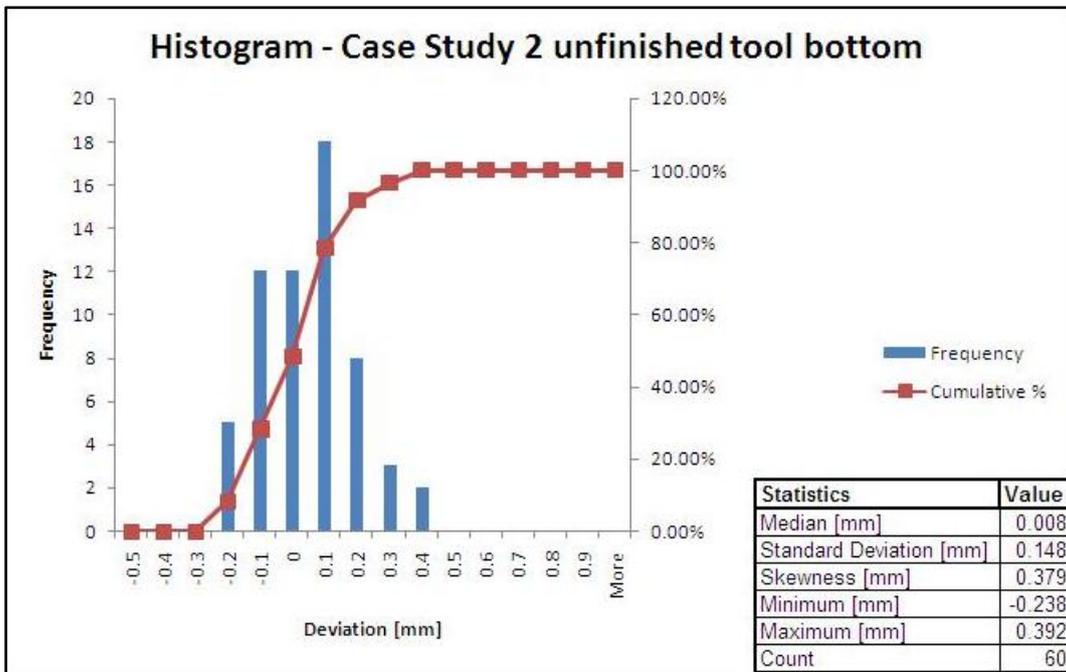


Figure 31: Histogram with statistics for case study 2 unfinished tool bottom

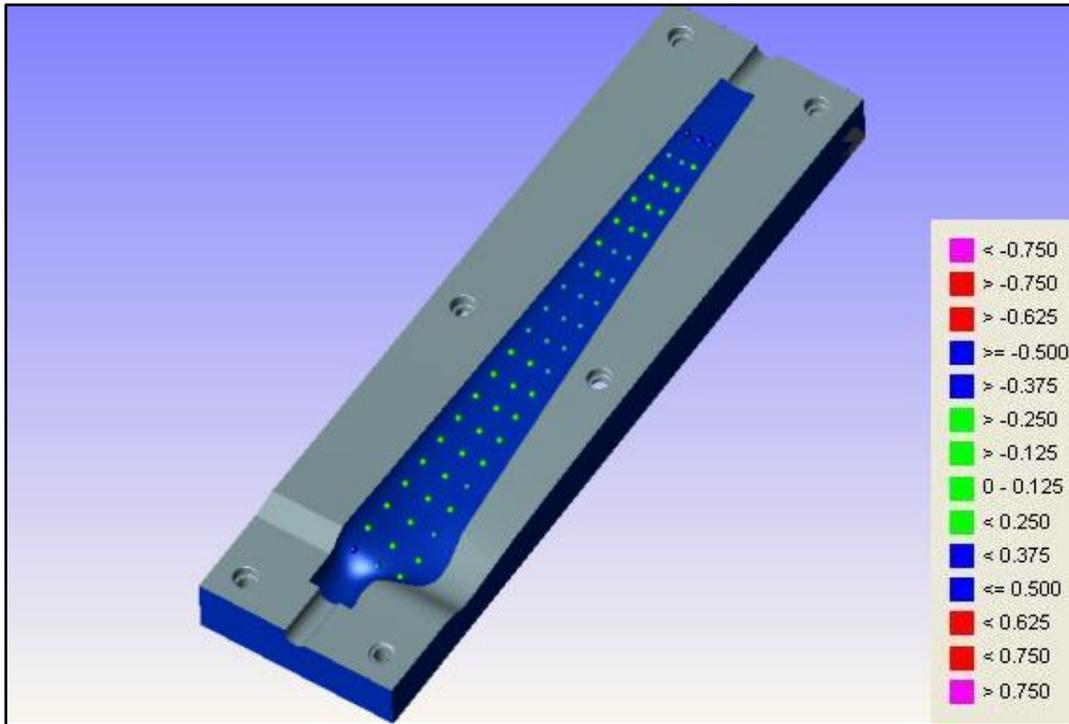


Figure 32: Measured points for case study 2 unfinished tool bottom indicating deviations [mm]

4.2.2 Processed RP components

If the summary of geometrical results of the finished tool bottom from case study 2 is considered in Figures 33 and 34, it is clear that the deviations follow a similar pattern as with the unfinished tool in Figures 31 and 32. The low median value and histogram shape illustrate that error distributions are centred around zero, again indicating that errors are random and no systematic trend is present. The standard deviation value of 0.220 mm is slightly larger than the value of 0.148 mm with the unfinished tool and as experienced with case study 1. This accuracy loss due to sanding of the mould is once again surprisingly low. A positive skewness value indicates that the tool is smaller than the CAD model. This value is larger than for the unfinished tool which is probably due to the material removed during sanding leading to a smaller tool. Figure 34 indicates deviations in similar areas as with the unfinished tool.

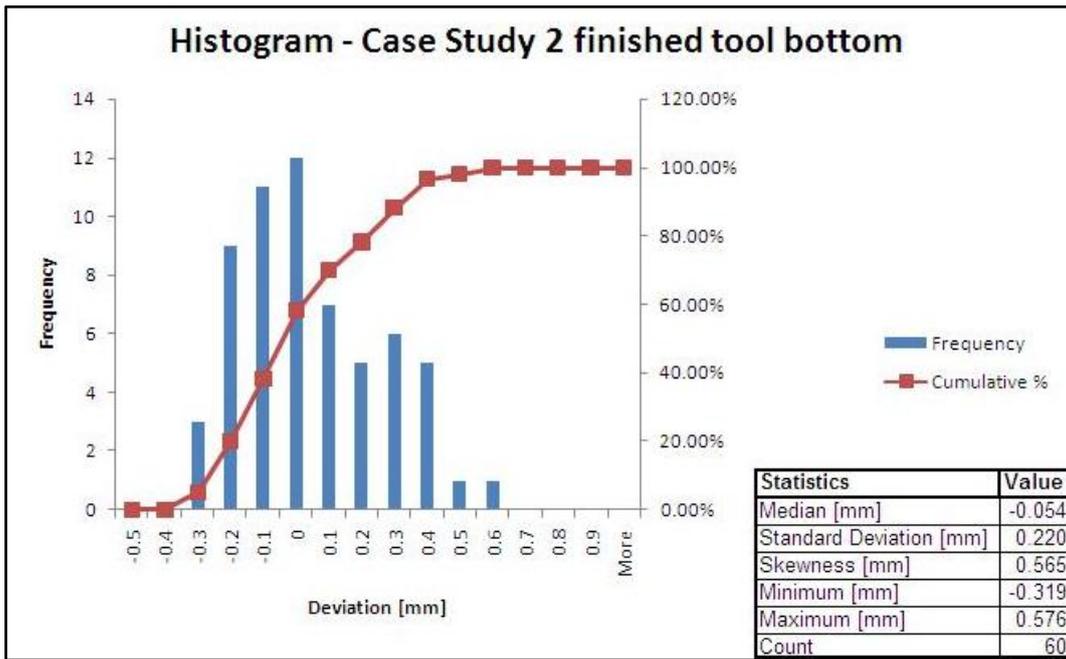


Figure 33: Histogram with statistics for case study 2 finished tool bottom

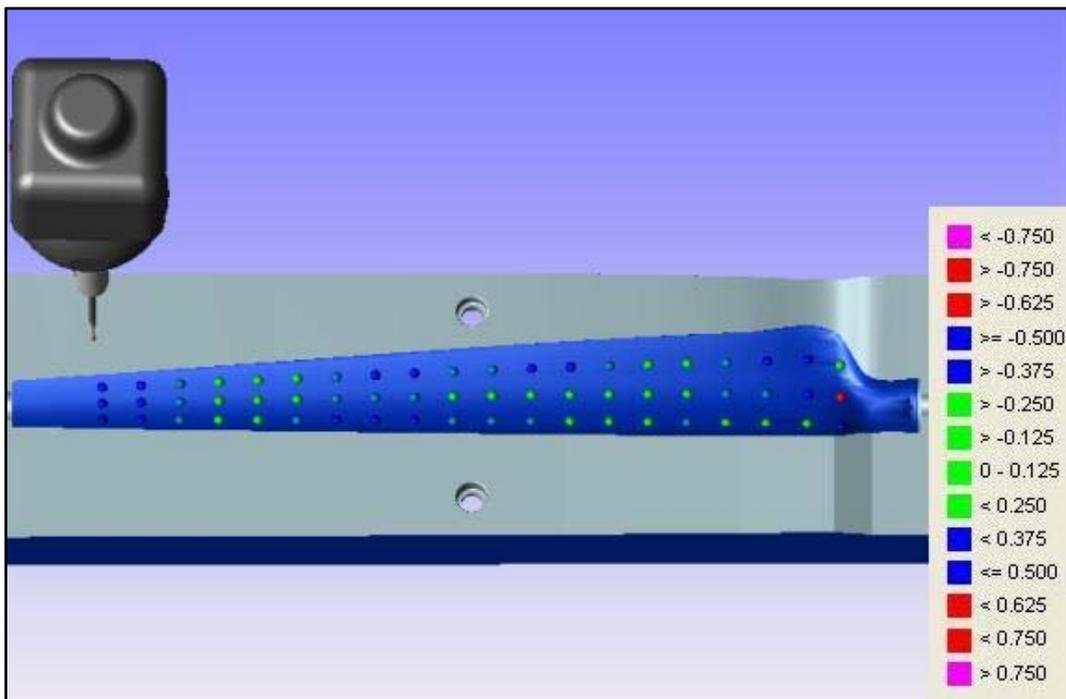


Figure 34: Measured points for case study 2 finished tool bottom indicating deviations [mm]

Figure 35 below is a summary of geometric results of the bottom tool after the production of 15 blades. Deviations follow a similar pattern as with the unused tool, but decreased accuracy is apparent and the standard deviation has increased from 0.220 mm to 0.295 mm. If the histogram is considered, it seems that most of the accuracy loss is in the form of a greater number of negative measurements which is probably due to material removal from the surface of the tool during demoulding operations. Other forms of wear was also observed during the manufacturing stages such as surface cracks starting to appear after the first two parts. This worsened as more parts were manufactured. Depending on the accuracy requirements for the composite parts, the mould wear rate might limit mould lifetime to for example 40 parts.

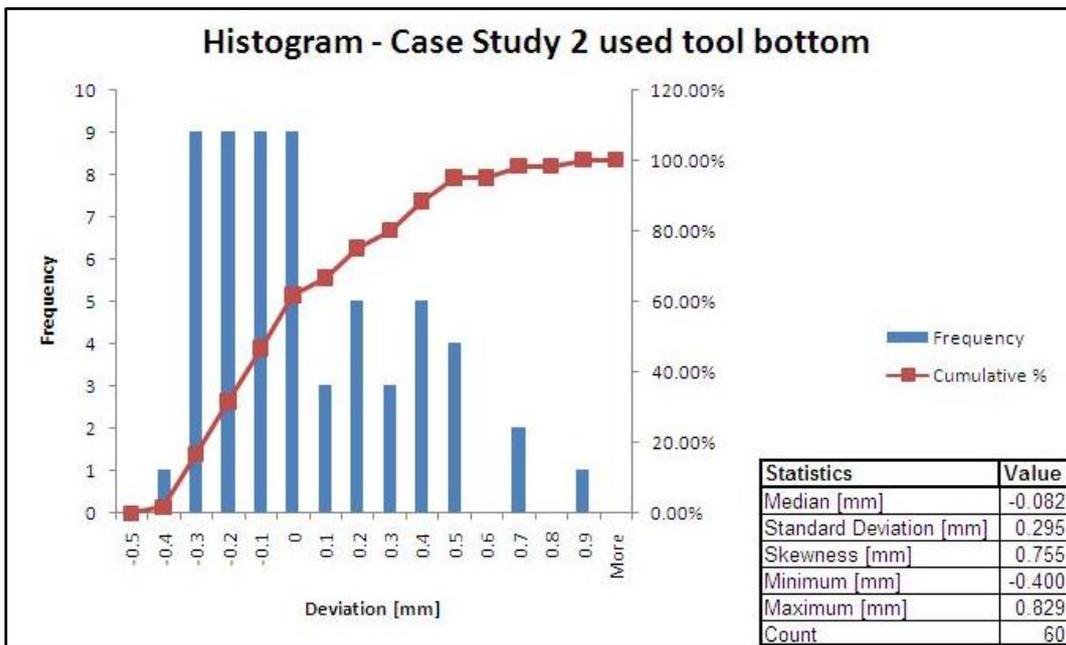


Figure 35: Histogram with statistics for case study 2 used tool bottom

4.2.3 Composite parts

The summary of geometrical results of one of the composite parts manufactured during case study 2 is provided below. The histogram indicates an inverse shape compared to the histograms of the used tool in Figure 35. If the measured points in Figure 37 are considered, it can be seen that the part is an inverse of the mould with the main deviations in similar areas as indicated in Figure 34. As expected, additional accuracy loss occurred during the moulding process, leading to an increased standard deviation value of 0.342 mm.

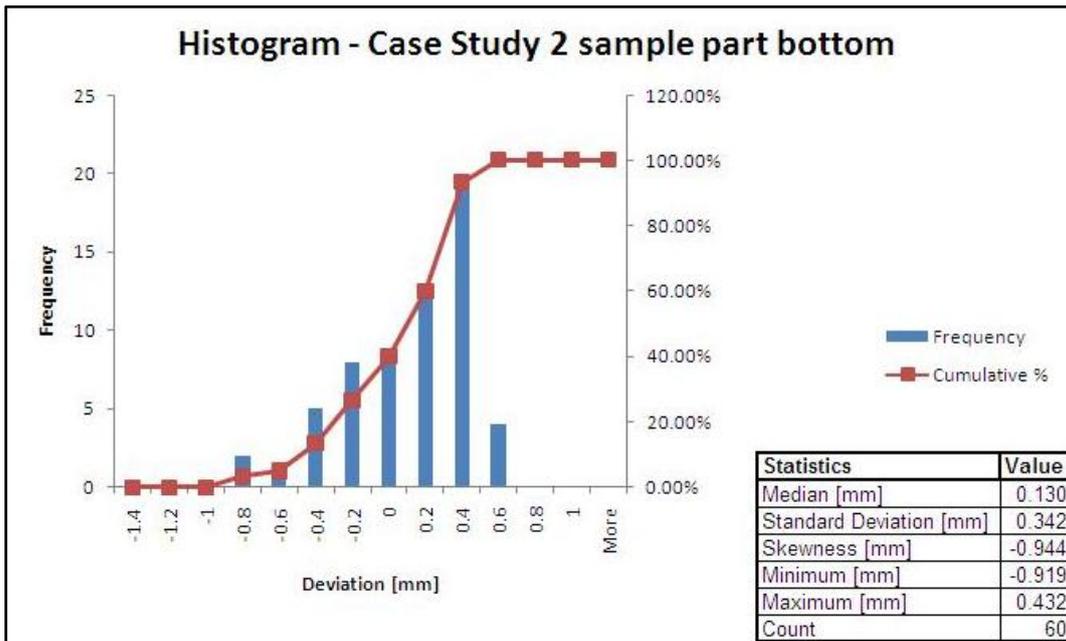


Figure 36: Histogram with statistics for case study 2 sample part bottom

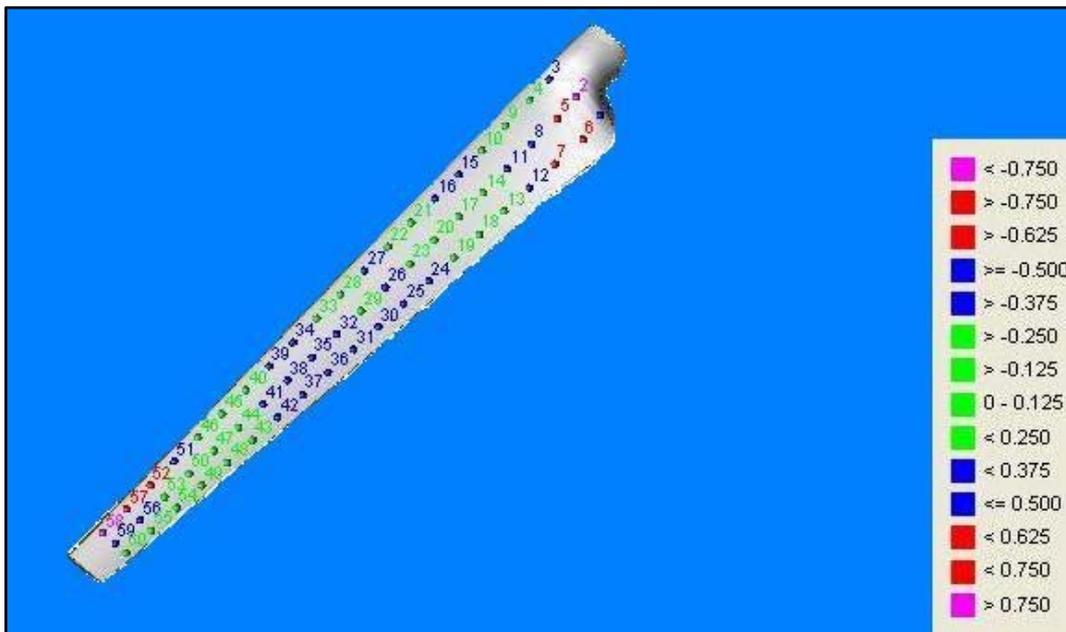


Figure 37: Measured points for case study 2 sample part bottom indicating deviations [mm]

The standard deviation values for the remaining samples are provided in Table 2 below. The first two parts are glass fibre and the rest carbon fibre. These are the last 6 out of 15 parts manufactured. It is clear that accuracy for the top and bottom

halves are very similar. It was expected that part accuracy would also decrease as mould accuracy decreased, but there is no such tendency in the part measurements. It might be possible that the major mould degradation occurred during manufacture of the first few parts and stabilised thereafter.

Table 4: Standard deviation values for 6 sample parts

Sample	Standard Deviation top [mm]	Standard Deviation bottom [mm]
1	0.407	0.339
2	0.408	0.342
3	0.382	0.329
4	0.339	0.423
5	0.372	0.442
6	0.390	0.333
Average	0.383	0.368

4.3 CNC aluminium parts

A set of three aluminium fan blades with the same shape as case study 2 were also measured with the CMM. Before the geometrical data is considered, it is firstly helpful to be aware of the method that was employed to constrain the blades during machining. The blades were machined from a block of aluminium with supports being left at the leading and trailing edge (Figure 38). These supports are removed after machining has been completed. Because of the thin profile of the blade, numerous problems were experienced with deflection under the cutting tool. This resulted in a number of steps on the blade surface, not dissimilar to the staircase effect experienced with the RT parts. These problems can be improved, but it is clear that as with RT, a potentially accurate machine incorrectly implemented may lead to inaccurate parts.



Figure 38: Aluminium part with supports visible

Figures 39 and 40 indicate geometrical data for one of the aluminium blades. The median value is close to zero and the histogram is also centred around zero, indicating that errors are random and no systematic trend is present. Figure 40 indicates that large deviations occur at the leading and trailing edge of the blade corresponding to where the supports were removed after machining. As these blades have been used in a set of underwater tests, other damage is also possible. For this reason the geometrical data provided in this section should not be viewed as conclusive regarding the abilities of CNC machining. It is however unlikely that the poor accuracy on the leading and trailing edge was caused by the underwater tests, and although inconclusive, it seems that this inaccuracy is due to the CNC process employed.

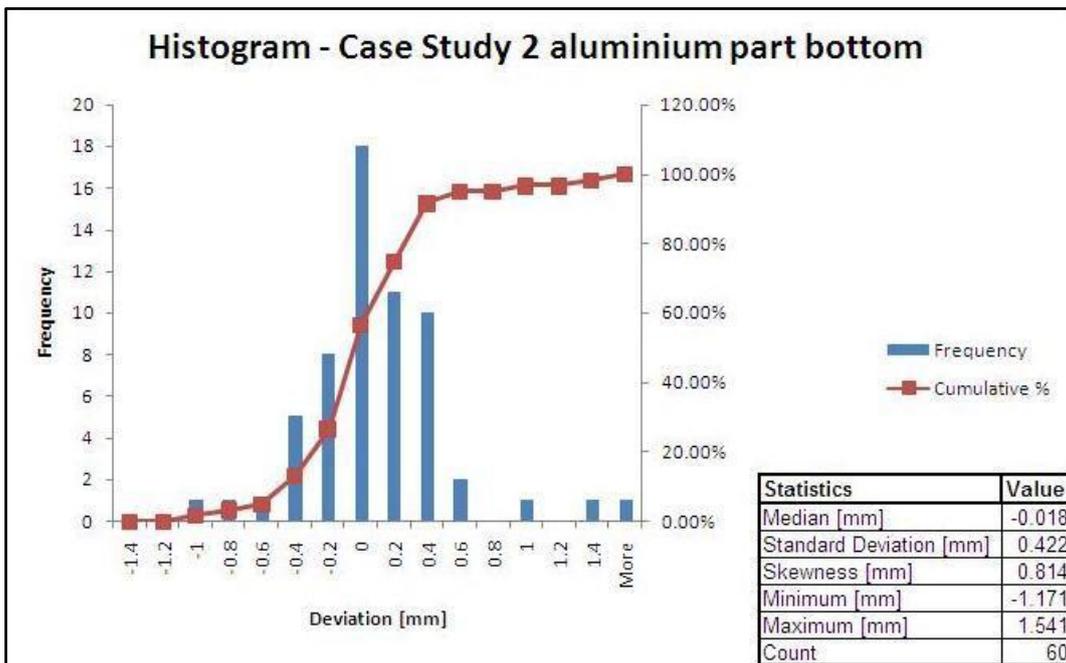


Figure 39: Histogram with statistics for case study 2 aluminium part bottom

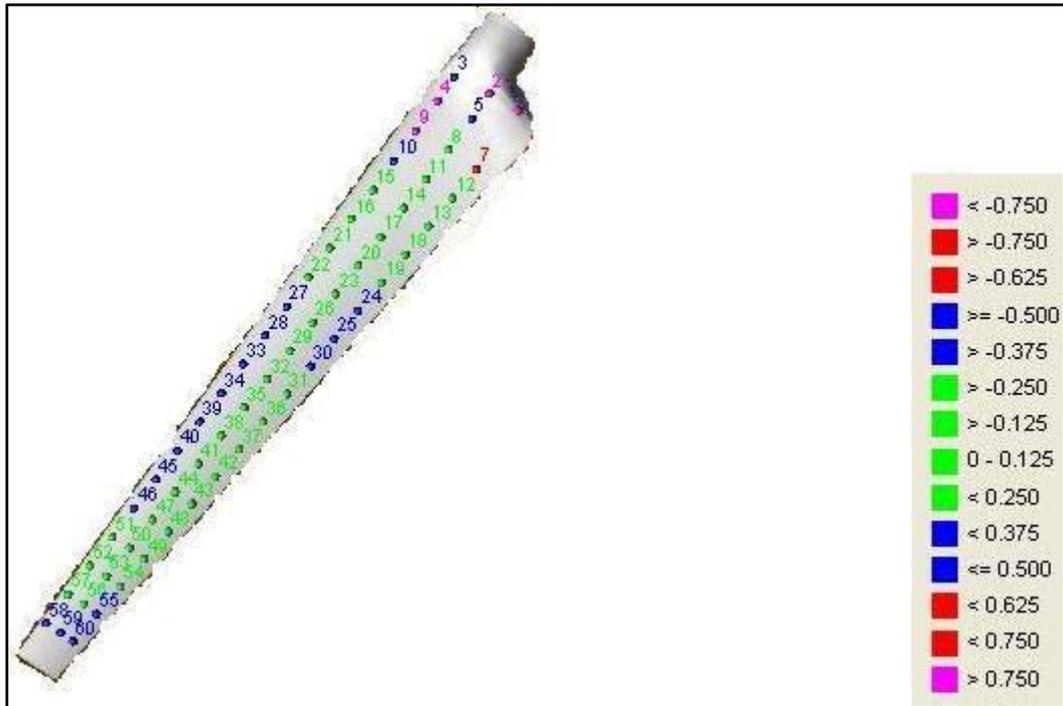


Figure 40: Measured points for case study 2 aluminium part bottom indicating deviations [mm]

4.4 Surface finish measurements

A Mitutoyo Surftest 211 was used to measure the surface finish of all the different mould conditions as well as parts. The roughest areas were the inclined surfaces of unfinished parts due to the mentioned staircase effect. Measurements on inclined surfaces were found to be on average 28% higher than on other surfaces of the unfinished parts.

Table 5 indicates the averages of approximately 40 measurements taken for each type of sample. The average roughness value of $16.29 \mu\text{m}$ for the green part is very close to the value of $17.34 \mu\text{m}$ obtained by Hugo (2008) for the same machine. As can be seen from the values in Table 5, the sanding and surface treatment process led to a dramatic improvement in surface finish. This is in contrast to the slight accuracy loss caused by surface treatment as experienced in Section 4.1 and 4.2. It was also observed that the difference between surface finish of horizontal and inclined surfaces were not very marked after surface treatment. As was to be expected, the surface finish of the composite part was very close to that of the mould.

Table 5: Surface roughness values - case study 1

Description	Average Value (μm)
Unfinished	16.29
Finished	1.33
Sample part	1.29

Table 6 below indicates all the relevant surface finish values for case study 2. Similar values to case study 1 were observed for unfinished tools, finished tools and composite parts. The values for the unfinished tool bottom were better than for the top tool, probably because this part was observed to be overly infiltrated with resin after printing which led to a smoother surface finish. A set of three carbon fibre sample blades were subjected to further surface polishing with 800 grit water-paper to obtain a very smooth surface for subsequent underwater tests. This resulted in very smooth surfaces with a roughness measurement of only 0.67 μm . The machined aluminium parts were found to have an average surface finish of 0.69 μm .

Table 6: Surface roughness values - case study 2

Description	Average Value (μm)
Unfinished top tool	14.74
Unfinished bottom tool	11.19
Finished top tool	1.83
Finished bottom tool	1.78
Used top tool	1.7
Used bottom tool	2.24
Average part	2.64
Polished part	0.67
Aluminium part	0.69

4.5 Conclusion and recommendations

To conclude this chapter, a summary of the standard deviations obtained for all parts in both case studies are provided in Tables 7 and 8. The accuracy loss between the unfinished and finished part and accuracy loss between the finished part and composite part was deemed to be reasonable and were of the same order in both case studies. The accuracy loss caused by the sanding step is insignificant and much less than expected. Results by Tari et al. (1998) indicate similarly low accuracy degradation after the sanding of a set of LOM moulds. In this study, the

standard deviation for a green part was found to be 0.160 mm and for the sanded part 0.171 mm.

It is also clear that degradation of 3DP rapid tools can be expected after a limited number of parts. It has to be decided by the designer whether this limited number is sufficient for the project at hand. A component like the fan blade from case study 2 might for example still give acceptable performance with 10% deviations in thickness. It is important to note that various RT technologies have widely differing accuracy capabilities and that it may be possible to obtain improved geometrical results if the 3DP process is substituted with a different RT process. It might be worthwhile to research whether other RT techniques will indicate a similar loss of accuracy for each successive processing step. The accuracy of the aluminium parts was not as good as anticipated, but reasons for this discrepancy are provided.

Table 7: Comparison of standard deviations in case study 1

Tool state	Standard Deviation [mm]
Unfinished	0.485
Finished	0.509
Average part	0.566

Table 8: Comparison of standard deviations in case study 2

Tool state	Standard Deviation top [mm]	Standard Deviation bottom [mm]
Unfinished	0.141	0.148
Finished	0.205	0.220
Used	0.360	0.295
Average part	0.383	0.368
Aluminium part	0.446	0.384

It seems as if the accuracy loss introduced by the printing of tools in multiple sections is reasonably low. The bonded tool from case study 2 was actually found to be more accurate than the unbonded tool from case study 1.

Surface roughness measurements also indicated that a worthwhile improvement is possible by polishing tools after printing. Roughness values of better than 2 μm are possible with care.

5. EARLY COST ESTIMATION MODELS

It is necessary that designers realise the magnitude of design decisions on product cost early in the design phase. Many authorities, such as Veldsman & Basson (1998a), advise that the best time to minimize cost is during the design stage. Over 75% of the final product cost is already decided during the design stage (Ullman, 2003). The relevance of cost models was fully discussed in the literature study and it was mentioned that one of the most important considerations when designers compare competing manufacture processes, is the cost. Cost models should therefore allow for all the different tooling options to allow designers considering a RTM process to make an informed final decision. Cost estimation models must help the designer to take tooling cost, labour and consumables cost into account to enable the identification of the most economical process for a particular part (Veldsman & Basson, 1998a). Cost models may also be used to identify costly design features, enabling simplification or elimination.

5.1 Background

During the generation of the cost models for this study, it was accepted that the designer would have a CAD model of the part in question available as well as knowing what the desired fibre type is. The designer does not need to have any other knowledge of the RTM process besides the design criteria as provided in Appendix A. Veldsman & Basson (1998a) also advise that the number of inputs required from the designer should be minimized and these inputs should be readily available.

As discussed in Section 2.1, many cost models do not take the geometrical complexity of parts into consideration. The model developed by Veldsman (1995) is superior in this sense as allowances are made for the geometrical features of the part. This is one of the reasons why all the cost models used in this study were based on Veldsman's (1995) work. This research was completed at the same facility and it therefore makes sense to build on the work of Veldsman (1995). All the cost factors that can be directly influenced by design, such as tooling design, should be accounted for in the cost model. In many cost models, such as the one by Barlow et al. (2002), factors such as tooling design were not taken into account. The model by Veldsman (1995) takes factors such as tooling design into account. Preliminary results also indicated good correlation with the costs predicted by Veldsman's (1995) model and actual costs incurred in this project.

One of the limitations of the cost models used in this study is that they were only used for parts of small (under 0.5 m) size. This makes the use of certain constant values for manufacture steps allowable. One example of this is the constant value used for the manufacturing time of the mild steel backing plate. It is not currently known what the effect of larger components will be on the accuracy of this cost model.

All the cost model calculations were performed for a batch size of 40 composite parts. This is a realistic maximum for accurate parts with the 3DP moulds. The other moulds are tougher and allow for the manufacture of more parts and this scenario is considered in Section 5.5.

It needs to be noted that the designer usually has little influence on the overhead costs and these are generally dictated by the company type and structure (Veldsman & Basson, 1998a). Nevertheless, the cost models used in this study accounted for overhead cost due to factors such as floor space used and major capital cost incurred for tooling.

5.2 Conventional composite moulds

In the work completed by Veldsman (1995), a patternmaker was employed to produce a wood pattern for the forming of a set of composite moulds for the RTM process. The use of patternmakers for such tasks is not as prominent today, but the use of composite moulds is still very relevant. It is easy to substitute the pattern from the patternmaker with a NC machined metal pattern or even RP pattern and still form the same type of composite mould. The rest of the process employed by Veldsman (1995) is similar to the process used in this project (as described in Chapter 3), besides the omission of vacuum bag mould sealing.

The cost model developed by Veldsman (1995) for his process was applied to the two case studies completed to indicate what the cost would be if composite moulds were employed in preference to the RT moulds. The cost model was coded in the Mathcad 12 software package and updated with current material, tooling and labour costs. These updated values may be viewed in Table 15 in Appendix D. After the relevant geometries for the two case studies were entered into this model, estimated manufacturing times and costs were calculated. Table 9 below indicates the predicted lead times and costs for the two case study parts. The total cost for the case study 2 part consists of Veldsman's (1995) estimation as well as the cost of R500.00 for the RP core.

Table 9: Cost and times for case studies as predicted by Veldsman (1995)

	Case study 1	Case study 2
Mould lead time	24h40min	26h20min
Mould material cost	R 128.00	R 260.00
Total mould cost	R 3840.00	R 3930.00
Part manufacture time	1h10min	1h
Part material cost	R 20.00	R 13.00
Total part cost	R 440.00	R 910.00

It is difficult to comment on the total mould cost as Veldsman's (1995) method was not physically performed, but the results seem very reasonable. The mould costs include the cost of a pattern which contributes nearly 50% to the cost for both case studies. If the actual part manufacture times of samples of each case study are considered in Table 10 and 11, the average times are 92 min and 71 min respectively. This indicates that the values in Table 9 are an under-prediction for both case studies. This is mainly due to the omission of the vacuum bagging step and other minor differences in the production method. It is necessary to note that the measured times for some of the manufacturing steps in Table 10 and 11 tend to decrease over time. This is a consequence of improvements in operator skill.

It was found that manufacturing steps that were common to both Veldsman's (1995) and this study's process chain indicated good correlation. One example is the predicted value of 11.6 min for part removal compared to the actual value of 12.3 min in Table 10. An area where major deviations from predicted to actual values were experienced is the predicted mould filling values. Veldsman (1995) used equations derived from Darcy's law to predict the filling times. The filling times predicted with this method are 52 min and 32 min for case 1 and 2 respectively. Compare this to the actual average values of 23.8 min and 1.9 min in Tables 10 and 11. The larger deviation in case study 2 is because of the fact that Veldsman's (1995) model does not take the resin distribution channels on the core surface into account when predicting filling times. It was therefore decided to use the RTM-Worx predictions for the cost model for the RT-RTM process. On the basis of the discussed results, Veldsman's (1995) cost model seems to give reasonable time and cost estimations and it was felt worthwhile to expand his model to allow for RT moulds and the differences in this project's process chain.

Table 10: Part manufacture times for case study 1

<u>Manufacturing step</u>	<u>Time [min]</u>							
Part number	1	2	3	4	5	6	7	Ave
Clean	5	4	6	5	6	5	4	5.0
Wax mould	5	3	4	2	4	4	3	3.6
Apply gel coat	n/a	n/a	n/a	n/a	n/a	n/a	6	6.0
Cut and place preform	22	17	15	18	20	17	13	17.4
Cut and place peelply	3	2	2	3	1	2	2	2.1
Cut and place Greenflow	n/a	n/a	n/a	n/a	1.5	2	2	1.8
Place ports	n/a	5	5	4	4	5	4	4.5
Fit vacuum bag	20	15	18	16	17	14	12	16.0
Prepare resin	3	3	4	3	4	4	4	3.6
Infusion	n/a	50	42	37	6	4	4	23.8
Remove part	15	14	12	12	11	10	12	12.3
Trim	4	3	4	4	3	4	3	3.6
Total	n/a	116	112	104	77.5	71	69	91.6

Table 11: Part manufacture times for case study 2

Manufacturing step	Time [min]							Ave
	1	2	3	4	5	6	7	
Print core	90	90	90	90	90	90	90	90.0
Bond core	10	10	10	10	10	10	10	10.0
Clean	6	6	4	4	3	3	3	4.1
Polish	2	3	3	2	3	2	3	2.6
Apply gel coat								0.0
Cut and place preform	20	16	17	16	14	15	14	16.0
Cut and place peelply	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Cut and place Greenflow	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Place ports	5	5	4	5	4	3	3	4.1
Apply clamping bolts			9	10		6	12	5.3
Fit vacuum bag	19	18	18	19	14	12	16	16.6
Prepare resin	5	4	4	4	3	4	3	3.9
Infusion	2	2	3	2	1	1	2	1.9
Remove part	15	13	12	12	12	11	13	12.6
Trim	5	5	5	4	5	3	4	4.4
Total	79	72	79	78	59	60	73	71.4

5.3 RP moulds

The method followed during the generation of a cost model for the RT-RTM process used the Veldsman (1995) model as base. Where possible, equations were created for the time taken for some of the additional steps such as the printing of the RT mould. In other cases, where similar actions were performed as in Veldsman's (1995) method, his equations were adapted or combined. In cases where neither of these approaches were practical, constant values based on the measured times were used.

Appendix D includes an example calculation for the RT-RTM cost model applied to case study 2. This model was created with the data from case study 1 as basis and the case study 2 calculation was then used to verify the accuracy. All equations that were added as well as modifications performed will now be discussed in this chapter.

5.3.1 Preliminary work

Before the cost calculation may be started, it is first necessary to make two basic decisions which are indicated in the first paragraph of the cost model in Appendix D. The designer needs to decide on the mould sealing method: vacuum or

clamped and the type of mould: one sided (vacuum infusion) or closed (RTM/VARTM). The example calculation for case study 2 made use of a clamped closed mould.

The designer then needs to enter relevant constants such as injection pressure, part geometry, material constants and the material costs into the model. The material costs are indicated in Table 15 in Appendix D.

Section 1 of the cost model then commences with the calculation of the extra mould area needed for clamping (refer to example calculation in Appendix D). The equations used are directly from Veldsman (1995).

5.3.2 Build time

The first additional equations are for the calculation of RP build time. RP build time is mostly dependant on the number of layers, in other words the part height. It is not always possible to accurately consider all the process parameters like acceleration and deceleration of the nozzle, warm up time and system delays. It is therefore very hard to accurately predict build time. (Hugo, 2008)

According to Xu et al. (2000) the time to produce a RP part can be separated into three components: data preparation, fabrication time and post processing time. For the fabrication component, he proposed an equation which makes use of a solidifying rate and delay time for each layer. The delay time considers the delay between layers due to factors such as nozzle accelerations and platform movement. The solidifying rate and delay times will also be unique for each type of RP machine. This equation was adapted for use in the cost model and was used in the following form:

$$T_{print2} = r_{cure}A_{ave} + t_{delay}n_{print} \quad [A_{ave} < 0.08 \text{ m}^2] \quad (5.1)$$

T_{print2} is the total printing time, r_{cure} is a factor which considers the effects of the solidifying rate and t_{delay} is the delay time per printed layer, A_{ave} is the average cross sectional area of the part and n_{print} is the number of RP layers to be printed. In the case of 3DP, the layer thickness is 0.1 mm. T_{print} is the actual measured printing time and is listed together with the initial constants in the model. The constants for this equation were calculated from the average values for the two case studies. It was found that Equation 5.1 is not able to accurately predict the printing times for both case study 1 and case study 2. This is mainly due to the fact that these parts have radically different geometries and it should also be kept in mind that the position in the build volume during printing may also have considerable influence. Multiple components may be stacked very closely in the RP build volume, resulting in reduced printing time per part. Many RP machines have software which gives accurate time estimations when the CAD models of the components are imported. It is preferable to use this estimation if it is available.

5.3.3 RP mould

Section 2 of the cost model calculates the cost for the completed RT mould. Equations 5.2 to 5.4 below calculate the mass of RP powder, binder and infiltration resin used on the basis of the mould volume, V_{mould} . These equations were provided by the Global Competitiveness Centre (GCC), the suppliers of all the RP parts. In practice these equations were found to give very good results.

$$m_{powder} = 0.0013V_{mould} + 0.0331 \quad (5.2)$$

$$m_{binder} = 0.0001329V_{mould} + 0.1 \quad (5.3)$$

$$m_{infiltrate} = 0.0008V_{mould} \quad (5.4)$$

In Equations 5.5 and 5.6 below, the calculated material mass is multiplied with the relevant material cost per kg and then with the overhead percentage and mark-up rate, resulting in the final customer price, P_{sell} . The running costs for the RP machine is also included in the overhead percentage.

$$P_{cost} = (1 + P_{Overheads})(m_{powder}P_{powder} + m_{binder}P_{binder} + m_{infiltrate}P_{infiltrate}) \quad (5.5)$$

$$P_{sell} = P_{cost}(1 + P_{Markup}) \quad (5.6)$$

In Equation 5.7 below, the cost of the steel backing plate is calculated by multiplying the price per area for mild steel with the length and width of the designed mould.

$$P_{plate} = P_{steel}L_{mould}W_{mould} \quad [L_{mould}W_{mould} < 0.08 \text{ m}^2] \quad (5.7)$$

To calculate the cost of filling the cavity at the back of the mould with resin, the cost of resin per m^3 , P_{resin} , is multiplied with the volume of the cavity to be filled.

$$P_{fill} = P_{resin}V_{resin} \quad (5.8)$$

When operations are done where the mould is coated with some type of finish, Veldsman's (1995) example is followed and the cost per area of the surfacing compound is calculated from measurements and simply multiplied with the surface area of the part (A_f) to find the material cost of the layer. A_f is used because even though the mould extremities may stretch further than the part, the area where the composite part is formed is of importance during sanding, painting and all such operations. Equation 5.9 and 5.10 below illustrate this approach and calculate the cost of the priming layer and final layer of paint respectively.

$$P_{priming} = P_{primer}A_f \quad [A_f < 0.08 \text{ m}^2] \quad (5.9)$$

$$P_{painting} = P_{paint}A_f \quad [A_f < 0.08 \text{ m}^2] \quad (5.10)$$

When the total mould material cost needs to be calculated, all the above mentioned cost components of the mould is summed. Note that the cost for the steel backing plate is multiplied by two to calculate the total cost, accounting for both mould halves for case study 2. The cost model prediction of R 4450.00 (refer to example calculation in Appendix D) is very close to the actual recorded cost of R 4580.00. The next step is to record the labour cost incurred during the preparation of the mould.

Time measurements (refer to Table 18 in Appendix D) made during case study 2 indicated that if the mould was printed in more than one section due to build volume constraints, it is necessary to make a 10 min allowance for each section to be bonded. Equation 5.11 is employed for this allowance. As the two sides of the case study 2 mould were printed in 4 sections, 20 minutes are added.

$$T_{bond} = 10N_{sections} \quad (5.11)$$

Where a surface finishing operation is done, Veldsman's (1995) example is once again followed and the relevant measured manufacturing times (refer to Table 17 in Appendix D) are used to calculate a constant which may be multiplied with the surface area of the part to give a time estimation. Equation 5.12 below is used to calculate the labour time (T_f) to sand the surface of the mould. The same approach is used to calculate the labour time for priming (T_{prime}) and painting (T_{paint}) in Equations D19 and D20 in Appendix D.

$$T_f = 32A_f \quad [A_f < 0.08 \text{ m}^2] \quad (5.12)$$

Due to the exothermic reaction and possible expansion/contraction during curing when the hollow mould backing is filled with resin, a maximum layer thickness of 30 mm resin is poured into the mould in between initial curing phases. Equation 5.13 below calculates the number of layers, n_{resin} , to be poured into the mould. The total mould height, h_{total} , is taken and 5 mm for the mould wall thickness is subtracted before it is divided by 30 mm. The resultant number is then rounded up to the nearest integer to give the number of layers.

$$n_{resin} = \text{round up}[(h_{total} - 0.005)/0.03] \quad (5.13)$$

In Equation 5.14 below, the time taken to fill the mould cavity is calculated. The required number of resin layers is simply multiplied with the average time taken to prepare and pour the resin per layer. If the measured times in Table 17 in Appendix D are considered, the calculated average time for this action is 10 min.

$$T_{resin} = 10n_{resin} \quad (5.14)$$

Equation 5.15 indicates the use of a constant value of 25 minutes for the manufacture and fitment of the steel backing plate. The source for this value is once again the measured times in Table 17 in Appendix D.

$$T_{plate} = 25 \quad (5.15)$$

The final step in the mould cost section is to calculate the total cost. All the manufacturing times are added together and multiplied with the labour rate of R 250.00 per hour. The calculated mould material cost is then added to this figure, giving the total cost as indicated in Equation D25 in Appendix D. The mould lead time may also be calculated by adding the total labour time, printing time, infiltration time and part cleaning time (Equation D26 in Appendix D). An allowance, T_{clean} , is also made for the removal of excess powder after printing the RP tool. Cleaning times for various materials used in the 3DP are provided by Louw (2004).

5.3.4 Part cost

Section 3 in the cost model calculates the cost of a composite part produced with the RT-RTM process. The model for the calculation of material cost is just as used by Veldsman (1995). He proposed three different models: one for parts with low fibre volume fractions of around 20%, one for parts with high fibre volume fractions of approximately 40% and one for parts requiring additional stiffness. All three models incorporate the cost of applying a gel coat, vacuum bag, peelply and Greenflow. The model for parts with high fibre volume fractions was used for both case study calculations. The equations for these three models are provided in the cost model example calculation in Appendix D (Equation D27 to D30).

The labour time estimation for the part commences with the calculation of the mould cleaning time and polishing time. These equations again take on the form as explained for Equation 5.12 and may be viewed in Appendix D (Equations D31 and D32).

It is also necessary to make a time allowance for the placement of the resin inlet and outlet ports. An average time of 2 minutes was measured for port placement (see Tables 10 and 11) and this is multiplied with the number of ports (n_{port}) in Equation 5.16, giving the total time allowance for port placement.

$$T_{port} = 2n_{port} \quad (5.16)$$

When the cutting and placement of the fibre reinforcement for the part is considered, the model proposed by Veldsman (1995) is employed (see Equation D34 to D38 in Appendix D). When the fibre preform needs to be glued/stitched in place an allowance, T_{stitch} , needs to be added to the fibre placement time. Measurements, as indicated in Table 10 and 11, indicated that an allowance of 12 minutes is sufficient. The blade of case study 2 is approached as a flat plate during the fibre placement calculations.

The equations used to calculate the placement times for the peelply and Greenflow layers was based on the equation Veldsman (1995) proposed for fibre placement predictions. This model is provided in Equation 5.17. The constant n_R is for the number of layers to be placed and therefore becomes one for the Greenflow and peelply layers. The $3OA_P$ term in Equation 5.17 is an allowance for the application of a gel coat and therefore becomes zero in the new equation. S_P in this

equation is simply the perimeter of the part and K_5 is a constant which is zero for this case (see Appendix D for further explanation). The equation for both the peelply and Greenflow placement time is the same and is illustrated in Equation 5.18 below. This equation gave reasonable time estimations which compared very well with the measured values in Tables 10 and 11.

$$T_{RLP} = 1 + (0.5S_P + 0.5 + 0.25K_5)n_R + 30A_P \quad (5.17)$$

$$T_{peelply} = 1 + (0.5S_P + 0.5 + 0.25K_5) \quad (5.18)$$

The cutting, placing and sealing of the vacuum bag around the mould constitutes a considerable time component. The first step is to calculate the time taken to cut and place the vacuum bag. Because of the nature of this action, Equation 5.17 is once again used as base. The $30A_P$ allowance for a gel coat is again omitted and an additional 200 mm is added to the part perimeter, S_P . This is to make a sufficient allowance for the vacuum bag to be sealed with tacky tape around the edges. The resultant model is indicated in Equation 5.19 below.

$$T_{bag_place} = 1 + [0.5(S_P + 0.2) + 0.5 + 0.25K_5] \quad (5.19)$$

To calculate the time taken to create the vacuum bag seal, Veldsman (1995) again provides a suitable equation, which he used to estimate the time taken to produce the mould seals for the composite moulds. This equation is modified for a single seal and 200 mm is once again added to the part perimeter. The resultant model is indicated in Equation 5.20 below. The value for K_3 may be calculated with Equation D42 to D44 in Appendix D.

$$T_{tacky_tape} = 0.14[5 + 15(S_P + 0.2) + K_3 + 2(S_P + 0.2)] \quad (5.20)$$

The total time for the vacuum bag is then simply the sum of Equations 5.19 and 5.20.

A time allowance for the preparation of the resin before infusion is also necessary. In this model a constant value of 3.6 minutes was employed based on the measured times as indicated in Tables 10 and 11.

$$T_{resin_prep} = 3.6 \quad (5.21)$$

As mentioned earlier, the mould filling prediction completed with RTM-Worx was used in preference to the method modelled on Darcy's equation. The Darcy based model is however incorporated in Equation D48 to D55 in Appendix D for comparative purposes.

The time estimation for mould opening, closing and part release is directly from Veldsman (1995) and is indicated in Equation D56 in Appendix D. Likewise with Equation D57 which is used to calculate the part trimming time after removal from the mould.

All the relevant labour times may then be added together to calculate the total part labour cost. With case study 2, the time allowances for the peelply and

Greenflow layers are omitted due to the closed mould nature.

The last set of calculations to be done before the final part cost may be calculated is the cost contribution due to the vacuum pump, mould cost and floor space rent. These amounts are calculated in Equations D59 to D64 in Appendix D. The final part cost, C_P , is then calculated as indicated in Equation 5.22 below. The part material cost is represented by M_{P2} , the RP core cost by P_{core} , the labour cost by multiplying the labour time (T_{L2}) with the labour rate (P_{labour}) and the capital cost due to the vacuum pump, mould and floor space is represented by C_1 to C_3 .

$$C_P = M_{P2} + P_{core} + T_{L2}P_{labour} + C_1 + C_2 + C_3 \quad (5.22)$$

5.3.5 Results

Table 12 below indicates the cost model results for case study 1 and 2 together with actual results.

Table 12: Cost model predictions for RT-RTM process

	Case 1	Actual case 1	Case 2	Actual case 2
Mould lead time	9h30min	12h45min	7h	8h20min
Mould material cost	R1750.00	R1810.00	R4450.00	R4580.00
Total mould cost	R2400.00	R2380.00	R5000.00	R5130.00
Part manufacture time	1h30min	1h30min	1h05min	1h11min
Part material cost	R 20.00	R 18.50	R 13.00	R 26.90
Total part cost	R 480.00	R 485.00	R 900.00	R 995.00

The longer mould lead time for case study 1 is due to the greater height of the part and consequently longer printing times. The predicted case study 1 mould lead time is inaccurate due to the problems with Equation 5.1. The other predicted times for case study 1 is close to the true times as this was used as base for many of the new constants. The predictions for case study 2 serves to verify the accuracy of the model. The total average part manufacturing time for case study 2 is 1h11min, sufficiently close to the predicted value of 1h05min. Even though the average value is close to the predicted value, the separate values for each part vary greatly because of operator influence (refer to Table 11). The operator is constantly improving his skill, leading to faster manufacture times.

The total mould cost estimation for both case studies are reasonably close to the actual cost. To verify the accuracy of the part cost prediction, the actual costs for case study 2 are indicated in Table 19 in Appendix D. The total average cost per part was R 837.90. This is only the direct cost (labour + materials). If the overhead costs due to the mould cost, vacuum pump and floorspace rent are added, the actual cost per part becomes R 995.00. This is within 11% of the predicted value of R 900.00. If the material cost component is considered, the pre-

dicted value of R 13.00 is significantly less than the actual cost. This is mainly due to the higher resin consumption than normal with case study 2 which is due to the channels on the blade core needing filling.

Overall it seems that this cost model is capable of predicting costs to within 15% of the actual values, even for parts with slightly deviating manufacturing times due to operator differences.

5.4 CNC aluminium moulds

Boothroyd (2002) provides a cost model for the manufacture of machined parts which takes all the material removal operations into account. This model may be used, but in this study actual data was available for case study 2 so this will be used in preference to this cost model for comparative purposes.

Although the male model of the blades was machined on a CNC machine, the machining of the female model for a mould should result in similar machining times. It was therefore deemed acceptable to use the measured times, as provided in Table 20 in Appendix D, for the case where a machined aluminium mould is used instead of a RT mould. Note that these times do not include the time needed to generate the CNC code. When the aluminium blank for the mould is ordered, certain allowances are needed. The maximum width of the block is taken and 30 mm is added to allow for the cutting tool width, 30 mm is added on each side for clamps and an additional 10 mm is then added all round to allow for squaring. The cost of the two 420x180x50 mm 6082-series aluminium blanks was quoted as R 680.40 each by Aluminium City in Cape Town. The CNC cost for machine time and operator was quoted as R 175.00/h and R 250.00/h respectively by the Stellenbosch University Mechanical Workshop. These figures were drawn into the part cost model and the results are presented in Table 13 below.

Table 13: Cost model results aluminium mould

	Case study 2
Mould lead time	13h50min
Mould material cost	R 1360.00
Total mould cost	R 7250.00
Part manufacture time	1h05min
Part material cost	R 13.00
Total part cost	R 1015.00

The total mould lead time falls in between the times needed for the composite and RT moulds. The total mould cost of R 7250.00 however, is significantly more than for the other options. This is the major reason for the high part cost of

R 1015.00 when small batch sizes such as 40 parts are considered. The part manufacture time is the same as for the RT-RTM case in Section 5.3, because the same process will be used.

5.5 Interpretation of results

When the three tooling options (composite, RT, CNC aluminium) are considered, results are much as expected. The composite mould option is the most affordable but is very time consuming. The CNC aluminium mould option has a reasonable lead time, but the mould cost is very high. The cost of the RT mould falls somewhere in between but this process is significantly quicker than the other options.

Something that has not been considered so far is the question of mould lifetime. It seems that the accuracy of RT moulds start deteriorating within a few parts, but according to Veldsman (1995) the composite mould is able to produce up to 1000 parts if an epoxy matrix mould is used. The aluminium mould is obviously tougher and should be able to last 10 000 parts. This is a conservative estimate for aluminium moulds as Veldsman (1995) mentions that metal moulds easily last for 100 000 parts with RTM manufacturing. If these batch sizes are entered in the cost models, the capital cost per part is greatly reduced. Table 14 below indicates the result of this investigation.

Table 14: Part cost at maximum mould lifetime

Mould type	Number of parts	Part cost
RT	40	R 900.00
Composite	1000	R 803.00
Aluminium	10000	R 818.00

The part cost of the parts produced in the 3DP mould does not seem so favourable if this is considered. It seems therefore that the major advantage offered by this process is the short lead time possible.

A major limitation of these cost models is that any deviation from the exact process followed will lead to inaccuracy in time predictions. Inconsistencies due to operator differences also influence the accuracy of the prediction.

6. CONCLUSIONS

This project focussed on the application of the 3D-printing RP method to the RTM manufacture of composite parts. The results obtained gave considerable insight into the feasibility of the resultant hybrid RT-RTM process. These areas of insight will now be briefly discussed.

6.1 Review of thesis objectives

6.1.1 Design a process chain for the manufacture of composite parts

The knowledge gained during the literature study and consultation with industry was successfully employed in the part manufacture process chain. This information enabled the choice of the method used to calculate fibre permeability, tool design guidelines and many other handy hints such as the use of spray-on adhesives for fibre positioning in the mould. This was incorporated in a process chain which allows the effective manufacture of composite parts utilising RT moulds and/or RP cores.

6.1.2 Complete a simple and complex part case study

The process chain was successfully implemented for the completion of both a complex and simple part case study. Parts of good quality were manufactured with both the vacuum infusion and VARTM variants of the standard RTM method. By manufacturing parts with radically different geometrical complexity a good understanding was developed for the capabilities of the hybrid RT-RTM process.

6.1.3 Create a set of part and mould design rules

Concise guidelines for RTM mould design, part design and design guidelines specifically for RP tooling is provided in Appendix A. These guidelines were created from knowledge gained from literature surveys, consultation with industry as well as practical knowledge gained during the part manufacture case studies. Guidelines for a wide variety of issues are provided, including material selection, part geometry, draft angles and placement of resin inlet and outlet ports.

6.1.4 Determine dimensional deviations with the proposed RT-RTM hybrid process

A Mitotoyo CMM and surface tester were employed for the geometrical survey of the rough moulds, finished moulds, composite parts, used moulds and aluminium sample parts. These measurements were compared to results obtained by other researchers and a statistical analysis was performed.

6.1.5 Develop a cost model for the manufacture of composite parts

A cost estimation model, based on the work of Veldsman (1995), was completed for the RT-RTM process. This will allow researchers, who might be inexperienced in this manufacturing field, to predict the cost of composite parts with reasonable accuracy and the minimum of effort.

6.2 Applicability of RP technology to RTM

RP technology for tooling and cores is definitely applicable to the RTM family of processes for a number of reasons. The correct application of the hybrid RT-RTM method might result in both a cost and time saving over more conventional production methods. The most meaningful area of application seems to be smaller and more complex components. The complexity possible with both the RT and RTM processes is considerable in many cases, but care should be taken to ensure proper mould filling with more complex part geometries. The high levels of complexity possible with RP parts may be used to advantage here by including complex resin distribution channels such as performed with the case study 2 part. It is very difficult to manufacture such intricate features with other methods.

The geometrical freedom allowed by the RP technology is probably the single most significant advantage thereof. When parts such as the case study 2 blade are manufactured, this is illustrated very clearly. When a blade profile is machined on a CNC machine, one of two difficulties often arises. If the female mould is machined, the very small radius of the trailing edge is very difficult to accurately machine. On the other hand, if the male model of the blade is machined, the thin foil section of especially the trailing edge deflects under the cutting tool pressure and leads to inaccuracies. This second issue was clearly observed with the aluminium parts from case study 2. A relatively inaccurate RP method such as 3D-printing indicated an improvement over the CNC option regarding these issues and therefore it may be expected that more advanced RP methods may lead to even more significant improvements.

Expected problems at the outset of this study included the porosity of the 3D-printed RP parts (hence the need for infiltration), low strength of these parts and dimensional deviation of the final composite parts. These expected issues were confirmed during the case studies, but solutions for most of these could be provided.

Probably the most significant limitation for the use of RP technology for RTM processes is the limited build volume of current machines. Larger RP parts may be built in sections, but this creates other issues such as extra labour and reduced accuracy. For practical purposes, this generally limits the maximum length of parts manufactured with the hybrid RT-RTM process to around 0.5 m depending on the RP machine in use.

Together with the limited build size, the other significant limitation of the RT

moulds as manufactured with the 3D-printer is the accuracy capability. Designers need to carefully consider the accuracy possible as provided in Chapter 4 before making decisions regarding the tooling option. For many applications however, the accuracy is more than sufficient.

As the practical work in the two case studies progressed, it became clear that the strength of the RP moulds is another limitation when the 3D-printing process is used. A different RP material or process may be employed to solve this problem, but in the case studies use was simply made of a mild steel reinforcement plate for the moulds.

It was also found that the porosity of the RP parts, together with dimensional deviation in the area of the mating surfaces, made proper mould sealing difficult. Infiltration of the green RP parts definitely reduced porosity but it remains an issue to consider. As before, a different type of RP process might reduce this problem. During case study 2 this problem was simply solved by enclosing the mould assembly with a vacuum bag.

A novel application of RP technology in RTM manufacture is for disposable cores. This simplifies the manufacture of composite parts with thicker cross sections and may also be employed to improve resin distribution as with the second case study completed. If hollow composite parts are required, soluble RP materials may be used or the core may be manufactured with one of the wax printing RP methods to be melted out after composite curing.

Because of mould accuracy deterioration after a number of parts, the RT-RTM method seems more suited to smaller production runs or for prototyping. Where only a small number of parts are required, the RT moulds represent less capital expenditure than for machined metal moulds. It needs to be noted however that RP methods utilising much stronger materials than used in the 3DP are available and may result in significantly increased mould lifetime.

6.3 Part manufacture process chain

The design of a process chain which allows the effective manufacture of composite parts utilising the RTM process in conjunction with RT moulds was the main focus of this study. The final process chain was strongly influenced by one proposed by Ferreira et al. (2005) during a similar investigation. Results from the literature survey as well as practical experience gained during preliminary work for the case studies were incorporated into the final process chain.

The process chain as described in Chapter 3 was found to be successful for the case studies completed. The process chain consists of both a virtual and physical domain. During the virtual domain, the provided design guidelines are implemented during the drafting of a CAD model of the mould. The CAD model is then used in a series of RTM-Worx resin flow simulations to verify that proper mould filling is possible. During the physical stage, the tools are created on the RP ma-

chine, prepared and then used in the composite manufacture process.

The resin flow simulations performed with RTM-Worx forms an integral part of the process chain. Even though filling time predictions calculated with this software package were found to be inaccurate, good results were obtained with the flow pattern predictions and were helpful with the mould design process.

Geometrical measurements performed with a CMM and surface tester also form an important verification system to ensure that RT and composite parts are acceptably close to the CAD model at each stage of the part manufacture process chain. The green RT moulds were measured directly after printing, after surface finishing and after use. The composite as well as aluminium sample parts were also subjected to coordinate measurements with the CMM as well as surface finish measurement with the surface tester. A statistical analysis was performed with the resultant data, indicating that the results obtained were in line with results obtained by other researchers using the same RP machine.

As was to be expected, the accuracy of the moulds deteriorated during the surface finishing operations as well as during composite part moulding. The deterioration caused by the sanding operation was very low and is not very significant when compared to the accuracy capabilities of the 3D-printer. The manufactured parts were less accurate than the mould, indicating, as expected, a geometrical data loss during the moulding process. If the same part moulding operation was employed with moulds manufactured by other means, a similar accuracy loss from mould to part may be expected. A slight reduction in accuracy was also detected in the area where moulds that were printed in sections were joined. This accuracy loss does not seem very significant and may indicate that the building volume limitation imposed by many RP machines can be solved by careful splitting of components. CMM measurements of the aluminium case study 2 sample parts indicated accuracy that was slightly worse than with the composite parts. This may be explained by the problems posed with CNC machining of such thin, foil-like geometries as well as the fact that these blades could have been damaged during a set of under-water tests.

In contrast to the slight accuracy reductions caused by mould finishing operations, the surface finish measurement indicated improvements. With careful sanding of the green mould, parts with a surface roughness value of better than 2 μm are possible.

To conclude, good quality parts were manufactured with both a vacuum infusion and VARTM process. This process chain may be used in future projects as well as being combined with other types of RP technology.

6.4 Use of cost estimation models

Cost models are a very helpful tool for the choice of the best manufacturing option for a part. Cost estimation models have two main functions: it helps designers

to eliminate expensive design features and enables a quick cost comparison with competing processes. As over 75% (Ullman, 2003) of the final product cost is already decided during the design stage, an early cost estimation model may be implemented as an effective design tool.

As Veldsman (1995) had already completed a cost model for a RTM manufacture process, it was decided to use this cost model as basis for the model for the RT-RTM process. This cost model had the added advantage over other cost models of taking the geometrical complexity of parts into consideration. Cost equations specific to the RT moulds and process followed were incorporated in the Veldsman (1995) model.

The main issue experienced with the cost model was the difficulty in accurately predicting the RP build time. It was therefore proposed to rather use the build time estimator incorporated into the software of many RP machines. Besides this problem, reasonable cost predictions for the parts manufactured were obtained. It seems reasonable to expect the predicted cost to be within 15% of the true cost.

The cost of the mould represents the major capital expenditure in the RTM process. The cost of aluminium machined moulds was found to be the highest, followed by composite moulds and then the RT moulds. The picture seems slightly different when the mould lifetime is also considered. The RT moulds have the shortest lifetime and the aluminium moulds the longest lifetime with the composite moulds somewhere in between. If this information is incorporated into the cost model, the RT option becomes the most expensive if large production runs of parts are considered. It therefore seems that the 3D-printed RT option is more suited to small production runs, typically less than 40 parts, and offers the advantage of shorter lead times than the other tooling options. When such small production runs are considered, RT moulds represent the most cost effective solution.

6.5 Recommendations and future work

It should be worthwhile to investigate the applicability of other RP techniques to RTM manufacture. The 3DP method which was used in this project is more affordable and faster than other techniques but is less accurate and mould lifetime is limited. This method therefore seems more applicable for small production runs of composite parts. If this method was substituted with a process such as SLS manufacture of metal moulds, accuracy should improve, mould lifetime should improve and less mould preparation steps will be necessary. The cost of individual composite parts may also be reduced due to the longer mould life. The use of such a method may make the hybrid RT-RTM process feasible for the industrial production of many composite parts.

A part such as the case study 2 blade will be used in an aqueous environment for most of its lifespan. It is not well known what the effect of water will be on such a composite part consisting of a conventional composite material surround-

ing a RP core. It might therefore be worthwhile to do a series of tests to investigate the environmental impact on such a component.

As very good results were obtained with the RP cores, it would be worthwhile to test such a core in conjunction with a different tooling option such as CNC aluminium moulds. If a RP core is used with such a tooling option it still provides the advantages offered by the resin runners on the core surface while providing other possible advantages such as the long mould life of aluminium moulds.

As the cost models developed during this study only considered parts of small (under 0.5 m) size, future work might include additions to enable accurate cost estimations for larger parts.

Due to the geometrical freedom with RP techniques, it might be possible to print a part core in such a way that reinforcements such as steel rods may be easily inserted. This will be of particular significance with parts such as the case study 2 fan blade, where it is desirable to have steel inserts to attach the blade to a hub. Research into this matter may be of value to the RT-RTM manufacturing method.

The results from these proposed future studies, together with the findings from this project, may enable designers to confidently implement RP techniques to composite manufacture processes such as RTM.

7. LIST OF SOURCES

Airtech, 2008. *Vacuum bagging and composite tooling*. [Online] Available at: www.airtechonline.com [Accessed 13 October 2008].

Alborough, H., 2009. Personal interview. 5 June, Rapid Prototypes, Cape Town.

Autodesk, 2009. *Moldflo*. [Online] Available at: www.moldflo.com/stp [Accessed 12 September 2009].

Barlow, D., Howe, C., Clayton, G. & Brouwer, S., 2002. Preliminary study on cost optimisation of aircraft composite structures applicable to liquid moulding technologies. *Composite Structures*, 57, pp.53-57.

Boccard, A., Lee, W.L. & Springer, G.S., 1994. Model for determining the vent locations and the fill time of resin transfer molds. *Journal of Composite Materials*, 29, pp.306-33.

Boje, L., 2009. Personal interview. 5 July, Seeff Properties, Stellenbosch.

Boothroyd, G., Dewhurst, P. & Knight, W., 2002. *Product design for manufacture and assembly*. 2nd ed. New York: Marcel Dekker.

Christian, P., Jones, I.A., Rudd, C.D. & Campbell, R.I., 2001. Monomer transfer moulding and rapid prototyping methods for fibre reinforced thermoplastics for medical applications. *Composites*, 32, pp.969-76.

De Beer, N., 2004. *An investigation towards developing capability profiles of rapid prototyping technologies with a focus on 3D-printing*. MSc Thesis. Stellenbosch: University of Stellenbosch.

De Vries, W., Korngold, J., Larson, D. & Luscher, T., 1992. *Design for manufacture guidelines: resin transfer molded composite structures*. Technical Report. New York: Rensselaer Polytechnic Institute.

Ding, Y., Lan, H., Hong, J. & Wu, D., 2004. An integrated manufacturing system for rapid tooling based on rapid prototyping. *Robotics and Computer-Integrated Manufacturing*, 20, pp.281-88.

Du Toit, H., 2009. Personal interview. 16 May, Custom 3D, Stellenbosch.

Engineer's Handbook, 2008. *Resin transfer molding*. [Online] Available at: <http://engineershandbook.com/MfgMethods/resintransfermolding.htm> [Accessed 16 November 2008].

EOS, 2009. *EOS RP machines*. [Online] Available at: www.eos.info [Accessed 11 September 2009].

- Ferreira, J.C. & Mateus, A., 2003. Studies of rapid soft tooling with conformal cooling channels. *Journal of Materials Processing Technology*, 142, pp.508-16.
- Ferreira, J.C., Simoes, L., Borges, J. & Beira, R., 2005. Rapid development of composite prototypes with rapid tooling in soft materials. In *Proceedings of the 2nd international conference on advanced research and rapid prototyping*. 28 September - 1 October, Leiria, Portugal. pp.291-96.
- Govignon, Q., Bickerton, S., Morris, J. & Kelly, P.A., 2008. Full field monitoring of the resin flow and laminate properties during the resin infusion process. *Composites: Applied Science and Manufacturing*, 39, pp.1412-26.
- Gutowski, T.G., 1997. *Advanced composite manufacturing*. New York: John Wiley and Sons.
- Hugo, P., 2008. *Suitability of layer manufacturing technologies for rapid tooling development in investment casting*. MSc Thesis. Stellenbosch: University of Stellenbosch.
- Huynh, Q.U., 2008. Personal interview. 11 October, Technical University of Berlin, Berlin.
- IWK, 2009. *myRTM*. [Online] Available at: www.iwk.hsr.ch/myRTM [Accessed 12 September 2009].
- JHM Technologies, 2009. *Resin transfer moulding systems*. [Online] Available at: www.rtmcomposites.com [Accessed 6 June 2009].
- Jonker, A., 2009. Personal interview. 10 February, North-West University, Potchefstroom.
- Kendall, K.N., Rudd, C.D., Owen, M.J. & Middleton, V., 1992. *Characterization of the resin transfer moulding process*. PhD Thesis. Nottingham, UK: Department of Mechanical Engineering at The University of Nottingham.
- Kim, S.G., Chu, W.S., Jung, W.K. & Ahn, S.H., 2007. Evaluation of mechanical and electrical properties of nanocomposite parts fabricated by nanocomposite deposition system (NCDS). *Journal of Materials Processing Technology*, 187, pp.331-34.
- Klosterman, D., Chartoff, R., Graves, G. & Osborne, N., 1998. Interfacial characteristics of composites fabricated by laminated object manufacturing. *Composites*, 29, pp.1165-74.
- Koorevaar, A., 2008. Correspondance. 5 November, Polyworx, Nijverdal, Netherlands.

- Kruth, J.P., Levy, G., Klocke, F. & Childs, T.H., 2007. Consolidation phenomena in laser and powder-bed based layered manufacturing. *CIRP Annals - Manufacturing Technology*, 56, pp.730-59.
- Lee, C.S., Kim, S.G., Kim, H.J. & Ahn, S.H., 2007. Measurement of anisotropic compressive strength of rapid prototyping parts. *Journal of Materials Processing Technology*, 187, pp.627-30.
- Levy, G.N., Schindel, R. & Kruth, J.P., 2003. Rapid manufacturing and rapid tooling with layer manufacturing (LM) technologies, state of the art and future perspectives. *CIRP Annals - Manufacturing Technology*, 52, pp.589-609.
- Louw, M., 2004. *Developing capability profiles for the ZPrinter 310 by combining different materials and infiltrating agents*. B.Eng Thesis. Stellenbosch: University of Stellenbosch.
- Lunn, P., 2004. Tooling materials ideal for resin infusion. *Reinforced Plastics*, September. pp.28-30.
- Luo, J., Liang, Z., Zhang, C. & Wang, B., 2001. Optimum tooling design for resin transfer molding with virtual manufacturing and artificial intelligence. *Composites: Applied Science and Manufacturing*, 32, pp.877-88.
- Lyons, B., 2006. Permanent and sacrificial 3DP molds for composite parts. *Rapid Prototyping*, 12, pp.1-4.
- Ma, S., Gibson, I., Balaji, G. & Hu, G.J., 2007. Development of epoxy matrix composites for rapid tooling applications. *Journal of Materials Processing Technology*, 75, pp.192-93.
- Marsh, G., 2009. Wave and tidal power - an emerging new market for composites. *Reinforced Plastics*, June/July. pp.20-24.
- Masood, S.H. & Song, W.Q., 2004. Development of new metal/polymer materials for rapid tooling. *Materials & Design*, 25, pp.587-94.
- Materialise, 2008. *Materialise Rapid Prototyping*. [Online] Available at: www.materialise.be [Accessed 15 August 2008].
- Modi, D., Correia, N., Johnson, M. & Long, A., 2007. Active control of the vacuum infusion process. *Composites: Applied Science and Manufacturing*, 38, pp.1271-87.
- National Science Foundation, 2009. *Rapid prototyping history*. [Online] Available at: <http://www.nsf.gov/about/history/nsf0050/manufacturing/rapid.htm> [Accessed 11 August 2009].

- Papargyris, D.A., Day, R.J., Nesbitt, A. & Bakavos, D., 2008. Comparison of the mechanical and physical properties of a carbon fibre epoxy composite manufactured by resin transfer moulding using conventional and microwave heating. *Composites Science and Technology*, 68, pp.1854-61.
- Polyworx, 2009. *RTM-Worx*. [Online] Available at: <http://www.polyworx.com> [Accessed 15 August 2009].
- Potgieter, M., 2008. Personal interview. 13 March, Centre for Rapid Prototyping and Manufacturing, Bloemfontein.
- Radstock, E., 1999. Rapid tooling. *Rapid Prototyping Journal*, 5, pp.164-69.
- Rao, R.V. & Padmanabhan, K.K., 2007. Rapid prototyping process selection using graph theory and matrix approach. *Journal of Materials Processing Technology*, 194, pp.81-88.
- Reinecke, J., 2007. *The design, manufacture and testing of a model ocean current turbine*. B.Eng Thesis. Stellenbosch: University of Stellenbosch.
- Rooks, B., 2002. Rapid tooling for casting prototypes. *Assembly Automation*, 22, pp.40-45.
- Rosochowski, A. & Matuszak, A., 2000. Rapid tooling: the state of the art. *Journal of Materials Processing Technology*, 106, pp.191-98.
- Rudgley, M., 2001. Rapid manufacturing - the revolution is beginning. In *Proceedings of the uRapid Conference*. May, Amsterdam, Netherlands. pp.441 - 444.
- Sadegh, R., Mohamad Reza, R. & Javad, A., 2009. Design and manufacture of a wax injection tool for investment casting using rapid tooling. *Tsinghua Science and Technology*, 14, pp.108-15.
- Smaldon, G., 2004. Technology update: vacuum infusion. *Reinforced Plastics*, January. pp.28-29.
- Tari, M.J., Bals, A., Park, J. & Lin, M.Y., 1998. Rapid prototyping of composite parts using resin transfer moulding and laminated object manufacturing. *Composites*, 29, pp.651-61.
- Tavenor, R., 2008. *Simulation and verification of resin flow in FRP mouldings under vacuum pressure*. B.Eng Thesis. Cape Town: University of Cape Town.
- Ullman, D.G., 2003. *The Mechanical Design Process*. 3rd ed. New York: McGraw Hill.

- Veldsman, G., 1995. *Aspects of design for manufacturability in RTM*. MSc Thesis. Stellenbosch: University of Stellenbosch.
- Veldsman, G. & Basson, A.H., 1998a. Cost comparison of RTM hand-lay and cast tooling. In *Proceedings of 2nd International Conference on Composite Science and Technology*. Durban, South Africa. pp.483-88.
- Veldsman, G. & Basson, A.H., 1998b. The role of cost estimation in the design for RTM. In *Proceedings of ECCM-8*. Naples, Italy.
- Veldsman, G. & Basson, A.H., 1999. Designing for RTM using manufacturing cost estimation models. In *Proceedings of the 1999 CIRP International Design Seminar*. Enschede, Netherlands. pp.321-30.
- Veldsman, G., Basson, A.H. & Van der Westhuizen, J., 1996. Composite mould design and cost estimation for resin transfer moulding. In *Proceedings of first International Conference on Composite Science and Technology*. Durban, South Africa. pp.571-76.
- Wang, D., Guo, D., Jia, Z. & Leng, H., 2006. Slicing of CAD models in color STL format. *Computers in Industry*, 57, pp.3-10.
- Weitzenbock, J.R., Sheno, R.A. & Wilson, P.A., 1999. Radial flow permeability measurement. Part A: Theory. *Composites Part A: Applied Science and Manufacturing*, 30, pp.781-96.
- Williams, C., Summerscales, J. & Grove, S., 1996. Resin Infusion under Flexible Tooling (RIFT):a review. *Composites*, 27, pp.517-24.
- Wohlers, T.T., 2003. *Wohlers Report 2003*. Annual Worldwide Progress Report. Fort Collins: Wohlers Associates.
- World Health Organization, 2000. Organic pollutants. In *Air quality guidelines for Europe*. 91st ed. Copenhagen: WHO. pp.106-08.
- Xu, F., Wong, Y.S. & Loh, H.T., 2000. Toward generic models for comparative evaluation and process selection in rapid prototyping and manufacturing. *Journal of Manufacturing Systems*, 19, pp.283-97.
- Yang, J., Jia, Y.X., Sun, S. & Ma, D.J., 2008. Enhancements of the simulation method on the edge effect in resin transfer molding processes. *Materials Science and Engineering*, 478, pp.384-89.
- Zhang, H., Wang, G., Luo, Y. & Nakaga, T., 2001. Rapid hard tooling by plasma spraying for injection molding and sheet metal forming. *Thin Solid Films*, 390, pp.7-12.

Zhong, W., Li, F., Zhang, Z. & Song, L., 2001. Short fiber reinforced composites for fused deposition modeling. *Materials Science and Engineering*, 301, pp.125-30.

APPENDIX A: RTM DESIGN GUIDELINES

As this study partly builds on the work completed by Veldsman (1995), his mould and part design guidelines were used as basis for this project. Guidelines from other researchers, as outlined in Section 2.1, were also incorporated. Lastly, practical experience gained during the execution of this project is also incorporated in the guidelines.

A.1: Part design guidelines

A.1.1: Material selection

- The most cost effective resin suitable for RTM is considered to be polyester resins, but more costly epoxy resins result in slightly more dimensionally stable parts. Vinylester resins are not as suitable for RTM as the other two types, being more susceptible to shrinkage. Veldsman (1995)
- Low viscosity resins are desirable for RTM as it enables better penetration into the dry reinforcement. Viscosity should ideally be lower than 15 Poise (Veldsman, 1995). Heating of resins may be used to lower viscosity, but note that this may initiate the curing reaction in most thermoset resins.
- Choose a resin with a sufficiently long pot life. This was discussed in Section 3.5.
- Avoid unnecessarily high fibre volume fractions if the part to be manufactured is not an advanced composite structure. As discussed in Chapter 2, higher fibre volume fractions require higher inlet pressures to ensure complete mould filling. A fibre volume fraction of 30-40% may be high enough (Veldsman, 1995).
- The use of distribution media, as discussed in Chapter 2, will simplify resin distribution and result in a decrease in required resin inlet pressure for mould filling. Use a layer of peelply between the fibre preform and distribution media to simplify the removal of the distribution layer after part curing.

A.1.2: Part geometry

- Aim for a minimum wall thickness of 2.5 mm (Veldsman, 1995).
- For very thick sections, incorporate cores to prevent resin-rich areas. This helps prevent part cracking or mould damage due to shrinkage during curing. Thick sections may also cause localised high exotherms leading to mould degradation. (Veldsman, 1995)

- It is very important to incorporate sufficiently large draft angles, especially with deep components. There are three main reasons for this: there may be adhesion between the surfaces, the absence of air between the surfaces leads to higher friction and the part may shrink or warp during curing (Veldsman, 1995). The first cause may be mitigated by the proper use of release agents, but the last two reasons are the primary reasons for draft angles. A minimum draft angle of 3° should be used and at least 5° for deeper components (Veldsman, 1995).
- Avoid sharp corners and small radii. Where two surfaces meet perpendicularly it is necessary to insert a fillet or chamfer to prevent resin rich areas from forming where it is difficult for the fibre reinforcement to conform to the sharp corners. Fillets and chamfers also make part and mould cleaning easier and improves mechanical properties by eliminating potential stress concentrations. Veldsman (1995) recommends certain minimum sizes for the fillets and chamfers based on part thickness (t). These minima are illustrated in Figures 41 and 42.

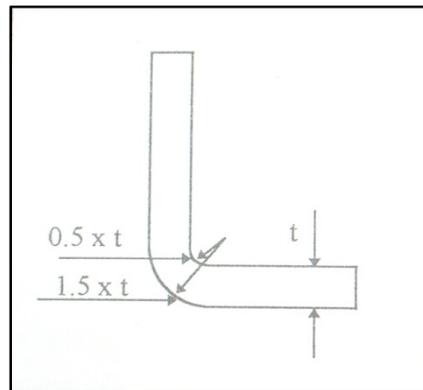


Figure 41: Filleting of corners (Veldsman, 1995)

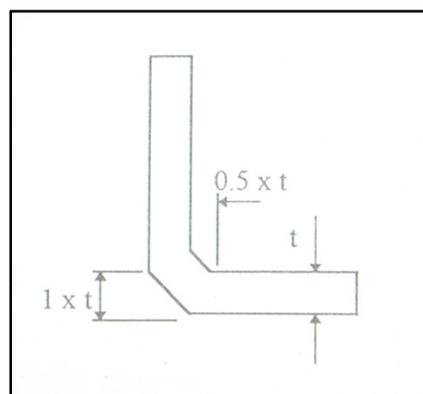


Figure 42: Chamfering of corners (Veldsman, 1995)

A.1.3: Varying part thickness

- There are two basic methods for introducing part thickness variations, namely ply drop-offs and inserts such as foam. These features increase costs and designers should therefore first consider if they are really necessary. (Veldsman, 1995)
- Ply drop-offs are used to introduce a gradual change of thickness or change in reinforcement material. It is preferable to drop-off plies in flat sections rather than in corners. This is easier to do consistently and also distribute loads more evenly. Figure 43 below illustrates this. (Veldsman, 1995)

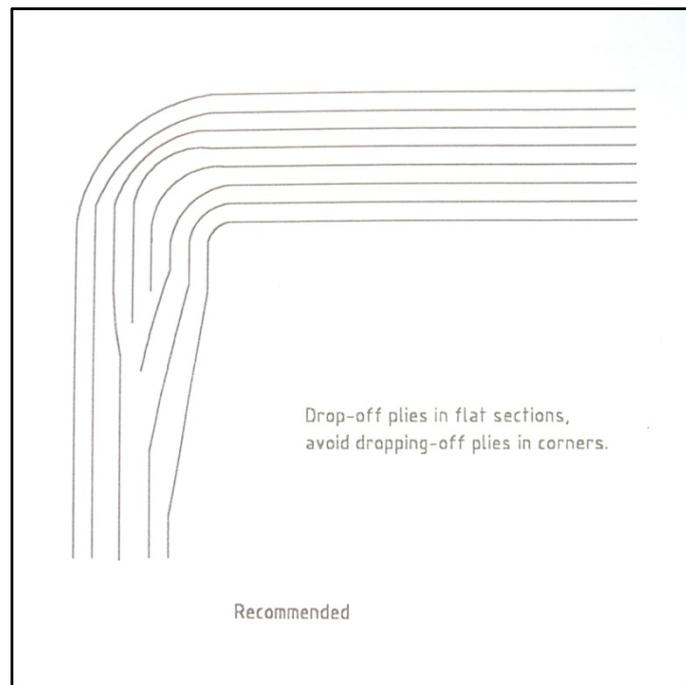


Figure 43: Positioning of ply drop-offs (Veldsman, 1995)

- To change part thickness, each successive ply is cut slightly shorter than the previous one, forming a 45° ramp. The ramp is then covered with one continuous ply. The staggering of layers helps prevent stress concentrations and the single covering ply prevents fibre wash-out during resin filling and helps to transmit stresses to the whole fibre assembly. Figure 44 illustrates this method. (Veldsman, 1995)

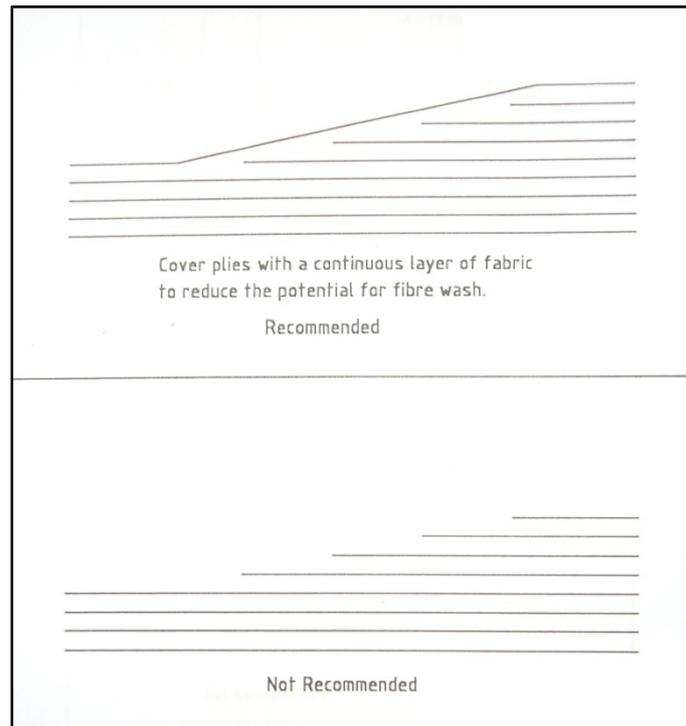


Figure 44: Staggering of plies (Veldsman, 1995)

- A transition between different types of reinforcement needs to be done with at least 13 mm overlap between plies to ensure good transition of forces. Figure 45 illustrates this. (Veldsman, 1995)
- Drop-offs should be easily visible and at regular intervals to simplify measurement and preparation for the lay-up technician. (Veldsman, 1995)
- Inserts are meant for more sudden increases in thickness than ply drop-offs. Inserts normally have a more significant impact on cost than ply drop-offs. (Veldsman, 1995) Inserts also have an effect on the resin flow path which designers need to take into account.
- Veldsman (1995) recommends that inserts are wrapped in reinforcement cloth before being placed in the mould, thereby improving adhesion between the insert and rest of the composite part.
- As resin rich areas should be avoided, make sure that the insert provides a smooth transition for the surrounding plies as in Figure 46 (Veldsman, 1995).

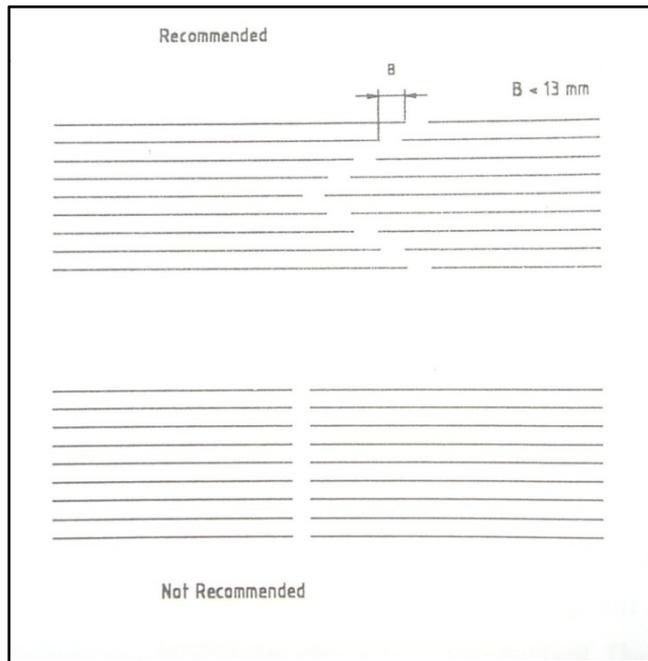


Figure 45: Material transition (Veldsman, 1995)

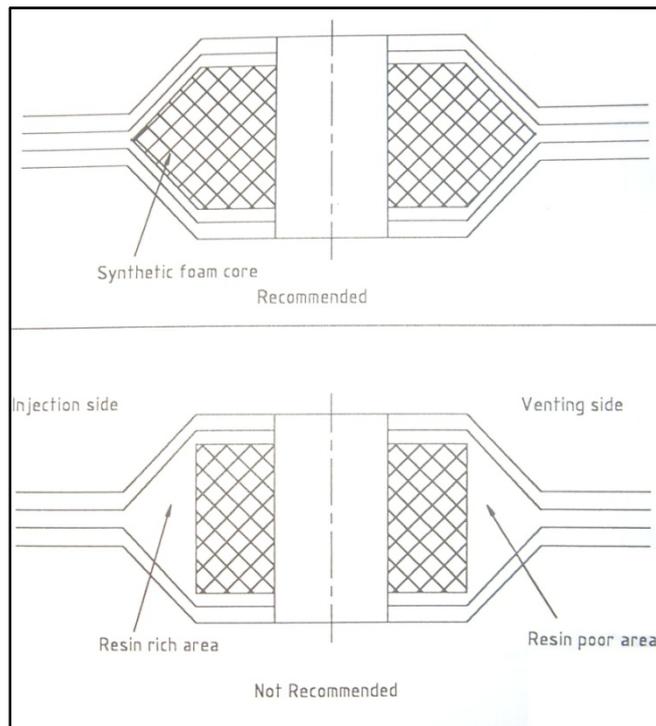


Figure 46: Example for the correct use of inserts (Veldsman, 1995)

A.1.4: Holes and inserts

- Minimize post-moulding operations. Consider whether features requiring post-moulding steps can be eliminated or can be incorporated into the moulding operation itself. (Veldsman, 1995)
- One group of features that is normally better to post-manufacture is holes. Moulded holes are labour intensive and force the reinforcement together at the hole as indicated in Figure 47 below. (Veldsman, 1995)

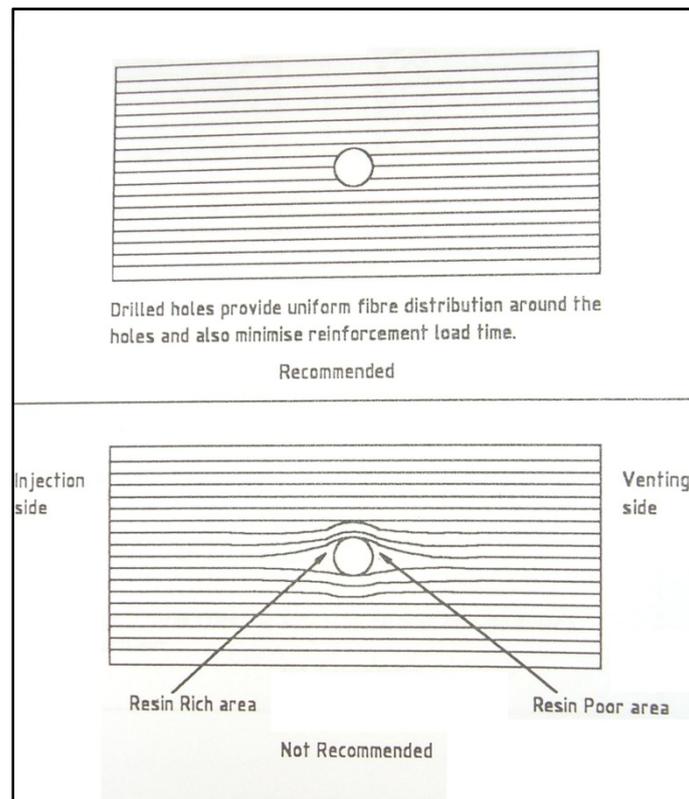


Figure 47: Hole placement practice (Veldsman, 1995)

- A good practice where precision holes are needed for objects such as bearings is to make use of short chopped fibre thermoplastic inserts. These short fibres are easier to accurately machine after moulding than long fibres. These short fibres can be used for any feature where secondary material removal is required. (Veldsman, 1995)
- Inserts made from materials such as metal may give good results, but keep the different thermal expansions of differing materials in mind.

A.2: Mould design guidelines

Many of the part design guidelines listed will also dictate mould design (Figure 48), but designers should also consider the guidelines given in this section.

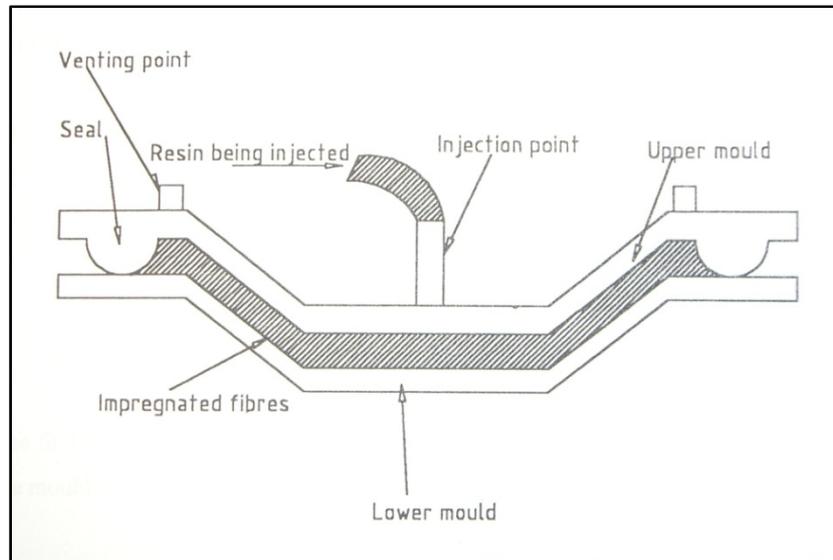


Figure 48: Schematic of RTM mould (Veldsman, 1995)

A.2.1: Overview

- The two faces of a closed mould should meet to form the part shape and should be provided with features to locate the mould halves accurately.
- Seals are necessary to prevent resin wastage and promote mould filling (Veldsman, 1995).
- During mould design, provision should be made for closing, resin injection, venting and opening.
- Moulds need to be stiff enough to prevent deformation during part manufacture and removal (Veldsman, 1995).
- The mould material should be able to withstand the maximum temperature in any planned post curing cycle or resin exotherm.
- The mould design should enable easy cleaning (Veldsman, 1995).
- Design for net-shape manufacturing and avoid post-moulding operations (Veldsman, 1995).

A.2.2: Necessary information

Before mould design can commence, it is first necessary to know certain parameters as these will influence the mould's design (Veldsman, 1995):

- Component shape
- Required mould lifetime (number of components)
- Required surface finish
- Resin system
- Processing temperatures

A.2.3: Material selection

Three main groups of moulds are in general use namely all-metal moulds, composite moulds and composite moulds with metal plated skins (Veldsman, 1995). This study adds RT moulds to this list. The technology for the normal three material groups is well known and design guidelines are provided by researchers such as Veldsman (1995). Technology specific guidelines for the RT option are provided in Section A.3.

A.2.4: Injection points

Injection port and vent placement is the most critical aspect for mould filling time and consequently cycle time. Placement of these ports also influences cleaning time. Simulation packages, like RTM-Worx, enable the optimization of port placement, but it is first necessary to have a good grasp of the basic placement guidelines.

Various types of injection ports may be used, from simple tubes glued into holes in the mould to computer controlled ports, enabling automation of the RTM process. When deciding on an injection port type, first consider the criteria listed below (Veldsman, 1995):

- Cleaning of the injection point should be possible without major difficulties.
- If possible, design injection port in such a way that the part does not need to be trimmed afterwards where the resin was injected.
- The injection port needs to be able to withstand the chemical attack from acetone used in mould cleaning and styrene emitted by the curing resin.
- Injection ports need to be able to withstand the maximum inlet pressure.

When injection port placement is considered, it is good practice to place it at the lowest point of the mould. Also try to place the injection port at the thickest section of the mould, making injection from thick to thin possible. This helps prevent dry areas. (De Vries et al., 1992 as quoted by Veldsman, 1995)

When large structures or parts with complex geometry are manufactured, more than one injection port may be necessary. Multiple ports or line gates may be used in these cases. Line gates attach to a single resin supply and function as a distributed source (Veldsman, 1995). Spiral plastic tubing, which connects to the resin supply and venting pipes, also serves as a handy distributed resin and/or venting source (Lunn, 2004). It is important to realise that too many resin ports should be avoided as air may be trapped when the different flow fronts meet (Veldsman, 1995). It is also good practice to place the resin source at the same height or higher than the inlet port.

A.2.5: Mould clamping and opening

The moulds need to stay securely closed and clamped when parts are in the process of being made. Mould halves should not be able to move relatively to each other and it should be relatively easy to open the mould halves after curing.

Moulds can either be kept closed by mechanical clamps or vacuum clamping. Mechanical clamps can be in the form of G-clamps, bolts and hydraulic/pneumatic clamps. G-clamps and bolts are slow to fit and are thus only suitable for smaller parts. Hydraulic and pneumatic clamping devices are more expensive, but lend themselves to large structures and automation.

When vacuum clamping is used, double seals are normally fitted along the perimeter of the moulds and injection pressures are limited by the vacuum (Veldsman, 1995). When smaller components are manufactured, vacuum bagging is a convenient method of mould closing and sealing, but increases costs. When designing moulds for vacuum clamping, place the inner seal so that it forms the edge of the part (Veldsman, 1995). This will arrest resin flow and there will be less edge trimming and removal of resin residues necessary when the composite part is removed.

A.2.6: Mould venting

Air can be removed from the mould by either being forced out of the venting ports by the resin flow front or by removing the air by vacuum before resin injection.

The list below gives some of the venting methods used when air is expelled by the resin flow front:

- To enable venting, some moulds are manufactured without perimeter seals. This allows the air to be expelled via the perimeter but results in high levels of resin wastage. Flash-gap vents make use of a continuous gap of 0.02 to 0.10 mm to expel air. (Veldsman, 1995)
- To reduce some of this resin wastage, some mould systems pinch the reinforcement around the mould perimeter, allowing air to be expelled through the pinched section, but reducing resin overspill. This is known as the trapped reinforcement method (Kendall et al., 1992). The main

drawback here is that the edges of the part needs trimming after curing.

- Kendall et al. (1992) describes the porous gasket method, where a porous gasket is sandwiched between the two mould halves, allowing excess air to be expelled. The limitation with this process is that pores become blocked and the gasket needs to be replaced after each moulding.
- In the vented seal technique (Kendall et al., 1992), the mould perimeter seal is manufactured with a number of discrete vents to allow air to escape. This method needs few post-processing steps, lowering cycle times.

When use is made of completely sealed moulds, air needs to be removed before resin injection. Vacuum removal is used in processes such as resin infusion and VARTM. This method has numerous advantages such as no resin overspill and minimal part trimming and lends itself to the manufacture of parts with high fibre volume fractions. This method is very sensitive to leaks which might cause small voids to form inside the part.

When designing venting port placement, keep in mind that the resin flows in a radial manner when introduced through the inlet ports. In contrast to injection ports, the vents are usually placed at the highest point and thinnest section of the mould. Also try to locate the venting ports as far away as possible from the inlet ports. (Veldsman, 1995)

A.2.7: Part removal

Planning for part removal is very important as good quality parts which cannot be removed from a mould is to no avail. Properly treat the mould with release wax/agents to prevent parts from bonding to the mould and causing part and mould damage. When removing parts from the mould, air can also be injected into the injection/venting ports to loosen deep components.

A.3: Rapid Tooling design

All the design guidelines discussed in Sections A.1 and A.2 are also applicable to RT moulds, but some technology specific guidelines need to be considered.

A.3.1: Resources

The RP machine that was used in this project is a Model 310 3D-printer manufactured by Zcorporation. The material chosen for this project is the Zcorporation ZP131 plaster powder, also known as microstone, and Zcorporation ZB58 binder. Metallic powders for 3DP have been developed especially for RT and RM applications (Levy et al., 2003), but due to cost constraints and logistical constraints ZP131 powder material was selected for this project. All tools were printed hollow with a 5 mm wall thickness to save material and reduce printing time.

Prime™ 20 LV, a low viscosity epoxy resin, is used as infiltration resin to strengthen as-printed/green 3DP parts. The green 3DP parts are not very strong and are very porous and therefore reinforced by infiltration with epoxy resin.

A.3.2: General

Rosochowski & Matuszak (2000) recommends that CAD models of RP tools should include tool related features such as draft angles, shrinkage allowance, split lines, runners and risers and features ensuring alignment of tool sections. These features are the same as mentioned in Section A.2 with the addition of shrinkage allowance. Designers should keep in mind that different RP methods and materials have different shrinkage factors.

Lyons (2006) advocates the use of an infiltration resin that is incompatible with the composite part's resin to ensure no part removal problems. As an example, if an epoxy infiltration resin is used to reinforce the green RP part, it would not be wise to use an epoxy resin for the composite part.

If the thickness of parts dictates the use of cores, but a hollow structure is desirable, green 3DP plaster materials are water soluble and can be dissolved after moulding as performed in a project by Lyons (2006). Printed wax cores can be melted out after moulding, also resulting in a hollow structure.

A.3.3: Mould surface finish

As discussed in Chapter 1, many RP parts have poor surface finish because of the layered manufacturing technique. Most rapid tools accurately replicate the surface qualities of the mould in the part (Rosochowski & Matuszak, 2000). It therefore makes sense to apply effort to ensure good surface qualities in the RT mould, thereby ensuring the same for all the manufactured parts. In the case of the 3DP moulds used in this project, much time was spent polishing the moulds to ensure good surface finish. Various types of surface coatings may also be applied to seal or improve the tool surface.

A.3.4: Build volume considerations

The build volume limitations of the chosen RP machine should be kept in mind, but it is possible to print the mould in sections to be joined at a later stage. The build volume of the Z310 3D-printer used in this project is 203x254x203 mm. If parts have to be printed in sections to mitigate this limitation, some part slicing guidelines should be applied. Hugo (2008) gives part slicing guidelines which he summarized in the following 10 points:

- 1) "Use Design for Assembly (DFA) principles where applicable."
- 2) "Do not cut through critical stress areas."
- 3) "Avoid cutting through thin sections."
- 4) "Add support structures to sections if needed."

- 5) “Add ribs to help prevent deformation.”
- 6) “Add webs to close open geometries to counteract distortion.”
- 7) “Try selecting cutting planes to ensure the least amount of geometrical distortion.”
- 8) “Try selecting cutting planes to facilitate the assembling of sections.”
- 9) “Minimize the number of parts.”
- 10) “Build on a secure base.”

As discussed in Chapter 2, designers of rapid tools should remember to keep the anisotropic nature of RP parts in mind. By carefully selecting the part orientation in the build volume, designers can ensure better accuracy on critical surfaces as well as better strength in required directions. The layered manufacturing principle employed by RP machines results in a stairstepping effect and leads to surface roughness. Some RP machines allow for a reduction in layer thickness, resulting in smoother parts but longer build times. This effect can also be limited by carefully considering the part positioning in the build volume (Hugo, 2008). The staircase effect is greatest on inclined planes. Try to position the part in such a way that long flat surfaces are in the horizontal position. This gives the smoothest surface, but longest build time (Hugo, 2008). The build time is dependent on the number of part layers; therefore the height of the part is critical. It should be clear that in most cases a trade-off is made between surface quality and build speed.

A.3.5: Rapid Tool reinforcement

Besides the infiltration of green RT parts to increase strength, other measures are also advisable. Tools are often printed with a hollow back to save RP material and should be filled with reinforcement like resin mixed with cotton flocks to improve strength. Tooling should still be provided with sufficient wall thickness to prevent distortion during the RP process. Additional reinforcement, like steel backing plates can also be used to increase mould stiffness. Moulds often need to withstand rough handling when difficulties are experienced in composite part removal and this added stiffness may therefore have an important effect on mould lifetime. Rapid tools may even be completely boxed-in with reinforcement structures.

APPENDIX B: RTM-WORX RESULTS

B.1: Resin flow simulations for case study 2 with no channels

The series of figures below indicate the resin distribution for the case study 2 composite part when no resin runners are present. It is clear that the flow is very unbalanced and that poor mould filling will result from this configuration.

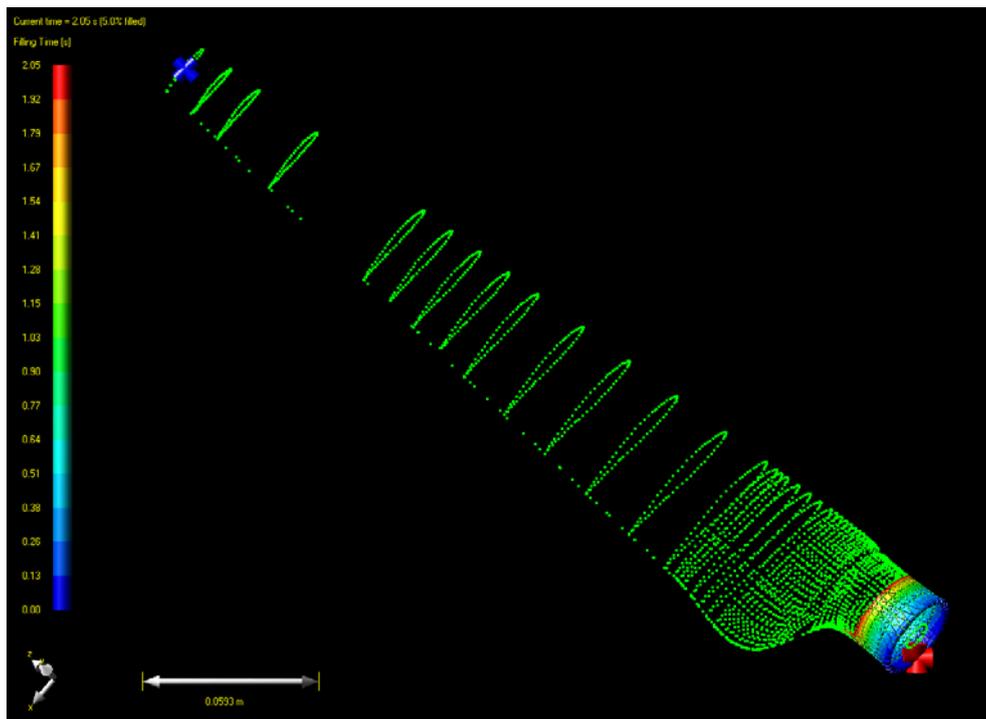


Figure 49: Case study 2 resin distribution for $t = 2$ s

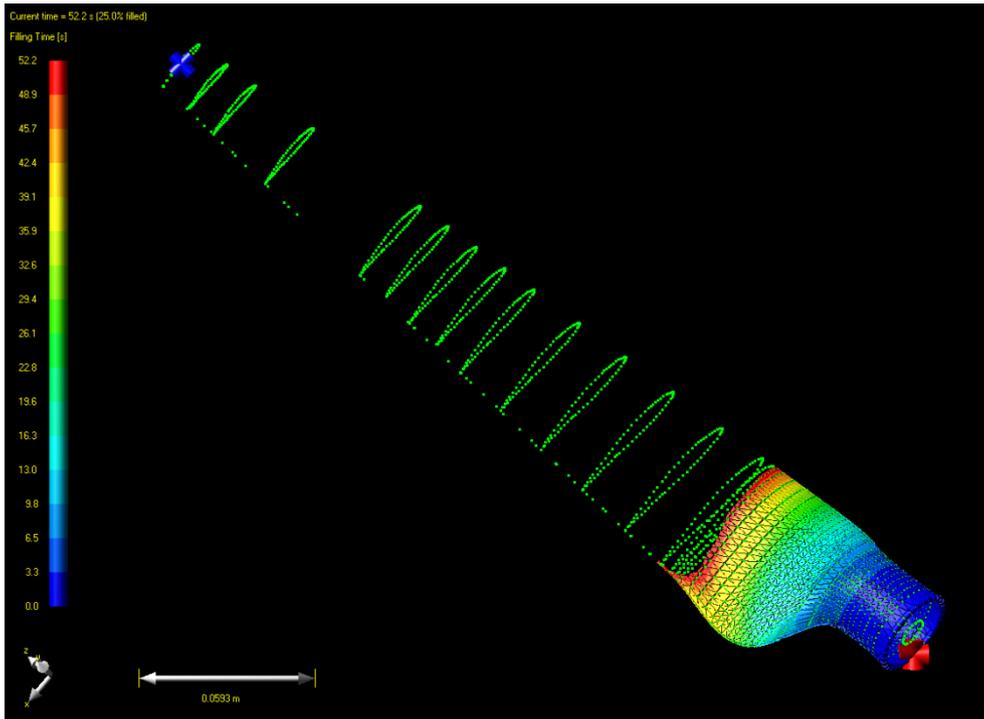


Figure 50: Case study 2 resin distribution for $t = 52$ s

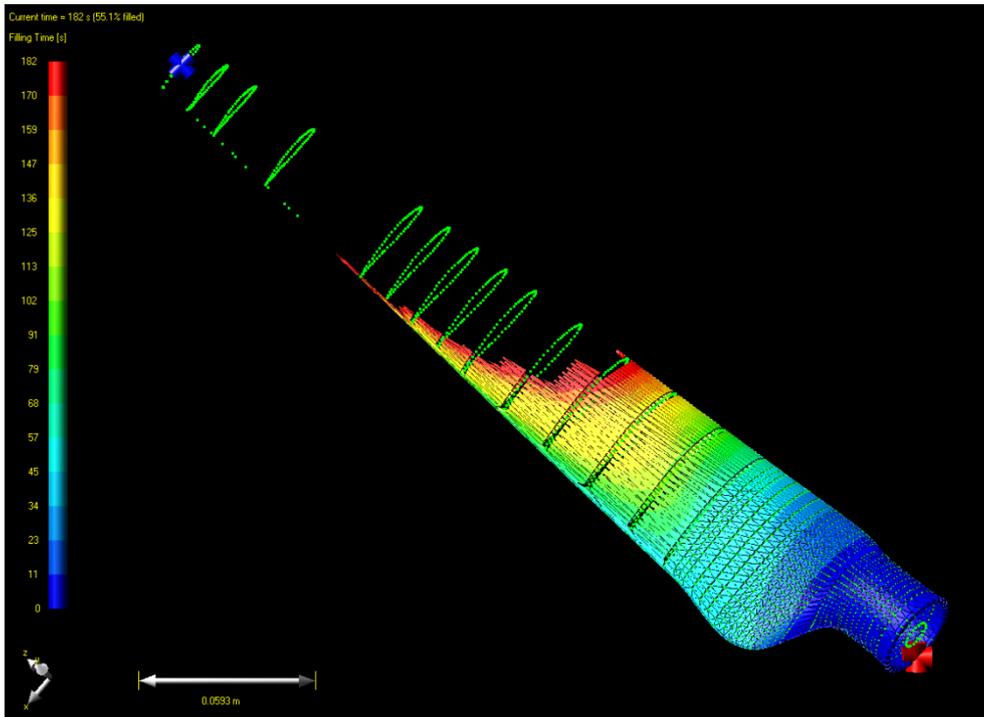


Figure 51: Case study 2 resin distribution for $t = 182$ s

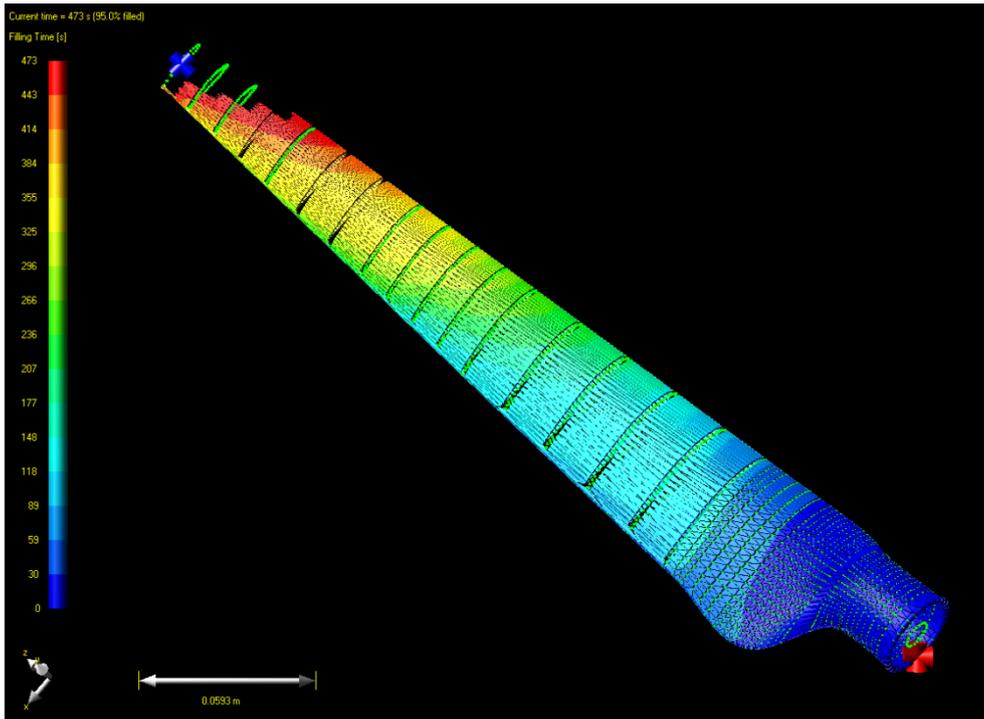


Figure 52: Case study 2 resin distribution for $t = 473$ s

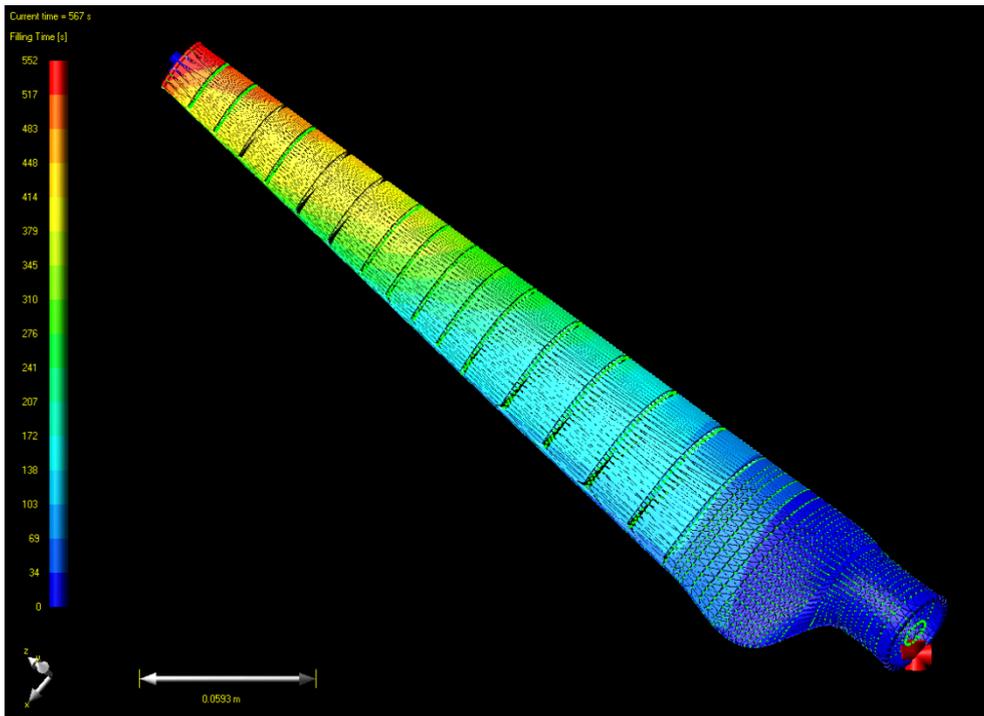


Figure 53: Case study 2 resin distribution for $t = 567$ s

B.2: Resin flow simulations for case study 2 with channels

The series of figures below indicate the resin distribution for the case study 2 composite part when resin runners are present. It is clear that the flow is reasonably balanced and that good mould filling should result from this configuration.

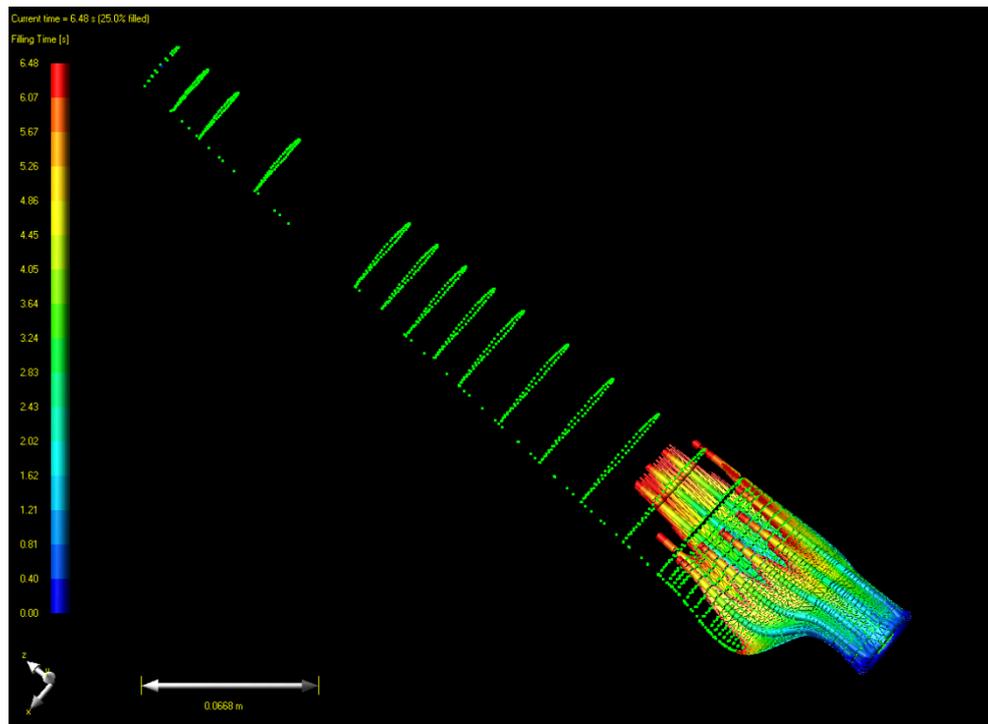


Figure 54: Case study 2 resin distribution for $t = 6$ s

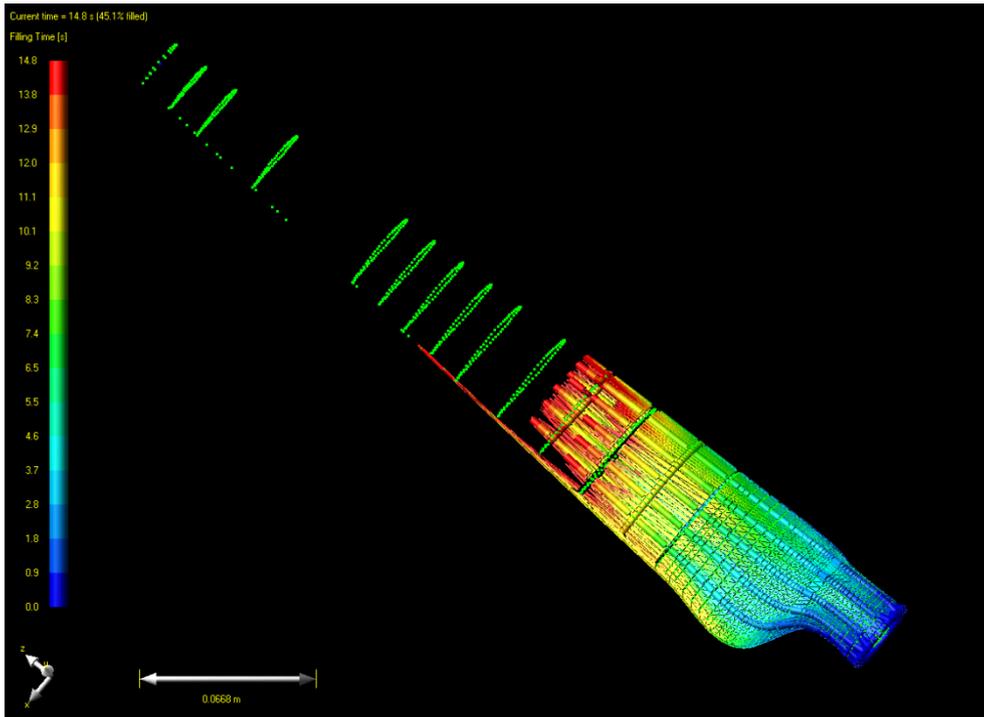


Figure 55: Case study 2 resin distribution for $t = 15$ s

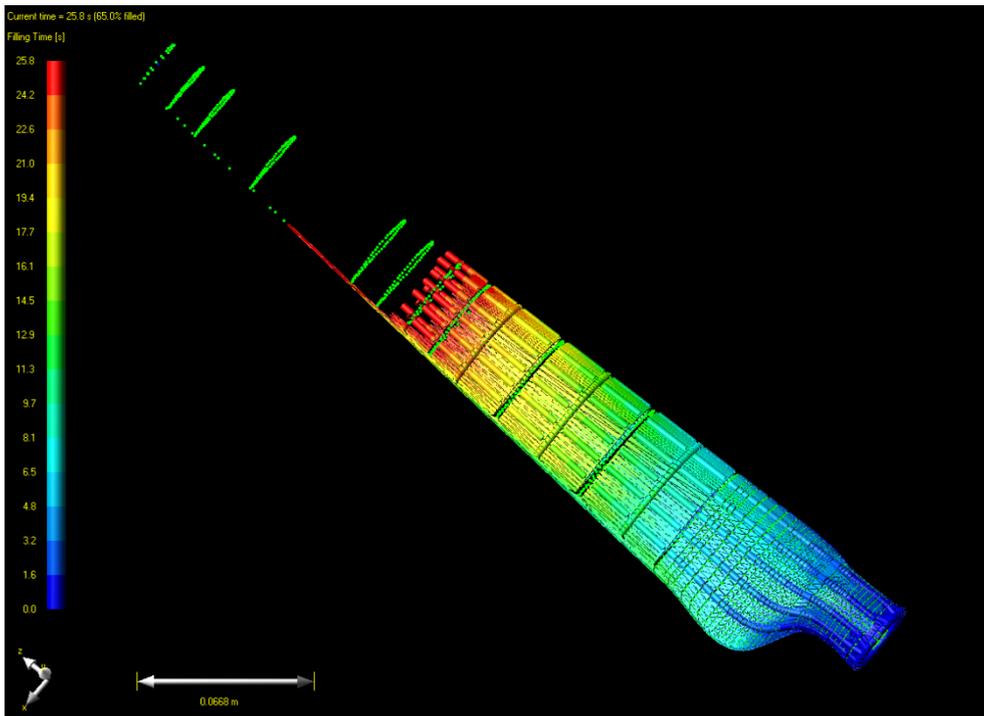


Figure 56: Case study 2 resin distribution for $t = 26$ s

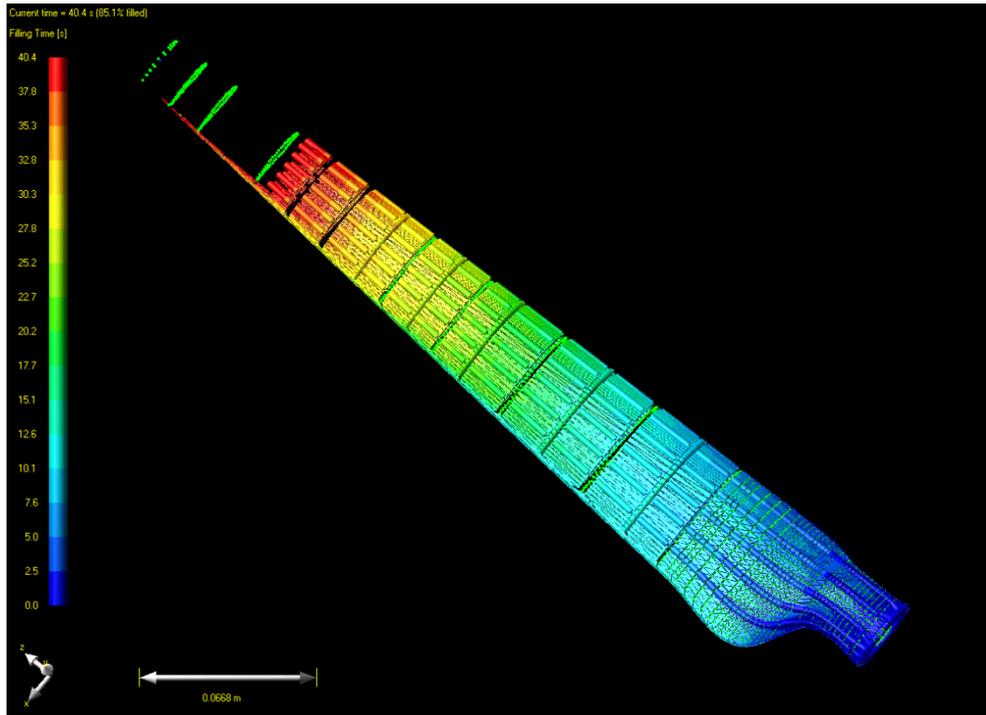


Figure 57: Case study 2 resin distribution for $t = 40$ s

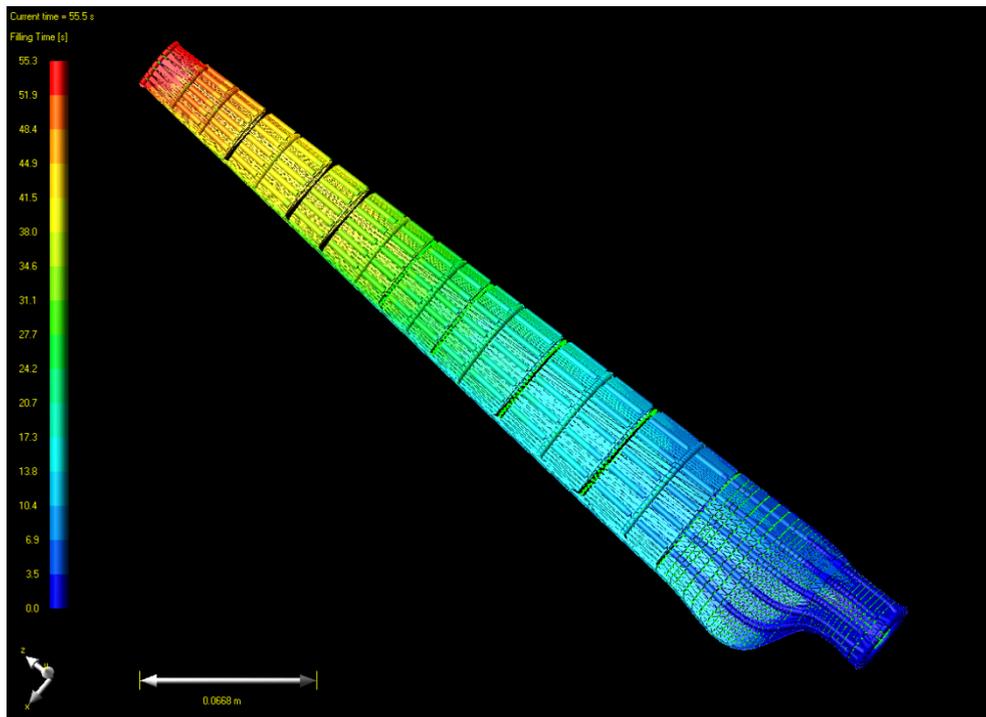


Figure 58: Case study 2 resin distribution for $t = 56$ s

APPENDIX C: GEOMETRICAL DATA

This section provides additional geometrical data for the case study 2 mould and parts. Please refer to Chapter 4 for discussion of these results.

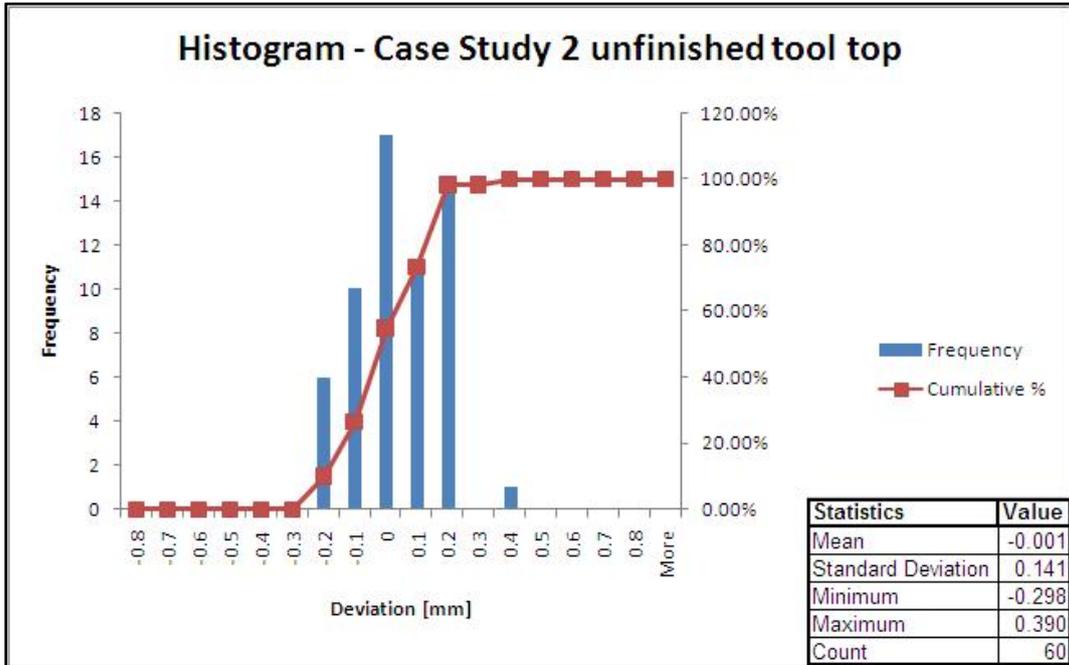


Figure 59: Histogram with statistics for case study 2 unfinished tool top

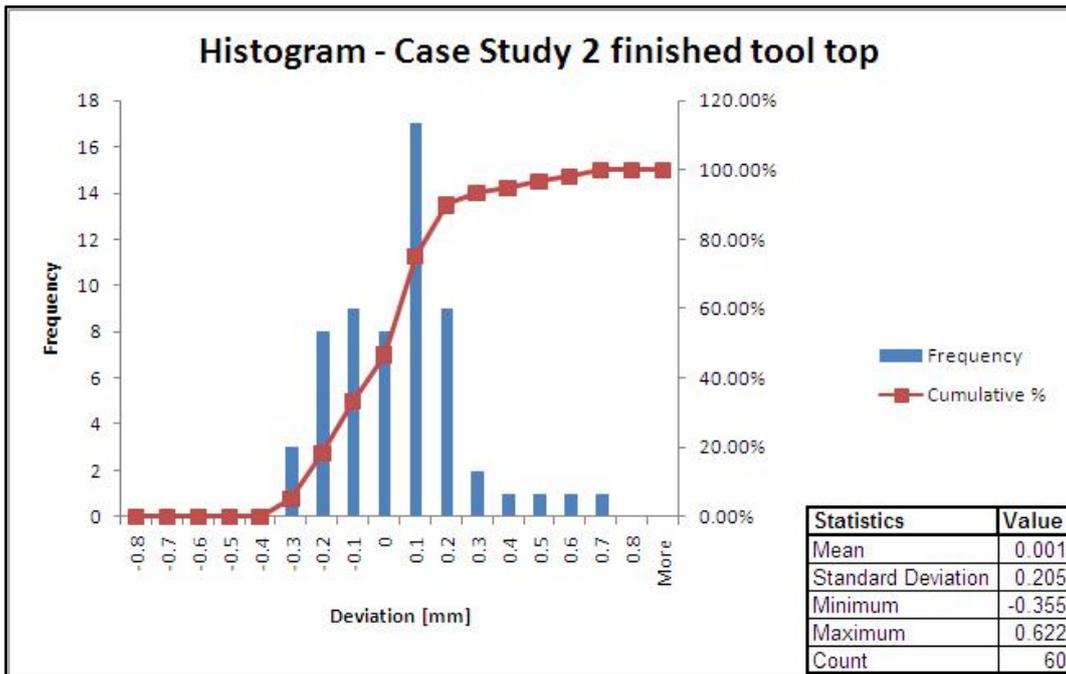


Figure 60: Histogram with statistics for case study 2 finished tool top

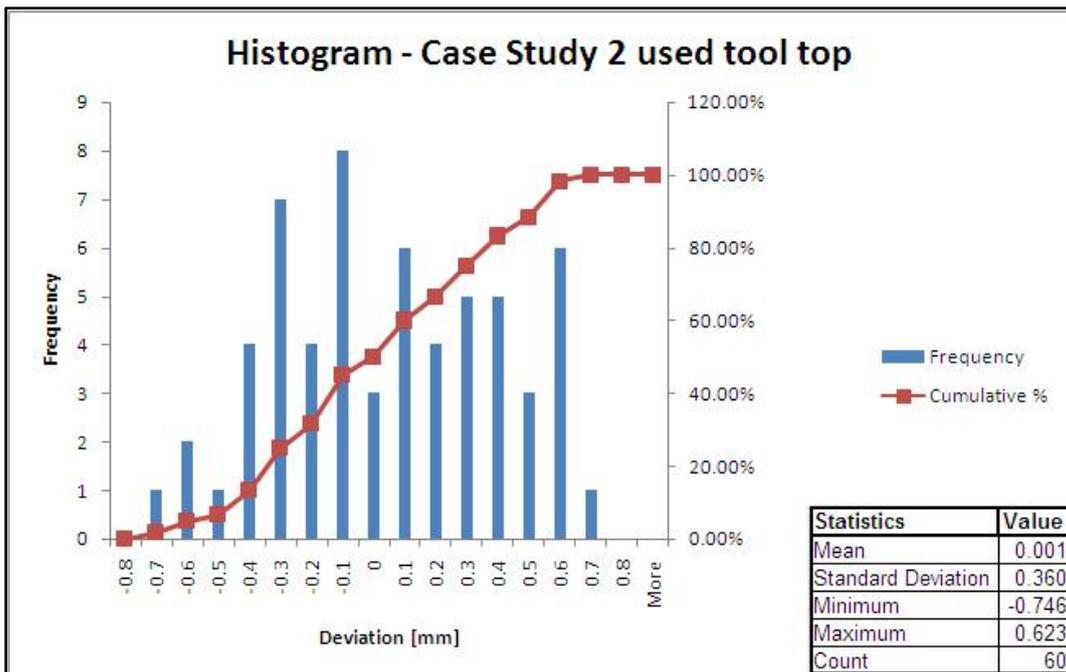


Figure 61: Histogram with statistics for case study 2 used tool top

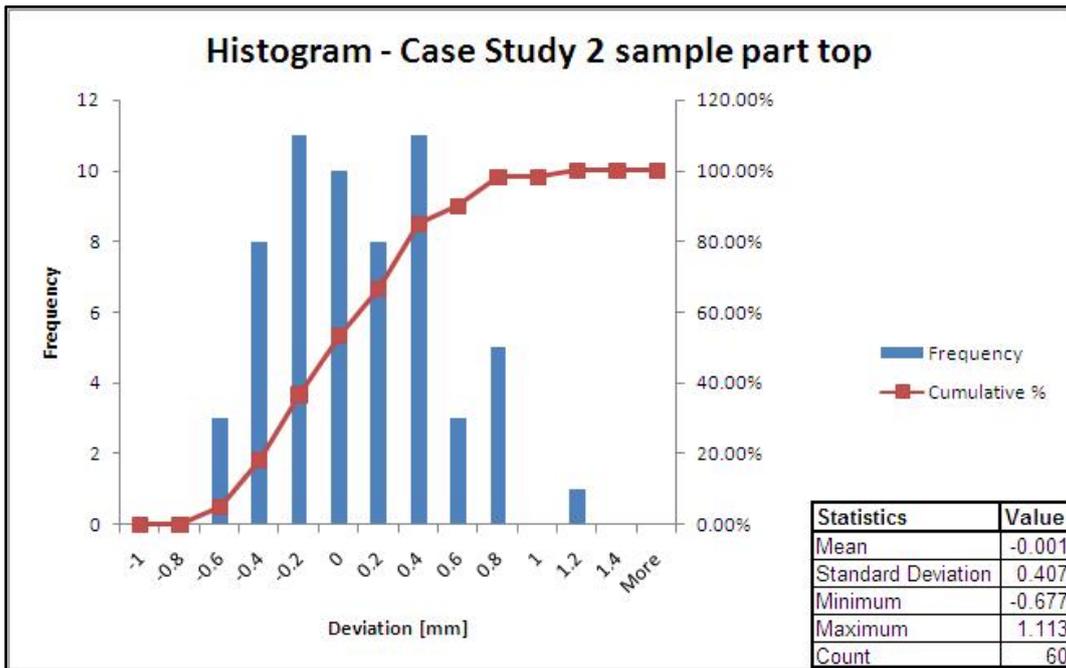


Figure 62: Histogram with statistics for case study 2 sample part 1 top

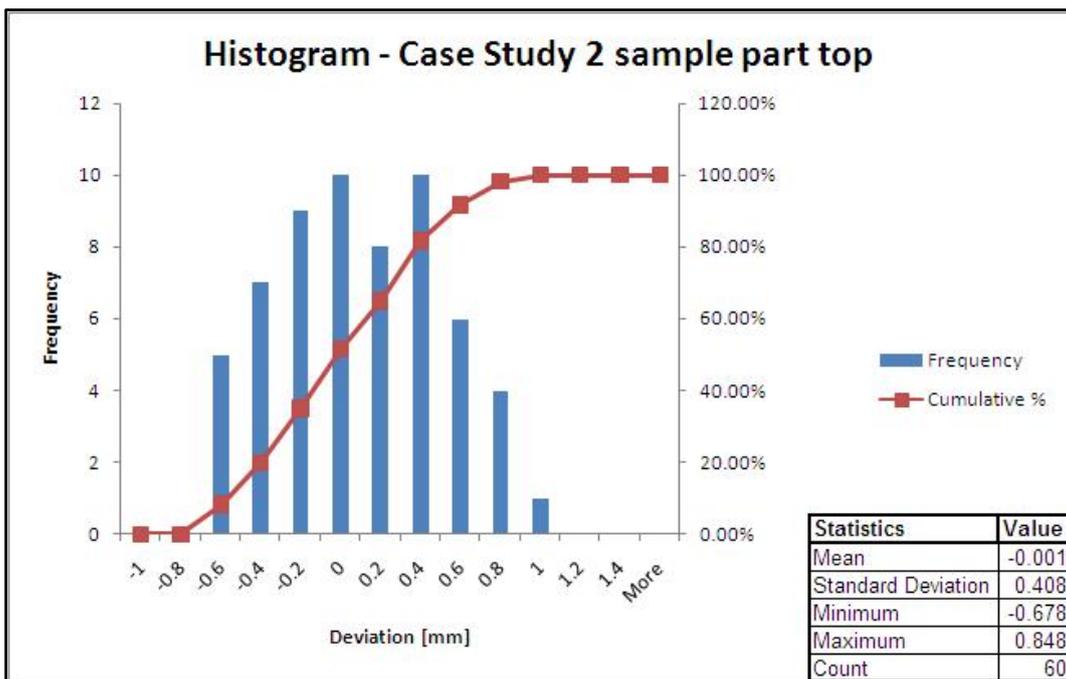


Figure 63: Histogram with statistics for case study 2 sample part 2 top

APPENDIX D: COST MODELS

D.1: Material costs and manufacturing times

Table 15: Updated material and other prices used in cost models

Direct materials	Unit	Cost/Unit
Matrix 90 epoxy gel coat	kg	R 199.00
Polyester gel coat	kg	R 47.00
Biaxial 800 g/m ² glass fibre	m ²	R 31.20
425 g/m ² woven roving glass fibre	m ²	R 24.21
195 g/m ² plain weave glass fibre	m ²	R 33.40
450 chopped strand mat glass fibre	m ²	R 24.77
Interglass 92125 twill weave glass fibre	m ²	R 49.00
Epoxy resin Sicomin SR 8500 / SD 8603	kg	R 109.19
901 polyester resin	kg	R 30.67
Microballoons - Aerocell 40	kg	R 59.45
Cotton flocks	kg	R 42.00
Adhesive Probond 333	kg	R 255.58
PB 170 liquid epoxy foam	kg	R 336.74
Ivory 340 5LV epoxy resin for infusion	kg	R 206.18
Vacuum consumables & other		
WL 7400 vacuum bag	m ²	R 15.60
P3 release film	m ²	R 12.30
Peeltex RT peelply	m ²	R 19.90
AT140 W tacky tape (22.5m)	roll	R 63.00
Partall mould release wax	340 mℓ	R 133.00
Acetone solvent	litre	R 14.85
Latex gloves (box of 100)	box	R 68.00
12mm resin pipe	m	R 6.00
Greenflow HPL	m ²	R 41.00
3M 77 spray adhesive	400 mℓ	R 175.00
Vacuum pump with reservoir	100 ℓ	R 30 000.00

Table 15: Costs continued

Labour and machining rates		
General labour	h	R 250.00
Pattern maker	h	R 350.00
CNC operator cost	h	R 250.00
CNC machining	h	R 175.00
Rent for industrial floor space in Stellenbosch p/m	m ²	R 40.00
Mould materials		
Mild steel 3mm backing plate	m ²	R 265.70
ZP131 RP material	kg	R 700.00
ZB58 RP binder	kg	R 1 842.00
Automotive primêr	ℓ	R 67.00
Spraypaint	200 mℓ	R 32.00

Table 16: Mould manufacture times for case study 1

<u>Manufacturing step</u>	<u>Measured time [min]</u>
3D Printing	590
Bonding of sections	0
Resin infiltration	20
First sanding	45
Priming coat	15
Second sanding	30
Final paint	10
Filling with resin	30
Manufacture of plate	15
Fitment of plate	10
Total [h]	12.75

Table 17: Mould manufacture times for case study 2

<u>Manufacturing step</u>	<u>Measured time [min]</u>
3D Printing	291
Bonding of sections	20
Resin infiltration	20
First sanding	60
Priming coat	20
Second sanding	30
Final paint	15
Filling with resin	15
Manufacture of plate	15
Fitment of plate	15
Total [h]	8.35

Table 18: Actual direct cost for case study 2 part

<u>Component</u>	<u>Amount</u>	<u>Price</u>
Wax	5 g	R 0.80
Fibre	0.1 m ²	R 3.30
Spray adhesive	5 g	R 2.20
Resin	100 g	R 20.60
Vacuum bag	0.24 m ²	R 3.70
Tacky tape	2 m	R 5.60
Silicone seal	20 mℓ	R 0.90
Core	1	R 500.00
Resin pipe	0.8 m	R 4.80
Labour	1h11min	R 296.00
Total		R 837.90

Table 19: Manufacturing times and costs for aluminium moulds

<u>Step</u>	<u>Time [min]</u>
bottom rough cut	155
bottom fine cut	193
top rough cut	176
top fine cut	247
polishing	30
setup time	30
total	831
Cost [R]	5886.25
Material cost [R]	1360.80
Total Cost [R]	7247.05
Lead time [h]	13.85

D.2: Cost estimation model example calculation for case study 2

An early cost estimation model for parts produced with rapid prototyped RTM moulds

Before the costs can be determined the designer has to determine the following:

- The type of sealing: vacuum or clamped;
- One sided mould (vacuum infusion) or closed mould (RTM/VARTM).

Applicable constants

$P_i := 75000 \cdot \text{Pa}$	Injection pressure [kPa]
$A_P := 0.026 \cdot \text{m}^2$	Surface area of part [m^2]
$S_P := 0.7 \cdot \text{m}$	Perimeter of part [m]
$G_1 := 0.04 \cdot \text{m}^2$	Geometrical constant for rectangular shape
$G_2 := 0.01 \cdot \text{m}$	Geometrical constant for a dome like shape
$S_M := 1.04 \cdot \text{m}$	Average perimeter of the mould [m]
$A_F := 0.026 \cdot \text{m}^2$	Total outside surface area of master model [m^2]
$t_P := 1 \cdot \text{mm}$	Maximum thickness of part [mm]
$r_{\text{cure}} := 0.06$	Curing rate per layer in XY plane of 3D printer
$t_{\text{delay}} := 0.55$	Delay time between printing of RP layers [s]
$h := 0 \cdot \text{m}$	Height of tophat section - refer to figure 4.4 Veldsman (1995) [m]
$L_{\text{Tophat}} := 0.35 \cdot \text{m}$	Length of tophat section [m]
$b := 0.05 \cdot \text{m}$	Width of tophat section [m]
$S_{PO} := 1.04 \cdot \text{m}$	Outside perimeter of mould [m]
$D := 0 \cdot \text{m}$	Diameter of dome [m]
$n_R := 2$	Total number of layers reinforcement to be placed for the part
$\mu := 2 \cdot \text{Pa} \cdot \text{s}$	Viscosity of resin [kg/m.s]
$v_F := 0.4$	Fibre volume fraction of preform
$P_0 := 75000 \cdot \text{Pa}$	Gauge pressure at resin inlet port [Pa]
$r_{\text{max}} := 0.35 \cdot \text{m}$	Farthest resin path from inlet port [m]
$R_0 := 0.012 \cdot \text{m}$	Inlet port radius [m]
$P_{\text{core}} := 500$	Cost of part core [R]

$n_{\text{clamp}} := 6$	Number of manual clamps
$P_{\text{labour}} := 250$	Labour cost per hour for general work [R]
$N_{\text{p}} := 40$	Maximum number of parts per mould
$n_{\text{p}} := 8$	Number of parts to be manufactured per day - max 8 with unheated mould
$V_{\text{mould}} := 1190$	Printed mould volume [cm ³]
$V_{\text{resin}} := 1430$	Resin used to fill mould cavity [cm ³]
$P_{\text{resin}} := 0.11$	Cost of Sicomin epoxy resin used for filling of mould [R/cm ³]
$P_{\text{powder}} := 700.024$	Powder cost (microstone ZP131) [R/kg]
$P_{\text{binder}} := 1842.17$	Binder cost (ZB58) [R/kg]
$P_{\text{steel}} := 265.70$	Cost of 3mm mild steel backing plate [R/m ²]
$P_{\text{primer}} := 24.60$	Cost of MS primer used to create smooth mould surface (2 layers) [R/m ²]
$P_{\text{paint}} := 36$	Cost of spraypaint used for final mould surface finish (2 layers) [R/m ²]
$P_{\text{infiltrate}} := 206.18$	Cost of LV epoxy resin used for filling of mould [R/kg]
$T_{\text{print}} := 291$	Printing time [min]
$P_{\text{Overheads}} := 0.5$	Overhead cost on top of RP material cost - GCC
$P_{\text{Markup}} := 0.6$	Markup on cost of RP parts - GCC
$h_{\text{total}} := 0.06\text{-m}$	Total height of mould/ mould halve [m]
$L_{\text{mould}} := 0.410$	Length of designed mould [m]
$W_{\text{mould}} := 0.110$	Width of designed mould [m]
$n_{\text{port}} := 2$	Number of inlet + outlet ports
$T_{\text{stitch}} := 12$	Time allowance if preform is stitched or glued [min].
$n_{\text{corner}} := 0$	Number of sharp corners on tophat section ($\theta < 135^\circ$) - fig 4.4 Veldsman
$T_{\text{clean}} := 55$	Time for machine setup, part removal and cleaning for 3DP part [min]:
$T_{\text{infiltration}} := 20$	Infiltration time for 3DP [min]:
$T_{\text{fill2}} := 1$	RTM-Worx simulation time for resin filling [min]
$N_{\text{sections}} := 2$	Number of sections to bond for RP mould

1. Calculations to be made prior to calculating the costs involved:

Additional area needed for vacuum clamping:

$$A_{v1} := \frac{P_i}{80 \cdot 1000N} \cdot A_p \cdot 1.3 \cdot m^2 \quad (D1)$$

Here A_p is the area of the part (m^2) and P_i is the injection pressure in Pa

For hand operated clamping devices the additional area can be calculated as follows:

$$A_{v2} := S_p \cdot 0.1 \cdot m + G_1 \quad (D2)$$

This model assumes that an additional 100mm around the part perimeter is needed for clamping

Total surface area of mould with applicable extra clamping area:

$$A_T := A_{v1} + A_p \quad A_T = 0.058 m^2 \quad (D3)$$

Average area for printed sections [cm^2]:

$$A_{ave} := \frac{V_{mould} \cdot m}{h_{total} \cdot 100} \quad A_{ave} = 198.333 \quad (D4)$$

Number of 0.1 mm RP layers to be printed:

$$n_{print} := \frac{h_{total}}{0.0001 \cdot m} \quad n_{print} = 600 \quad (D5)$$

Print time for 3DP [min]:

$$T_{print2} := t_{cure} \cdot A_{ave} + t_{delay} \cdot n_{print} \quad T_{print2} = 341.9 \quad (5.1) \quad (D6)$$

2. An early cost estimation model for the RP mould

Material cost:

If vacuum clamping is used, divide the extra area calculated in equation 1 by the part perimeter S_p and add this to L and W. For manually operated clamps add 0.1 m to L and W. The mould is printed hollow from the back with a thickness of 5 mm. Use these values to calculate the volume of the part.

Mass of powder and binder for 3DP [kg]:

$$m_{\text{Powder}} := 0.0013 \cdot V_{\text{mould}} + 0.0331 \quad m_{\text{Powder}} = 1.58 \quad (5.2) \quad (D7)$$

$$m_{\text{Binder}} := 0.0001329 \cdot V_{\text{mould}} + 0.1 \quad m_{\text{Binder}} = 0.258 \quad (5.3) \quad (D8)$$

Mass of resin used for raw part infiltration [kg]:

$$m_{\text{infiltrate}} := 0.0008 \cdot V_{\text{mould}} \quad m_{\text{infiltrate}} = 0.952 \quad (5.4) \quad (D9)$$

Cost and selling price for RP mould [R]:

$$P_{\text{Cost}} := (1 + P_{\text{Overheads}}) \cdot (m_{\text{Powder}} \cdot P_{\text{powder}} + m_{\text{Binder}} \cdot P_{\text{binder}} + m_{\text{infiltrate}} \cdot P_{\text{infiltrate}}) \quad (5.5) \quad (D10)$$

$$P_{\text{Sell}} := P_{\text{Cost}} \cdot (1 + P_{\text{Markup}}) \quad P_{\text{Sell}} = 4.267 \times 10^3 \quad (5.6) \quad (D11)$$

Cost of backing plate [R]:

$$P_{\text{plate}} := P_{\text{steel}} \cdot L_{\text{mould}} \cdot W_{\text{mould}} \quad P_{\text{plate}} = 11.983 \quad (5.7) \quad (D12)$$

Cost of filling back of mould with resin [R]:

$$P_{\text{fill}} := P_{\text{resin}} \cdot V_{\text{resin}} \quad P_{\text{fill}} = 157.3 \quad (5.8) \quad (D13)$$

Cost of priming coat [R]:

$$P_{\text{priming}} := P_{\text{primer}} \cdot \frac{1}{2} \cdot A_f \quad P_{\text{priming}} = 0.64 \quad (5.9) \quad (D14)$$

Cost of paint [R]:

$$P_{\text{painting}} := P_{\text{paint}} \cdot \frac{1}{2} \cdot A_f \quad P_{\text{painting}} = 0.936 \quad (5.10) \quad (D15)$$

$$P_{\text{mould_material}} := P_{\text{Sell}} + 2P_{\text{plate}} + P_{\text{fill}} + P_{\text{priming}} + P_{\text{painting}} \quad (D16)$$

$$P_{\text{mould_material}} = 4.45 \times 10^3$$

Labour cost:

Labour to bond sections if mould was printed in more than 1 part - add 10 minutes per section:

$$T_{\text{bond}} := 10 \cdot N_{\text{sections}} \quad (5.11) \quad (\text{D17})$$

Labour for finishing the mould (minutes):

$$T_f := 32 \cdot 60 \cdot A_f \frac{1}{2} \quad T_f = 49.92 \quad (5.12) \quad (\text{D18})$$

Labour for priming the mould (minutes):

$$T_{\text{prime}} := 6.3 \cdot 60 \cdot A_f \frac{1}{2} \quad T_{\text{prime}} = 9.828 \quad (\text{D19})$$

Labour for painting the mould (minutes):

$$T_{\text{paint}} := 4.2 \cdot 60 \cdot A_f \frac{1}{2} \quad T_{\text{paint}} = 6.552 \quad (\text{D20})$$

Labour for filling the mould with resin (minutes):

$$n_{\text{resin}} := \text{ceil} \left(\frac{h_{\text{total}} - 0.005 \cdot m}{0.03 \cdot m} \right) \quad n_{\text{resin}} = 2 \quad (5.13) \quad (\text{D21})$$

$$T_{\text{resin}} := n_{\text{resin}} \cdot 10 \quad T_{\text{resin}} = 20 \quad (5.14) \quad (\text{D22})$$

Labour for manufacturing and fitting backing plate (minutes):

$$T_{\text{plate}} := 25 \quad (5.15) \quad (\text{D23})$$

Total labour time, excluding printing, of the mould (hours):

$$T_{\text{total}} := \frac{T_{\text{bond}} + T_f + T_{\text{prime}} + T_{\text{paint}} + T_{\text{resin}} + T_{\text{plate}}}{60} \quad T_{\text{total}} = 2.188 \quad (\text{D24})$$

$$P_M := T_{\text{total}} \cdot P_{\text{labour}} + P_{\text{mould_material}} \quad P_M = 4.997 \times 10^3 \quad (\text{D25})$$

Total lead time for complete RP mould (hours):

$$T_{\text{lead}} := \frac{T_{\text{print2}} + T_{\text{clean}} + T_{\text{infiltration}} + T_{\text{total}}}{60} \quad T_{\text{lead}} = 6.985 \quad (\text{D26})$$

3. A cost estimation model for a part produced with RTM using low viscosity epoxy resin

Material cost:

Model 1: Consumer goods with low fibre volume fraction of approximately 20% incorporating gelcoat time:

$$M_{P1} := 440 \cdot t_P \cdot 1000 \cdot A_P \cdot \frac{1}{m^3} \cdot 1.1 + 50 \cdot A_P \cdot \frac{1}{m^2} \quad M_{P1} = 13.884 \quad (D27)$$

Model 2: Parts requiring higher fibre volume fraction of approximately 40%:

$$M_{P2} := 410 \cdot t_P \cdot 1000 \cdot A_P \cdot \frac{1}{m^3} \cdot 1.1 + 50 \cdot A_P \cdot \frac{1}{m^2} \quad M_{P2} = 13.026 \quad (D28)$$

Model 3: Parts requiring a higher stiffness to weight ratio:

$$n_C := \text{floor} \left(\frac{t_P}{3 \cdot \text{mm}} \right) \quad n_C = 0 \quad (D29)$$

$$M_{P3} := \left[440 \left(t_P \cdot 1000 \cdot \frac{1}{m} - n_C \cdot 2 \right) \cdot A_P \cdot \frac{1}{m^2} + n_C \cdot 20 \right] \cdot 1.1 + 50 \cdot A_P \cdot \frac{1}{m^2} \quad M_{P3} = 13.884 \quad (D30)$$

Labour cost

Labour to clean mould between part mouldings [min]:

$$T_{\text{clean2}} := 125 \cdot \frac{1}{m^2} \cdot A_f \quad T_{\text{clean2}} = 3.25 \quad (D31)$$

Labour to polish mould with release wax [min]

$$T_{\text{wax}} := 90 \cdot \frac{1}{m^2} \cdot A_f \quad T_{\text{wax}} = 2.34 \quad (D32)$$

Labour to place inlet and outlet port piping [min]

$$T_{\text{port}} := 2 \cdot n_{\text{port}} \quad T_{\text{port}} = 4 \quad (5.16) \quad (D33)$$

Time for cutting and placing reinforcement for flat plate (T_{RLP}) and dome shape (T_{RLD}) [minutes] incorporating gelcoat time. Use linear interpolation for shapes in between. T_{stitch} is an allowance made for the stitching of fibre preforms where applicable. Add 10 seconds for inserts:

If $(A_P - 1) > 0$

$$K_4 := \left(A_P \cdot \frac{1}{m^2} - 1 \right) \quad \text{else} \quad (D34)$$

$$K_5 := 0 \quad (D35)$$

$$T_{RLP} := 1 + \left(0.5 \cdot S_P \cdot \frac{1}{m} + 0.5 + 0.25 \cdot K_5 \right) \cdot n_R + 30 \cdot A_P \cdot \frac{1}{m^2} \quad T_{RLP} = 3.48 \quad (5.17) \quad (D36)$$

$$T_{RLD} := 1 + \left(8.48 \cdot D \cdot \frac{1}{m} + 0.75 + 0.375 \cdot K_5 \right) \cdot n_R + 30 \cdot A_P \cdot \frac{1}{m^2} \quad T_{RLD} = 3.28 \quad (D37)$$

$$T_{RL} := 0 \cdot T_{RLD} + 1 \cdot T_{RLP} + T_{stitch} \quad T_{RL} = 15.48 \quad (D38)$$

Time to cut and place peelply layer assuming a square cut [min]:

$$T_{peelply} := 1 + \left(0.5 \cdot S_P \cdot \frac{1}{m} + 0.5 + 0.25 \cdot K_5 \right) \quad T_{peelply} = 1.85 \quad (5.18) \quad (D39)$$

Time to cut and place Greenflow™ layer [min]:

$$T_{greenflow} := 1 + \left(0.5 \cdot S_P \cdot \frac{1}{m} + 0.5 + 0.25 \cdot K_5 \right) \quad T_{greenflow} = 1.85 \quad (D40)$$

Time to cut, place and seal vacuum bag around mould assembly, assuming an additional 100 mm is added to length and width of mould [min]:

$$T_{bag_place} := 1 + \left[0.5 \cdot \left(S_P \cdot \frac{1}{m} + 0.2 \right) + 0.5 + 0.25 \cdot K_5 \right] \quad T_{bag_place} = 1.95 \quad (5.19) \quad (D41)$$

Please refer to figure 4.4 (Veldsman-1995).

If $h > 50\text{mm}$:

$$K_1 := 2 \cdot \left[10 + \left(60 \cdot h \cdot L_{Tophat} \right) \cdot \frac{1}{m^2} \right] \quad K_1 = 20 \quad (D42)$$

If $b > 50\text{mm}$:

$$K_2 := 10 + \left(60 \cdot b \cdot L_{Tophat} \right) \cdot \frac{1}{m^2} \quad K_2 = 11.05 \quad (D43)$$

If h and $b > 50\text{mm}$:

$$K_3 := K_1 + K_2 \quad K_3 = 31.05 \quad (D44)$$

Time to seal bag with tacky tape [min]

$$T_{tacky_tape} := \left[5 + 15 \cdot \left(S_P \cdot \frac{1}{m} + 0.2 \right) + K_3 + 2 \cdot \left(S_P \cdot \frac{1}{m} + 0.2 \right) \right] \cdot 0.14 \quad T_{tacky_tape} = 7.189 \quad (5.20) \quad (D45)$$

$$T_{bag} := T_{bag_place} + T_{tacky_tape} \quad T_{bag} = 9.139 \quad (D46)$$

Time to prepare resin for infusion [min]:

$$T_{resin_prep} := 3.6 \quad (5.21) \quad (D47)$$

Mould filling time for radial flow (t_{fill_R}) and channel flow (t_{fill_C}) and total time (T_{fill}) [minutes]:

$$K_6 := 5.45 \cdot (1 - v_F) \quad (\text{D48})$$

$$K_7 := \frac{24100 \cdot P_0}{r_{\text{max}} \cdot \mu} \quad (\text{D49})$$

$$K_{\text{permeability}} := \frac{40 \cdot e^{K_6}}{1.013 \cdot 10^{12} + K_7 \cdot m \cdot s} \quad (\text{D50})$$

$$M := \frac{\mu \cdot (1 - v_F) \cdot R_0^2}{4 \cdot K_{\text{permeability}} \cdot P_0 \cdot m^2} \quad M = 0.556 \text{ s} \quad (\text{D51})$$

$$t_{\text{fill}_R} := M \cdot \left(\frac{r_{\text{max}}}{R_0} \right)^2 \cdot \left[2 \cdot \ln \left(\frac{r_{\text{max}}}{R_0} \right) + \left(\frac{R_0}{r_{\text{max}}} \right)^2 - 1 \right] \quad t_{\text{fill}_R} = 2.717 \times 10^3 \text{ s} \quad (\text{D52})$$

$$t_{\text{fill}_C} := 2 \cdot M \cdot \left[\left(\frac{r_{\text{max}}}{R_0} \right) - 1 \right]^2 \quad t_{\text{fill}_C} = 881.933 \text{ s} \quad (\text{D53})$$

$$\alpha := 0.58$$

$$T_{\text{fill}} := \frac{\alpha \cdot t_{\text{fill}_R} + (1 - \alpha) \cdot t_{\text{fill}_C}}{60 \cdot s} \quad T_{\text{fill}} = 32.443 \quad (\text{D54})$$

Note: Rather use $T_{\text{fill}2}$ as predicted with RTM-Worx, especially as the core has channels

The geometry constant α can be determined in the following way with reference to figure 4.5 Veldsman (1995):

a) The location of the farthest vent from the inlet port P is identified (V_{max}) and a line is drawn between P and V_{max} (line Q in fig 4.5). A line perpendicular to line Q is then drawn (line g-g').

b) Tangentials to the perimeter are drawn, parallel to line Q and between lines g-g' and V_{max} (Lines d1, d2, d3). Lines are drawn from P to the tangential points nearest to P on the left- and right-hand side of P (d1 and d2).

c) A semicircle of radius R_{max} (P to V_{max}) with its origin at P is drawn and the points of intersection between this and lines Pd1 and Pd2 are noted (R1 and R2). The parameter α is the ratio of the area of the part bounded by P, d1, V_{max} , and d2 (hashed area in figure 4.5) and the area of the circle segment bounded by PR1R2.

$$\alpha = \text{Area}(Pd_1V_{\text{max}}d_2) / \text{Area}(PR_1R_2) \quad (\text{D55})$$

Mould opening, closing and release times [minutes]:

$$T_{\text{occr}} := 10 + 0.34 \cdot n_{\text{clamp}} + 40 \cdot A_P \cdot \frac{1}{m} \quad T_{\text{occr}} = 13.08 \quad (\text{D56})$$

Part trimming time [minutes]:

$$T_{\text{trim}} := 2 + 1.5 \cdot S_P \cdot \frac{1}{m} \quad T_{\text{trim}} = 3.05 \quad (\text{D57})$$

Total labour time [hour]:

$$T_{L2.1} := \frac{T_{\text{clean2}} + T_{\text{wax}} + T_{\text{port}} + T_{\text{RL}}}{60}$$

$$T_{L2.2} := \frac{T_{\text{bag}} + T_{\text{resin_prep}} + T_{\text{fill2}} + T_{\text{occr}} + T_{\text{trim}}}{60}$$

$$T_{L2} := T_{L2.1} + T_{L2.2} \quad T_{L2} = 0.916 \quad (\text{D58})$$

The cost of the machinery and floor space used:

a) The cost due to the vacuum pump over 5 years using a purchase price of R30000

$$C_1 := 13.65 \quad (\text{D59})$$

b) Cost due to capital input into the mould:

$$n_M := 1 \quad \text{Number of moulds drawn from master model} \quad (\text{D60})$$

$$N_1 := \frac{N_P}{n_P \cdot 20} \quad \text{Number of months over which capital is to be reclaimed} \quad (\text{D61})$$

$$A_{\text{cost}} := (P_M) \cdot \frac{0.2252 \cdot 1.2252^{N_1}}{1.2252^{N_1} - 1} \quad \text{Cost of mould per month to be recovered} \quad (\text{D62})$$

$$C_2 := \frac{A_{\text{cost}}}{n_P \cdot 20} \quad \text{Capital cost per part} \quad C_2 = 142.062 \quad (\text{D63})$$

c) Cost due to floorspace used using average rent cost of R40/m² for industrial property in Stellenbosch according to Louis Boje - Seef (2008):

$$C_3 := \frac{8.5 + 2 \cdot A_T \cdot \frac{1}{m^2}}{20 \cdot n_P} \cdot 40 \quad C_3 = 2.154 \quad (\text{D64})$$

Total cost per part:

$$C_P := M_{P2} + P_{\text{core}} + T_{L2} \cdot P_{\text{labour}} + C_1 + C_2 + C_3 \quad C_P = 899.805 \quad (5.22) \quad (\text{D65})$$