



**UNIVERSITI PUTRA MALAYSIA**

**NUMERICAL INVESTIGATION OF FIBRE ORIENTATION IN  
SHORT GLASS FIBRE REINFORCED INJECTION-MOULDED  
THERMOPLASTIC COMPOSITES**

**EDI SYAMS ZAINUDIN**

**FK 2002 50**

**NUMERICAL INVESTIGATION OF FIBRE ORIENTATION IN  
SHORT GLASS FIBRE REINFORCED INJECTION-MOULDED  
THERMOPLASTIC COMPOSITES**

**By**

**EDI SYAMS ZAINUDIN**

**Thesis Submitted to the School of Graduate Studies, Universiti Putra  
Malaysia, in Fulfilment of Requirement for the  
Degree of Master of Science**

**July 2002**



To My Family



Abstract of thesis presented to the senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science.

**NUMERICAL INVESTIGATION OF FIBRE ORIENTATION IN  
SHORT GLASS FIBRE REINFORCED INJECTION-MOULDED  
THERMOPLASTIC COMPOSITES**

**By**

**EDI SYAMS ZAINUDIN**

**July 2002**

**Chairman: Assoc. Prof. Ir. Dr. Mohd. Sapuan Salit**

The aim of this simulation work is to carry out a comparative study of the fibre orientation distribution (FOD) in the short glass fibre reinforced injection moulded thermoplastic (S<sub>g</sub>FRIMT) composites. The objective of this research is to use a numerical method to investigate the effect of two significant parameters namely, speed of injection and thickness of specimen, on the FOD of the S<sub>g</sub>FRIMT composites. The numerical simulation is conducted by Moldflow Plastics Insight (MPI) software. MPI software is used to investigate the flow behaviour and to examine the effects of processing conditions on the mouldings. Effects of the thickness of the specimen and injection speed are considered since they have great influence on the mechanical properties of the products.

The effect of the injection speed on the FOD is not significant in the thicker plaque. The difference of FOD between the 2 mm and 4 mm plaques has been reported and it was observed that thinner plaque received more aligned fibres at the flow direction due to higher shearing flow generated compared to the thicker one.



The fibre orientation is observed for variations from the skin to the core. In the skin the fibres are highly aligned in the flow direction, whereas in the core the fibres are mainly aligned in the direction transverse to the flow. The more the short fibres are aligned in the moulded parts the better the mechanical behaviour is. Higher injection speeds influence the fibres so as to align along the flow direction but decreases from the skin to the middle/core plane.

The overall result of executing the MPI program over the published results gives a full agreement upon the FOD in S<sub>g</sub>FRIMT composites. The simulated results also agree with other published numerical works. These verify the use of MPI simulation method.



Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains.

**PENYELIDIKAN BERANGKA BAGI PENGHALAAN GENTIAN  
TERHADAP KOMPOSIT PLASTIK HABA PENGACUAN SUNTIKAN  
BERTETULANG GENTIAN KACA PENDEK**

Oleh

**EDI SYAMS ZAINUDIN**

**Julai 2002**

**Pengerusi: Prof. Madya Ir. Dr. Mohd Sapuan Salit**

**Fakulti: Kejuruteraan**

Matlamat penyelidikan penyelakuan ini adalah untuk membuat kajian perbandingan terhadap taburan penghalaan gentian (FOD) di dalam komposit plastik haba pengacuan suntikan bertetulang gentian kaca pendek ( $S_g$ FRIMT). Objektif kajian ini juga untuk menggunakan kaedah penyelakuan berangka bagi mengkaji kesan dua parameter utama iaitu, kelajuan penyuntikan dan ketebalan spesimen terhadap FOD bagi komposit  $S_g$ FRIMT ini. Penyelakuan berangka ini diselenggarakan oleh sebuah pengaturcaraan komersil iaitu Pengaturcaraan Moldflow Plastics Insight (MPI). Aturcara MPI ini digunakan untuk mengkaji kesan keadaan-keadaan pemprosesan terhadap pengacuan yang dihasilkan. Kesan-kesan ketebalan spesimen dan kelajuan penyuntikan diambilkira kerana mereka mempunyai pengaruh kuat dalam menentukan sifat-sifat mekanik sesuatu produk yang dihasilkan.

Didapati kesan kelajuan penyuntikan ke atas FOD adalah tidak begitu ketara terhadap plak yang lebih tebal. Perbezaan FOD dia antara kedua-dua cakera, 2 mm dan 4 mm telah dilaporkan dan didapati, cakera yang nipis

mempunyai lebih banyak gentian yang terbentuk sejajar dengan arah aliran suntikan. Ini disebabkan kesan daripada tindakan aliran ricih yang lebih banyak terhasil pada cakera berkenaan berbanding dengan cakera yang lebih tebal.

Penghalaan gentian sentiasa diperhatikan kesan perubahannya daripada dinding ke teras spesimen yang dikaji. Pada dinding, gentian adalah selalunya sejajar dengan arah aliran manakala pada teras, gentian-gentian biasanya bertentangan dengan arah aliran. Semakin banyak gentian yang sejajar dihasilkan di dalam pengacuan, semakin kuatlah sifat mekanik bahan yang dihasilkan. Kelajuan yang tinggi pada suntikan menyebabkan gentian akan bergerak sejajar di sepanjang arah aliran tetapi akan berkurangan kesejajarannya daripada dinding ke teras/tengah satah.

Akhirnya, keseluruhan keputusan kajian perbandingan yang menggunakan aturcara MPI berbanding keputusan-keputusan yang telah diterbitkan di jurnal-jurnal adalah sehaluan/sekata dalam menyatakan kesan FOD bagi komposit S<sub>g</sub>FRIMT. Keputusan penyelakuan ini juga sehaluan dengan kerja-kerja penyelakuan berangka yang telah diterbitkan. Ini semua mengesahkan lagi kepenggunaan kaedah penyelakuan MPI ini.

## ACKNOWLEDGEMENTS

Praise be to ALLAH the ALMIGHTY in giving me the help, guidance and patience to complete this thesis.

I would like to express my sincere thanks to the chairman of the supervisory committee, Assoc. Prof. Ir. Dr. Mohd Sapuan Salit for his continuous help, support, friendship, hospitality and encouragement throughout this work. I thank him for the brotherly handling of all matters concerning my research. I am also indebted to Assoc. Prof. Dr. Shamsuddin Sulaiman and Assoc. Prof. Dr. Megat Mohamad Hamdan Megat Ahmad for their technical advice and comments. I thank them all for their patience in reading, revising and commenting my thesis, and I thank their constructive advices and guidance.

I am most grateful to the Universiti Putra Malaysia for the financial support conceded to my study. I would like to thank the staff of Institute of Advanced Technology and the staff of Department of Mechanical and Manufacturing Engineering, UPM for availing their computing facilities to conduct this work, and for not hesitating to give any needed resources.

Great appreciation is also extended to colleagues and to all those who contributed directly or indirectly to the success of this study, may ALLAH bless them all.





This thesis submitted to the Senate of Universiti Putra Malaysia has been accepted as fulfilment of the requirements for the degree of Master of Science. The members of the Supervisory Committee are as follows:

**Mohd. Sapuan Salit, Ph.D., P.Eng.**  
Associate Professor,  
Faculty Engineering,  
Universiti Putra Malaysia.  
(Chairman)

**Shamsuddin Sulaiman, Ph.D.**  
Associate Professor,  
Postgraduate Studies,  
International Medical University.  
(Member)

**Megat Mohd. Hamdan Megat Ahmad, Ph.D.**  
Associate Professor,  
Faculty of Engineering,  
Universiti Putra Malaysia.  
(Member)

-----  
**AINI IDERIS, Ph.D.**  
Professor / Dean  
School of Graduate studies,  
Universiti Putra Malaysia

Date:



## TABLE OF CONTENTS

	<b>Page</b>
DEDICATION	ii
ABSTRACT	iii
ABSTRAK	v
ACKNOWLEDGEMENTS	vii
APPROVAL	viii
DECLARATION	x
LIST OF TABLES	xiv
LIST OF FIGURES	xv
NOMENCLATURE	xix
<b>CHAPTER</b>	
<b>1 INTRODUCTION</b>	
1	
1.1 Overview	1
1.2 Objectives of the Research	2
1.3 Significance of this Study	2
1.4 Structure of the Work	3
<b>2 LITERATURE REVIEW</b>	
2.1 Introduction	6
2.2 Reinforcement Mechanism	6
2.3 Glass Fibre Reinforced Polymer (GFRP) Composites	8
2.4 Fibre Reinforcement	8
2.5 Thermoplastics and Thermosets	10
2.6 Fibre Orientation	11
2.7 Rule of Mixture Expression	13
2.8 Fibre Orientation Distribution	14
2.9 The Effects of Fibre Reinforcement on Polymer Melt Properties	17
2.9.1 The Effect of Injection Speed and Cavity Thickness	18
2.9.2 The Effect of Melt and Mould Temperature on FOD	18
2.9.3 The Effect of Fibre Length	19
2.9.4 The Effect of Fibre Concentration	19
2.9.5 The Effect of Convergent and Divergent Flow	20
2.9.6 Walls Effect	21
2.9.7 FOD in the Weld Lines	22
2.9.8 Gate Type and Gate Location Effects	23
2.10 Fibre Orientation Prediction and Determination	24
2.11 Closure	28
<b>3 METHODOLOGY</b>	
3.1 Introduction	29
3.2 Outline of the Simulation Programme	30



3.3	Moldflow Software	32
3.3.1	Definition and Prediction of Fibre Orientation	33
3.3.2	Fibre Orientation Distribution Function	35
3.3.3	Description of Orientation Tensor	37
3.3.4	Prediction of Fibre Orientation Using MPI	37
3.3.5	Flow Analysis	39
3.3.6	A Fibre Orientation Model	39
3.4	Computational Works	43
3.4.1	Modelling Prerequisites	44
3.5	Closure	46
4	<b>SOFTWARE VERIFICATION: COMPARISON OF THE SIMULATION WORK WITH PUBLISHED EXPERIMENTAL RESULTS</b>	
4.1	Introduction	47
4.2	Part Geometry and Moulding Conditions	48
4.2.1	Modelling	49
4.3	Orientation Tensors	50
4.4	Results and Discussions	51
4.5	Other Significant Comparisons	59
4.5.1	Comparisons between Gupta and Wang (1993) Results and MPI Solutions	59
4.5.2	Results and Discussions	60
4.5.3	Comparisons between Hsu (1998) Results and MPI Solution	66
4.5.4	Results and Discussion	68
4.5.5	The Effect of Plaque Thickness on FOD	68
4.6	Closure	72
5	<b>THE EFFECT OF INJECTION SPEED AND MOULDING THICKNESS ON DETERMINING FOD IN SgFRIM POLYAMIDE COMPOSITE</b>	
5.1	Introduction	73
5.2	Moulding Conditions	73
5.3	Results and Discussions	75
5.3.1	Comparison of FOD at Different Distance from the Gate	75
	A. 4mm Plaque	75
	B. 2mm Plaque	78
5.3.2	The Effect of Injection Flow Rates onto FOD	80
	A. 4mm Plaque	80
	B. 2mm Plaque	80
5.3.3	The Effect of Plaque Thickness on FOD	83
	A. High Injection Speed	83
	B. Low Injection Speed	83
5.4	Closure	87
6	<b>CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK</b>	
6.1	Conclusions	88
6.2	Recommendations for Further Work	89



<b>REFERENCES</b>	91
<b>APPENDICES</b>	95
A An Example of The Fibre Flow in Disc Shape	96
B An Example of the Moulding Conditions and Flow Analysis by MPI Software for the Application in Chapter 4	98
C Example Output Screen of Materials Properties, Moulding Condition and Flow Analysis Provided by MPI Software	108
<b>VITA</b>	111



## LIST OF TABLES

Table		Page
2.1	Comparison of properties between aluminium and glass fibre reinforced polyamide 66	6
2.2	Weight saving of fibre reinforced plastics pedal box system compared to steel	9
4.1	Injection moulding conditions	49
4.2	Tensor component for various fibre orientation states ( $a_{11}$ : flow direction; $a_{22}$ transverse to flow direction; $a_{33}$ perpendicular to flow direction) (Hsu, 1997)	51
4.3	Moulding conditions	66
5.1	Injection moulding conditions	74
5.2	The combination of variables, injection flow rates and moulding thicknesses for each plaque thickness	75



## LIST OF FIGURES

Figure		Page
1.1	Overview of the structure of research programme	4
2.1	Lee (1996) studied the design method and applications of short fibre reinforced rubber composites	12
2.2	Gupta and Wang (1993) carried out simulation and experimental verification on the fibre orientation of SFRIMT composites	15
2.3	Barbosa and Kenny (1999) carried out a comprehensive analysis of the relationship is between processing condition, fibre orientation distribution (FOD) and final properties of the short fibre thermoplastics composites	16
2.4	Tensile modulus vs. position of the specimen for a plate of neat polypropylene and glass fibre reinforced PP with 20% wt and 40% wt. (Barbosa and Kenny, 1999)	17
2.5	Chung and Cohen (1985) in their investigation on the effect of the radius capillary moulds on the flow properties of short-fibre filled thermoplastics, which indicated that a 'wall' effect occurs as is dependent on capillary radius, shear rate, fibre concentration and temperature	22
2.6	Lielens (1999) investigated the orientation distribution in injection moulding of dumbbell-shaped part and considered two types of injection gates analysed: a pinpoint gate and a linear one	24
2.7	McGrath and Wille (1995) determined of 3D fibre orientation distribution in thermoplastic injection moulding using another automated NDE method i.e. optical sectioning method	27
3.1	The overall picture of the present study	31
3.2	For a symmetric result, numbering starts at 1 at the top of the mould/plastic interface, through 11 at the centre of the cavity	33
3.3	Orientation ellipsoid defined by general 2nd order orientation tensor	34
3.4	Possible forms of fibre sections in a polishing surface (Neves et al., 1998).	35
3.5	Definition of the coordinate system used, in the plane angle $\phi$ , the out of plane angle $\theta$ and the unit vector $p$ . The direction 1,2 and 3 refer to flow, transverse flow and thickness directions, and respectively (Neves et al., 1998)	36



3.6	Flow regions during the injection moulding process (Anon, 1996)	38
3.7	The alignment of fibres (Anon, 1996)	43
3.8	The moulding model is created and meshed using the Moldflow Modeller software	44
3.9	The material is selected from the materials database, provided by Moldflow	45
3.10	The processing and boundary conditions to be selected before analysis could be run	46
4.1	Nominal dimensions of the disc (Neves et. al., 1999)(all units are in mm)	49
4.2	Sections cut from the disc for fibre orientation analysis (Neves et. al., 1999)(all units are in mm)	49
4.3a	MPI 396-element model of the disc (Anon, 2001)	50
4.3b	Predicted fibre orientation by MPI at skin (grid 1) and core (grid 11) layer	52
4.4a	Fibre orientation in flow direction at 20 mm from the gate	53
4.4b	Fibre orientation in flow direction at 35 mm from the gate	54
4.4c	Fibre orientation in flow direction at 50 mm from the gate	55
4.5a	Effect of the 10 cm <sup>3</sup> /s (flow rate) in the flow direction at 280°C melt temperature and at 35mm from the gate	56
4.5b	Effect of the 14 cm <sup>3</sup> /s (flow rate) in the flow direction at 280°C melt temperature and at 35mm from the gate	57
4.5c	Effect of the 32 cm <sup>3</sup> /s (flow rate) in the flow direction at 280°C melt temperature and at 35mm from the gate	58
4.6	Shape of experimental mould cavity and locations of the 12.7 mm x 12.7 mm samples taken to examine the fibre orientation. (All the dimensions are in mm)	60
4.7	Predicted fibre orientation for case (i) by Gupta and Wang at $x_3/b=0$ (a), 0.3 (b), 0.6 (c) and 0.9 (d). ( $x_3$ is the gapwise direction, with $x_3 = 0$ at the mid-plane).	61



4.8	Predicted fibre orientation for case (ii) by Gupta and Wang at $x_3/b=0$ (a), 0.3 (b), 0.6 (c) and 0.9 (d). ( $x_3$ is the gapwise direction, with $x_3 = 0$ at the mid-plane).	62
4.9	Predicted fibre orientation for case (i) by MPI software at $x_3/b=0$ (a), 0.3 (b), 0.6 (c) and 0.9 (d). ( $x_3$ is the gapwise direction, with $x_3 = 0$ at the mid-plane)	64
4.10	Predicted fibre orientation for case (ii) by MPI software at $x_3/b=0$ (a), 0.3 (b), 0.6 (c) and 0.9 (d). ( $x_3$ is the gapwise direction, with $x_3 = 0$ at the mid-plane)	65
4.11	Two thicknesses of pin-gated plaques and positions where fibre orientation is measured.	67
4.12	Predicted fibre orientation for case 4 mm plaque thickness at 1 s by MPI software at a) surface of plaque and b) plaque mid-plane	69
4.13	A through-thickness image of the 4 mm plaque at a) position A (near the gate) and b) position B (centre) at 1 s injection time by Hsu (1997)	70
4.14a	A through thickness image of 2 mm plaque at position A (near the gate) at 1 s injection time by Hsu (1997)	71
4.14b	A through thickness image of 2 mm plaque at position B (centre) at 1 s injection time by Hsu (1997)	71
5.1	Two thicknesses of pin-gated plaques and positions where fibre orientation is measured (all unit in mm)	74
5.2	Orientation tensor value ( $a_{11}$ ) near the gate (position A) and position B of the 4 mm plaque at 1 s fill time	76
5.3	Orientation tensor value ( $a_{11}$ ) near the gate (position A) and position B of the 4 mm plaque at 3 s fill time	77
5.4	Orientation tensor value ( $a_{11}$ ) near the gate (position A) and position B of the 2 mm plaque at 1 s fill time	79
5.5	Orientation tensor value ( $a_{11}$ ) near the gate (position A) of the 4 mm plaque at 1 s and 3 s fill times	81
5.6	Orientation tensor value ( $a_{11}$ ) near the gate (position A) of the 4 mm plaque at 1 s and 3 s fill times	82
5.7	Orientation tensor value ( $a_{11}$ ) far from the gate (position B) of the 2 mm and 4 mm plaques at 1 s fill time	84



5.8	Orientation tensor value ( $a_{11}$ ) near the gate (position A) of the 2 mm and 4 mm plaques 1 s fill time	85
5.9	Orientation tensor value ( $a_{11}$ ) far from the gate (position B) of the 2 mm and 4 mm plaques 1 s fill time	86



## NOMENCLATURE

$a_{ij}$	Second order of orientation tensor
$D$	Fibre Diameter
$E$	Elastic modulus
$E_m$	Matrix modulus
FOD	Fibre orientation distribution
GFRPA	Glass Fibre Reinforced Polyamide
GFRPC	Glass Fibre Reinforced Polymer
GFRPE	Glass Fibre Reinforced Polyester
GFRPP	Glass Fibre Reinforced Polypropylene
$C_i$	Interaction coefficient
$L$	Fibre length
$m$	matrix phase
MPI	Moldflow Plastics Insight (MPI) software.
$p$	particulate phase
$R_x, R_y$	Effective radius in x and y direction
SFRP	Short-fibre reinforced plastics
S <sub>g</sub> FRIMT	Short glass fibre reinforced injection-moulded thermoplastic
$V$	volume fraction
$x,y,z$	$x,y,z$ coordinates

### Greek Symbols

$\omega_y$	the vorticity (whirling)
$\gamma_{ij}$	deformation tensors



$v_k$	the velocity component
$\delta_{ij}$	Unit tensor
$\rho$	Density
$\delta$	Elastic deformation
$\eta$	Viscosity
$\theta$	Fibre in plane angle
$\varphi$	Fibre out of plane angle

### Subscripts

$i, j, k$  Indices

Note: other symbols are defined in the text.

# CHAPTER 1

## INTRODUCTION

### 1.1 Overview

Short-fibre reinforced plastics (SFRP) are being widely used for technical and industrial applications due to their light weight, good mechanical properties, easiness of manufacturing and low fabrication cost. The increasing number of applications of short fibre composites makes it more important to understand and predict their mechanical and thermal properties, where these properties depend strongly on fibre orientation and volume fraction. The fibre volume fraction is usually known from the initial mixing ratio of fibre to matrix whereas the fibre orientations have to be determined numerically and experimentally since they are influenced by the fabrication process (Mlekusch, (1999) and Chung and Kwon (2000)).

Short fibre composites composed of reinforcing discontinuous fibre and polymeric matrix material. Injection moulding is one of the most productive way by which short fibre composites can be processed in high precision. However, due to complex flow pattern in the cavity, a certain orientation of fibres is likely to happen. This flow-induced fibre orientation results in anisotropy that affects mechanical properties as well as microscopic structure and final shape of the product (Gupta and Wang, 1993). To improve the properties of the part, it is necessary to predict the fibre orientation, which causes the anisotropy. Computational analysis of flow in injection moulding enables us to predict flow-



induced fibre orientation and resulting anisotropy of the moulded part. Moreover, it is possible to predict other properties of the moulded part such as residual stress, bulk shear and stress, weld lines, air traps and final shape of the part. Predicted information must be very helpful for engineers in designing process conditions and geometries of the injection mould.

## **1.2. Objectives of the Research**

The idea of this simulation work is to carry out a comparative study of the fibre orientation distribution (FOD) in the short glass fibre reinforced injection moulded thermoplastic (S<sub>g</sub>FRIMT) composites. The aim of this research is to use a numerical method to investigate the effect of two significant parameters namely, speed of injection and thickness of specimen, on the FOD of the S<sub>g</sub>FRIMT composites. The numerical simulation is conducted by Moldflow Plastics Insight (MPI) software. To achieve this aim, the following objectives are proposed:

- To compare the results arising from the MPI program with other published experimental findings.
- To analyse the effects of injection speed on fibre orientation.
- To analyse the effects of part thicknesses on fibre orientation.

## **1.3 The Significance of this Study**

Prediction of the fibre orientation distribution in short glass fibre injection moulded thermoplastic composite is performed using the numerical simulation. MPI software is used to investigate the flow behaviour and to examine the effects

of processing conditions on the mouldings. Effects of the thickness of the specimen and injection speed are considered since they have great influence on the mechanical properties of the products.

Short glass fiber-reinforced thermoplastic composites are becoming very popular in many application fields as a consequence of the possibility of combining the toughness of thermoplastic polymers with the stiffness and strength of reinforcing fibers. Moreover, the use of reinforcing short glass fibers can yield materials with a large variety of physical characteristics, depending on the type of the composite and processing conditions used for its preparation. Furthermore, the attainable lower weight due to their low density can produce a decrease of vehicles gas emission, thus enhancing the quality of life (Chung and Kwon, 2000).

#### **1.4 Structure of the Work**

The first chapter presents an introduction to short glass fibre reinforced injection-moulded thermoplastic ( $S_g$ FRIMT). This chapter also gives the objectives and the significance of the research. The structure of the study is given in Figure 1.1.

In the following chapter (Chapter 2), the literature related to  $S_g$ FRIMT composites and fibre orientation distribution (FOD) is reviewed in accordance with their importance and relevance. The experimental determination of FOD and the predicted works are also reviewed.

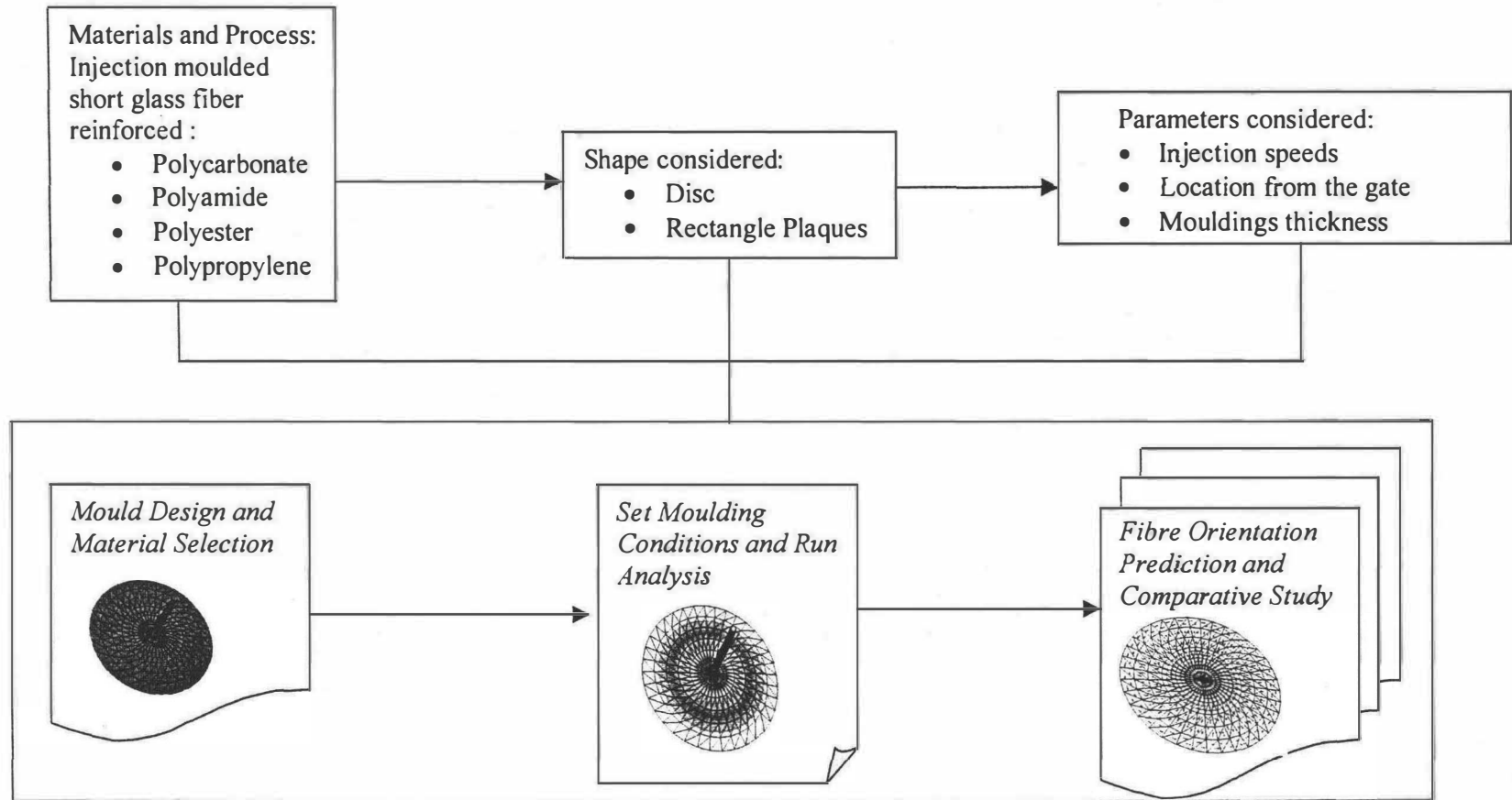


Figure 1.1: Overview of the structure of research programme