UNIVERSITI PUTRA MALAYSIA

INJECTION MOULDING SIMULATION OF WOOD–FILLED POLYPROPYLENE THIN-WALLED COMPOSITE PARTS

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By

MOHD AZAMAN MD DEROS

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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INJECTION MOULDING SIMULATION OF WOOD-FILLED POLYPROPYLENE THIN-WALLED COMPOSITE PARTS

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May 2015

Chair: Professor Mohd Sapuan Salit, PhD, PEng
Faculty: Engineering

Currently, many industries are moving towards the production of products that exhibit properties, such as small thickness, low weight, small dimensionality, and environmental friendliness. In this project, a shallow thin-walled part (thickness = 0.7 mm) was designed to investigate wood-filled polymer composites in terms of the processability and quality of moulding parts. Numerical simulation (MoldFlow software) assisted with the Taguchi method, signal-to-noise (S/N) ratio and analysis of variance (ANOVA) was carried out in this research. This study focused on the in-cavity residual stresses, volumetric shrinkage and warpage behaviour associated with the thin-walled moulded part using different types of wood-filled polymer composites (PP + 40 %wt wood, PP + 50 %wt wood, and PP + 60 %wt wood). The analysis demonstrated that the shallow thin-walled part is preferable for moulding the wood-filled polymer composite material due to the low residual stress (i.e. centre of the part surface, 15-23 MPa) and warpage (0.02-0.42 mm) measured than flat thin-walled parts. The material PP + 60 %wt wood is not suitable for moulded thin-walled parts because of the early solidification (short shot) and the statistical results with a percentage contribution of residual error that was higher than the moulding parameters. However, the material PP + 50 %wt wood is the preferred type of wood-filled polymer composite for moulded thin-walled parts. The predicted in-cavity residual stresses for PP + 50 wt% wood are approximately 20.10 MPa, which is lower than the values of approximately 20.60 MPa and 31.10 MPa predicted for PP + 40 wt% wood and PP + 60 wt% wood, respectively. The differences in value of the contour-pattern distribution for PP + 50 wt% wood are small (in the ranges of -0.709 % to -0.174 **%)** compared to those for the other types of wood-filled polymer composites. The research revealed that the packing pressure and mould temperature are important parameters to reduce the residual stresses and volumetric shrinkage. To reduce warpage, the important processing parameters are the packing pressure, packing time and cooling time for moulded thin-walled part using wood-filled polymer composites. The in-cavity residual stress results indicated that the stress variation across the thickness exhibits a high tensile stress at the part surface, which changes to a low tensile stress peak value close to the surface, with the core region experiencing a parabolic tensile stress peak. The volumetric shrinkage was lower near the gate than at the end-of-fill location along the flow path. The results also indicated that the volumetric shrinkage

correlates with the warpage measured on the moulded part. The optimum parameter ranges for obtaining the minimum in-cavity residual stresses, volumetric shrinkage and warpages are as follows: a mould temperature of 40-45 °C, a cooling time of 20-30 sec, a packing pressure of $0.85P_{inject}$, and a packing time of 15-20 sec. The melt flow index (MFI) is inversely proportional to the residual stress, volumetric shrinkage and warpage formation on the moulded thin-walled part. The value of the melt flow index must be considered in injecting wood-filled polymer composites rather than making the selection based on the filler loading content. Visualisation of the simulation results shows that the minimum warpage distribution appears more uniform for the moulded thin-walled part using PP + 50 wt% wood than for that using PP + 10 wt% glass fibre and PP. The warpage at the midpoint of the part surface injected using PP + 50 wt% wood is 0.04mm lower than that value of 0.08mm using PP + 10 wt% glass fibre. This phenomenon can be attributed to changes in the distribution of residual stresses that occur in the core regions: PP + 50 wt% wood is 15.77MPa lower than PP + 10wt% glass fibre (17.17MPa). Furthermore, the volumetric shrinkages of PP + 10 wt% of glass fibre are observed to begin to become uniform at 3.95% from 2.3 sec, which is faster than that of PP + 50 wt% wood at 2.23% from 2.5 sec take longer or more time. More time required for the solidification process tends to minimise warpages occurring at the regions.

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SIMULASI PENGACUANAN SUNTIKAN KOMPOSIT POLIPROPELINA TERISI KAYU DALAM BAHAGIAN BERDINDING NIPIS

Oleh

MOHD AZAMAN MD DEROS

Mei 2015

Pengerusi: Professor Mohd Sapuan Salit, PhD, PEng
Fakulti: Kejuruteraan

Masa kini, banyak industri mengorak ke arah pengeluaran produk-produk yang mempamerkan sifat-sifat seperti nipis, ringgan, kecil, dan mesra persekitaran. Dalam projek ini, sebuah bahagian cetek berdinding nipis (ketebalan = 0.7 mm) direkabentuk untuk mengkaji komposit polimer terisi kayu dari segi kebolehprosesan dan kualiti bahagian acuan. Simulasi berangka (perisian MoldFlow) dibantu dengan kaedah Taguchi, nisbah isyarat hingar (S/N) dan analisa varians (ANOVA) telah dijalankan dalam kajian ini. Kajian ini menumpukan terhadap kelakuan tegasan baki, pengecutan isipadu dan keledingan yang berkaitan dengan pengacuanan bahagian berdinding nipis menggunakan komposit polimer terisi kayu daripada jenis-jenis yang berbeza (PP + 40 %wt kayu, PP + 50 %wt kayu, and PP + 60 %wt kayu). Analisis menunjukkan bahawa bahagian cetek berdinding nipis adalah lebih baik untuk pengacuanan bahan komposit polimer terisi kayu disebabkan oleh tegasan baki yang rendah diukur (iaitu bahagian tengah permukaan, 15-23 MPa) dan keledingan (0.02-0.42 mm) berbanding bahagian rata berdinding nipis. Bahan PP + 60 %wt kayu adalah tidak sesuai untuk pengacuanan bahagian berdinding nipis kerana pemejalan awal (tembakan pendek) dan keputusan statistik menyumbang peratusan baki ralat yang lebih tinggi berbanding parameter acuan. Walau bagaimanapun, bahan PP + 50 %wt kayu adalah pilihan bagi jenis komposit polimer terisi kayu untuk pengacuanan bahagian berdinding nipis. Tegasan baki dalam-rongga untuk PP + 50 wt% kayu diramalkan lebih kurang 20.10 MPa, iaitu lebih rendah berbanding nilai-nilai yang lebih kurang 20.60 MPa dan 31.10 MPa diramalkan untuk PP + 40 wt% kayu dan PP + 60 wt% kayu, masing-masing. Perbezaan nilai taburan kontur-corak untuk PP + 50 wt% kayu adalah kecil (dalam julat iaitu -0,709 % hingga -0,174 %) berbanding dengan komposit polimer terisi kayu untuk lain-lain jenis. Kajian ini mendedahkan bahawa tekanan padatan dan suhu acuan adalah parameter penting bagi mengurangkan tegasan baki dan pengecutan isipadu. Untuk mengurangkan keledingan, parameter pemprosesan yang penting adalah tekanan padatan, masa padatan dan masa penyejukan untuk pengacuanan bahagian berdinding nipis menggunakan komposit polimer terisi kayu. Keputusan tegasan baki dalam-rongga menunjukkan variasi tegasan merentasi ketebalan mempamerkan tegasan tegangan tinggi pada permukaan, yang mana berubah kepada tegasan tegangan nilai puncak yang rendah di kawasan dekat permukaan, dengan rantau teras mengalami parabola puncak

tegasan tegangan. Pengecutan isipadu adalah lebih rendah berhampiran pintu berbanding di lokasi-akhir di sepanjang arah aliran. Keputusan juga menunjukkan bahawa pengecutan isipadu berkaitan dengan kelidingan yang terukur pada bahagian acuan tersebut. Julat optimum parameter untuk mendapatkan minimum tegasan baki dalam-rongga, pengecutan isipadu dan keledingan adalah seperti berikut: suhu acuan 40-45 °C, masa penyejukan 20-30 saat, tekanan padatan $0.85P_{suntik}$, dan masa padatan 15-20 saat. Indeks aliran leburan (MFI) adalah berkadar songsang dengan pembentukan tekanan baki, pengecutan isipadu dan keledingan pada pengacuanan bahagian berdinding nipis. Nilai indeks aliran leburan perlu dipertimbangkan dalam menyuntik komposit polimer terisi kayu berbanding membuat pilihan berdasarkan kandungan beban pengisi. Keputusan visualisasi simulasi menunjukkan bahawa agihan keledingan minimum kelihatan lebih seragam untuk pengacuanan bahagian berdinding nipis menggunakan PP + 50 wt% kayu daripada menggunakan PP + 10 wt% gentian kaca and PP. Keledingan di titik tengah bahagian permukaan yang disuntik menggunakan PP + 50 wt% kayu ialah 0.04mm lebih rendah daripada nilai 0.08mm yang menggunakan PP + 10 wt% gentian kaca. Fenomena ini boleh dikaitkan dengan perubahan dalam taburan tegasan baki yang berlaku di kawasan teras: PP + 50 wt% kayu ialah 15.77MPa lebih rendah daripada PP + 10wt% gentian kaca (17.17MPa).Tambahan pula, pengecutan isipadu PP + gentian kaca 10wt% diperhatikan untuk mula menjadi seragam di 3.95% pada 2.3 saat, yang lebih cepat berbanding dengan PP + 50 wt% kayu di 2.23% pada 2.5 saat yang mengambil masa yang lama atau lebih masa. Lebih banyak masa diperlukan untuk proses pemejalan adalah cenderung untuk mengurangkan keledingan yang berlaku di kawasan-kawasan tersebut.

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ءَاتُونِى زُبَرَ ٱلْحَدِيدِ ۖ حَتَّىٰٓ إِذَا سَاوَىٰ بَيْنَ ٱلصَّدَفَيْنِ قَالَ ٱنفُخُوا۟ ۖ حَتَّىٰٓ إِذَا جَعَلَهُۥ
نَارًا قَالَ ءَاتُونِىٓ أُفْرِغْ عَلَيْهِ قِطْرًا ﴿٩٦﴾

Bring me sheets of iron" until, when he had leveled [them] between the two mountain walls, he said, "Blow [with bellows]," until when he had made it [like] fire, he said "Bring me, that I may pour over it molten copper" Surah Al-Kahf (The Cave) 18:96

Inspiration from Surah Al-Kahf (The Cave) 18:96, "we believe the combination with different type of materials will be change the behavior of a new type material".

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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This is to confirm that:

- the research conducted and writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

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TABLES OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

3C	Computer, communication and consumer
ABS	Acrylonitrile butadiene styrene
ANN	Artificial neural network
ANOVA	Analysis of variance
BPANN	Back propagation artificial neural network
CTE	Coefficient of thermal expansion
DOE	Design of experiment
DOF	Degree of freedom
GA	Genetic algoritm
GF	Glass fibre
GPS	General purpose polystyrene
HDPE	High density polyethylene
L:T	Length to thickness
LCD	Liquid crystal display
MA	Maleic anhydride
MAPP	Maleic anhydride polyethylene
MFI	Melt flow index
MS	Mean square
PA66	Polyamide 66
PA9T	Polyamide 9T
PBT	Polybutylene terephthalate
PC/ABS	Polycarbonate/acrylonitrile butadiene styrene
PE	Polyethylene
P_{inject}	Injection pressure
PLA	Polylactide
PP	Polypropylene
P_{PACK}	Packing pressure
PS	Polystyrene
PVT	Pressure, velocity and temperature
S/N	Signal to noise ratio
SOS	Sum of square
T_{MOULD}	Mould temperature
TV	Television
VS	Volumetric shrinkage
WPC	Wood polymer composite

CHAPTER 1

INTRODUCTION

1.1 Background

Thin-walled moulding technology has attracted increasing attention, particularly in electronic packing applications. These industries are moving towards the production of products with some criteria such as thinness, low weight, small dimensionality, environmental friendliness and good structural strength. The efforts typically made to reduce material costs and increase productivity include reducing the thickness of parts and using low-cost materials such as lignocellulosic fillers (i.e., wood flour) to replace fibreglass filler or as fillers in thermoplastic composites. Therefore, manufacturers are interested in research and development for creating 3C (computer, communication and consumer) products specifically using lignocellulosic fibres. In 2006, a casing mobile phone made of polylactide (PLA) reinforced with kenaf fibres was launched by NEC Corporation using a modified PLA developed by UNITIKA LTD (Zini and Scandola, 2011). Šercer et al. (2009), created an innovative wood thermoplastic composite for use in developed loudspeaker boxes, which yielded good results in processability and repeatability.

The future of lignocellulosic fibre thermoplastic composites will ultimately depend on many factors, including new product identification, product quality, consumer reaction and perceptions, and the success of research and development efforts. Lignocellulosic fibres are promising, sustainable and biodegradable green materials that can be used to achieve durability as fillers in thermoplastic composite. La Mantia and Morreale (2011) reported that the most widely known and used natural-organic fillers in producing thermoplastic composite are wood flour and wood fibres. The processing of lignocellulosic thermoplastic composites is usually limited to temperatures below 230 °C to minimise fibre degradation, as reported by Sanadi et al. (1998).

Reducing the thickness of parts to less than 1 mm and simultaneously applying wood fibre as a filler material is extremely challenging in a moulded product using injection moulding. Processing at low temperatures makes it difficult for the polymer melt to flow into the mould cavities and often leads to an inconsistent distribution of residual stresses, volumetric shrinkage and warpage in moulded products, particularly in thin-walled parts. Residual stresses, shrinkage and warpage are the three major challenges in injection moulding. Cheng et al. (2009) reported the effect of non-uniform stress and shrinkage distributions on warpage deformation. The distribution of residual stresses caused by non-uniform shrinkage ultimately generated the most significant warpage problems, particularly in thin-walled parts. Oktem et al. (2007) also reported that warpage and shrinkage were the most frequently involved factors in the defects of thin-walled plastic parts in terms of quality. The primary cause of warpage is commonly known to be variations in shrinkage during the injection processing of thin-walled plastic parts.

Several methods can be used to minimise the part quality problems of moulded thin-walled parts by considering the geometrical part design, mould system design, cooling system design, moulding parameters and material used. Subramanian et al. (2005) reported that the geometry and mechanical properties of a material also play critical roles in the warpage and that the final warpage of a part strongly depends on its mechanical stiffness, which is a function of the geometrical configuration and of the material's mechanical properties. The maximum deflection is inversely proportional to the thickness (high deflection occurs with thin parts). The structural rigidity of a thin-walled part is greatly dependent on the geometry of part designs. Hence, the initial stage of this research was conducted to investigate processability using wood-filled thermoplastic composites in different moulded geometries of thin-walled part designs (shallow or flat, thin parts).

Plastic injection moulding is a discontinuous and complicated process involving the interaction of several variables to control the quality of the moulded parts. These variables can be classified in terms of moulding parameters, materials, product design and mould design. The process requires appropriate setting parameters. The selection of appropriate machining parameters for the injection-moulding process becomes more difficult for applications that involve thin-walled parts and that use lignocellulosic thermoplastic composites (i.e., wood-filled polypropylene composites). Therefore, a statistical design of experiments (DOE) can be used to identify the optimum interactions among the variables in the injection-moulding process. According to Giboz et al. (2007), the level of warpage and shrinkage is highly dependent on the moulding process parameters. These authors proposed that efforts to reduce warpage and shrinkage to an acceptable level should be focused on the careful control of the moulding process parameters. In this research, the next stage of optimisation concerns the selection of variables in the moulding process parameters (filling time, packing pressure, packing time, cooling time, mould temperature, injection pressure, etc.) and the determination of their effects on part quality.

The selection of a method for the statistical design of experiments should be based on multiple criteria, including practicality, efficacy, ease of construction and adequate accuracy. These criteria, when considered collectively, favour the Taguchi method. Because of these considerations, the application of the Taguchi method, the signal-to-noise and analysis of variance (ANOVA) appears to be a more practical approach to the statistical design of experiments than other methods, which appear to be more complicated. Furthermore, many industries concur with this assessment and have employed the Taguchi method to improve their products or manufacturing processes. The Taguchi approach appears to provide practical and effective tools for solving challenging quality problems. This method has been used quite successfully in several industrial applications such as the optimisation of manufacturing processes and design (Wang et al., 2013; Hakimian and Sulong, 2012).

During the injection-moulding process, the moulding processing parameters are the main criteria in controlling the quality of the final part. Each moulding parameter (i.e., the packing pressure, packing time, mould temperature, etc.) has a significant effect on the formation of residual stress, volumetric shrinkage and warpage for moulded thin-walled parts. The injection-moulded parts undergo shrinkage and warpage caused by residual stresses and temperature changes. These residual stresses are usually developed during solidification in the post-filling stage rather than during the filling stage. Choi and Im (1999) studied specific parameters at the packing and cooling stages to analyse the residual stresses. The pressure at the filling stage is much lower than that at the packing stage; thus, the pressure has little effect on the shrinkage and warpage of parts. Zhou and Li (2005b) observed that residual stresses that accumulated during the post-filling and cooling stages will lead to warpage in parts after demoulding. During the packing stage, the frozen-in stress caused by the packing pressure should be considered when measuring residual stresses. Similarly, during the cooling stages, due to the low thermal conductivity of polymers and the difference in temperature between the molten resin and the mould, an uneven temperature field arises, particularly along the gap-wise direction. This non-uniform temperature field distribution ultimately leads to differential shrinkage, thermal residual stress, and warpage in moulded parts (Zhou and Li, 2005a).

Subramanian et al. (2005) reported the mechanical properties of materials also play an important role in controlling the warpage. Therefore, a potential solution for moulding thin-walled parts is to use a fibre-filled thermoplastic composite, which typically increases the material modulus of the moulded part compared with an unfilled moulded part. Hakimian and Sulong (2012) observed that loading glass fibres in the polymer provides a valuable effect on the formation of warpage and the shrinkage properties in moulded micro-gear parts. These phenomena are due to the orientation of the fibres along the direction of the injection flow during the moulding process.

A literature review reveals that limited research has been conducted on the use of lignocellulosic-filler-reinforced thermoplastic composite materials for moulded thin-walled parts in the injection-moulding process. The initial stage this research was to investigate the advantages and disadvantages of flat or shallow thin-walled parts moulded using wood-filled thermoplastic composite. In the following stage, the optimal parameters for three different types of wood-filled thermoplastic composite materials were determined. In addition, the effects of the moulding parameters (packing pressure, packing time, mould temperature and cooling time) during the post-filling stage of the wood-filled thermoplastic composite materials were determined on shallow thin-walled parts with thicknesses of 0.7 mm (Figure 1.1) with respect to the filling, in-cavity residual stresses, volumetric shrinkage and warpage for thin-walled parts in the injection-moulding process. Finally, further investigation was conducted on the comparison of the filled and unfilled thermoplastic composites in moulded thin-walled parts, specifically using neat polypropylene (PP), PP + 10 wt% glass fibre and PP + 50 wt% wood composite.

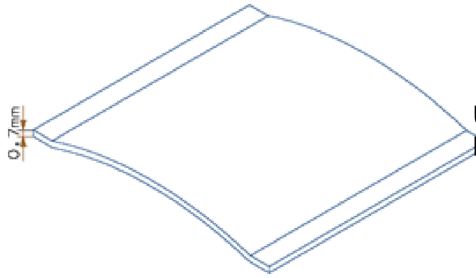

Figure 1.1. A spherical shallow thin-walled plastic shell (isometric view)

1.2 Problem statements

The industry trend is to produce a product with consideration of properties such as thinness, lightweightness, smallness and environmental friendliness. Typical action is taken in an effort to decrease material costs and increase the productivity of parts per hour, commonly by reducing the thickness of the parts and using low-cost material sources such as natural-fibre filler as a replacement for fibreglass filler in thermoplastic composites. However, when decreasing the thickness to less than 1 mm and using natural fibres as fillers, it is an extremely challenging task to predict the residual stresses occurring on the parts, which are the result of the formation of shrinkage and warpage.

List of problem statements that should be solved in this research:

a) Is the wood-filled thermoplastic composite suitable for injecting on thin-walled parts using the injection-moulding process? And what processing conditions in the injection-moulding process should be controlled to produce a high-quality thin-walled moulded part?
b) What is the effect of the moulding processing parameters and value of the residual stresses, volumetric shrinkage and warpage distribution in moulded thin-walled parts using wood-filled thermoplastic composite? Are interactions present among these behaviours?
c) How do the filled and unfilled thermoplastic composites in moulded thin-walled parts compare in terms of the filling phase, residual stresses, volumetric shrinkage and warpage?

1.3 Hypothesis

An investigation of the processability of wood-filled thermoplastic composite materials injected in thin-walled parts was performed. Simulations were used to observe the distribution of residual stresses, shrinkage and warpage during solidification in the post-filling stage (packing stage and cooling stage). This research aimed to analyse and identify the relationship of the hypothesis as follows:

$$\frac{P_{PACK}}{(MFI)(T_{MOULD})} \ \alpha \ \text{(Residual stresses); (Volumentric shrinkage); (Warpage)}$$

Remarks:
$P_{PACK} = \text{Packing pressure, MPa;}$
$MFI = \text{Melt flow index, grams/10min;}$
$T_{MOULD} = \text{Mould temperature, °C}$

Some approaches were used to develop and identify the aforementioned hypothesis:

1. Simulation and investigation of the processability of wood-filled thermoplastic composite materials on shallow and flat thin-walled parts. This study focused on the effect of the filling on cavity residual stresses and warpage.
2. The optimisation of the moulding processing parameters in the post-filling stage (packing pressure, packing time, mould temperature and cooling time) was investigated concerning their effect on the residual stresses, volumetric shrinkage and warpage behaviour. The optimisation was assisted using the Taguchi method and ANOVA to study wood-filled thermoplastic composites with various filler loadings and melt flow index (MFI) values.
3. Simulation and investigate the effect of moulding parameter at post-filling stages (packing pressure, packing time, mould temperature and cooling time) against in-cavity residual stresses, volumetric shrinkage and warpage formation on moulded thin-walled part with varying filler loadings (40–60 wt%) for wood-filled thermoplastic composites.

Several assumptions were used to generate the above hypothesis:

1. The wood filler has an irregular particulate shape (powder) with a filler size less than 0.5 mm.
2. The minimum wall thickness for a moulded thin-walled part using wood-filled thermoplastic composite materials is 0.7 mm.

3. The gate size should be similar to or larger than the part thickness.
4. The melt temperature range is 180–195 °C to avoid material properties degradation.
5. The packing time range is 15–20 sec and the cooling time range is 20–30 sec; these ranges are sufficient to provide better results for the moulded part quality.

1.4 Objectives

The objectives of this research are:

1. To simulate the processability of wood-filled polypropylene composite thin-walled parts (shallow and flat thin-walled parts).
2. To optimise the moulding processing parameters at the post-filling stage on thin-walled parts with various filler loadings (40-60 wt%) based on their effect on the residual stress, shrinkage and warpage properties.
3. To simulate and investigate the residual stress distribution for thin-walled parts during the post-filling stage using PP + wood composites.
4. To simulate and investigate the shrinkage and warpage distribution on thin-walled parts during the post-filling stage using PP + wood composites.
5. To investigate the processability and identify the interaction of warpage between residual stresses and volumetric shrinkage formation in moulded thin-walled parts for unfilled and filled thermoplastic composites.

1.5 Significance of Study

Natural fibres such as wood fibres are very promising, sustainable and biodegradable green materials that can be used to achieve durability without the use of toxic chemicals. Furthermore, natural fibre composites can replace traditional polymer composites with a lower environmental impact and are known as ‘eco-composites’ or ‘green composites’. These materials are suitable for typical application such as on thin-walled parts that do not require excellent mechanical properties. Hence, the significance of this study is to build a new research platform to explore the potential of processability to use natural plant fibre sources to reinforce thermoplastics injected on thin-walled parts using the injection-moulding process.

This research also represents an early study in the field of natural-fibre-reinforced thermoplastic composites that focuses on thin-walled parts injected by injection moulding. Therefore, this research also provides a new scope of research for future researchers who can refer to these findings as a platform in brainstorming new ideas for further investigations concerning the application of natural-fibre-reinforced thermoplastic composite on thin-walled parts or other materials.

1.6 Scopes and Limitations of the Study

The scope of research is to identify the processability and certain moulding properties of wood-filled thermoplastic composites for moulded thin-walled parts using the conventional injection moulding process. Using computer simulation to ensure that the scope of the research follows these research objectives, some limitations of the research are needed and are listed below:

a) The thickness of the shallow, thin-walled part is 0.7 mm.
b) The process involved is the injection-moulding process. The analysis of the processing parameters focuses on the post-filling stage (packing pressure, packing time, mould temperature and cooling time).
c) The simulation analysis is performed using commercial software, Autodesk MoldFlow Insight 2011 (Serial No: 357-1191113642).
d) The materials used for the simulation in the MoldFlow Thermoplastic Composite Database include:
   - PP + 40%wt wood (Trade name: NCell 40: GreenCore Composites)
   - PP + 50%wt wood (Trade name: Isoform Lip Cpcw 50: Isokon)
   - PP + 60%wt wood (Trade name: WPC-2-mv: Fraunhofer Institute)
   - PP (Trade name: SABIC PP PHC27: SABIC Europe B.V)
   - PP + 10 wt% glass fibre (Trade name: Polypro R200G: Idemitsu Kosan Co Ltd)
e) The properties, such as the in-cavity residual stresses, volumetric shrinkage and warpage, were investigated.
f) The optimisation was assisted by the Taguchi method and ANOVA.

1.7 Layout of the Thesis

The thesis is primarily divided into eight chapters as follows:

Chapter 1 provides background concerning the research, including the problem statement, hypothesis, objectives, significance of the study and limitations expected in this research.

Chapter 2 overviews on the literature review of previous work conducted on the thin moulding process using injection moulding. A comprehensive review is presented on technical and ecological views concerning the processability of lignocellulosic thermoplastic composites (i.e. wood-filled) used in moulded thin-walled product. In-depth reviews were conducted concerning the optimisation of the moulding process and the effect of moulding parameters on the part quality (i.e., residual stresses, volumetric shrinkage and warpage) of moulded parts.

Chapter 3 describes the overall research methodology. This research methodology includes the simulation analysis on moulded thin-walled parts with thicknesses of 0.7 mm with a selection of materials from the database and post-filling parameters on the fill time, in-cavity residual stresses, volumetric shrinkage and warpage. This research also uses the Taguchi method and ANOVA for optimisation and to identify the significance of parameters affecting the residual stress, volumetric shrinkage and warpage in moulded thin-walled parts.

Chapter 4 present simulation analysis results of the processability in moulded thin-walled parts using wood-filled thermoplastic composites. The simulation results on the filling, in-cavity residual stresses and warpage were used to identify the types of part design that should be preferable in moulded thin-walled parts.

Chapter 5 discusses the optimisation analysis assisted by the Taguchi method and ANOVA to identify the best parameter setting and significant moulding parameters for moulded thin-walled parts using different types of wood-filled thermoplastic composites (with the filler loading ranging from 40 wt% - 60 wt%). In-depth discussions are presented concerning the residual stresses, volumetric shrinkage and warpage formation on moulded shallow thin-walled parts due to the moulding parameter settings used and material properties such as the viscosity.

Chapter 6 reports on the simulation analysis of the in-cavity residual stress behaviour formation in moulded thin-walled parts using wood-filled thermoplastic composites. The discussion more specifically investigates the effect of the moulding parameters during the post-filling stages on the in-cavity residual stress formation.

Chapter 7 which present findings on the simulation analysis of the volumetric shrinkage and warpage behaviour formation in moulded thin-walled parts using wood-filled polymer composites. The discussion more specifically investigates the effect of the moulding parameters during the post-filling stages on the volumetric shrinkage and warpage behaviour formation.

Chapter 8 detailing discusses the simulation analysis of unfilled and filled thermoplastic composites on moulded thin-walled parts. A detailed discussion is presented concerning the processability and the interaction of warpage on the formation of residual stresses and volumetric shrinkage in moulded thin-walled parts.

Chapter 9 stated the synchronization discussion, overall conclusion of the research project and recommendations for further work.

REFERENCES

Altan, M., 2010. Reducing shrinkage in injection moldings via the Taguchi, ANOVA and neural network methods. *Materials & Design*, 31(1), pp.599–604.

Altan, M. & Yurci, M.E., 2010. Optimization of Residual Stresses in the Surface Regions of Injection Moldings. *Polymer-Plastics Technology and Engineering*, 49(1), pp.32–37.

Arif, A. & Fazal, M., 2003. Numerical prediction of plastic deformation and residual stresses induced by laser shock processing. *Journal of Materials Processing Technology*, 136(1-3), pp.120–138.

Ashori, A., 2008. Wood-plastic composites as promising green-composites for automotive industries! *Bioresource technology*, 99(11), pp.4661–4667.

Autodesk Moldflow Insight, 2011a. Moldflow Thermoplastic Database.

Autodesk Moldflow Insight, 2011b. Autodesk Moldflow Insight Help.

Azdast, T., Behravesh, A.H., Mazaheri, K. & Darvishi, A.H., 2008. Numerical simulation and experimental validation of residual stress induced constrained shrinkage of injection molded parts. *Polimery*, 53, pp.304–310.

Baaijens, F.P.T., 1991. Calculation of residual stresses in injection molded products. *Rheologica Acta*, 30, pp.284–299.

Bax, B. & Müssig, J., 2008. Impact and tensile properties of PLA/Cordenka and PLA/flax composites. *Composites Science and Technology*, 68(7-8), pp.1601–1607.

Bledzki, A.K. & Gassan, J., 1999. Composites reinforced with cellulose based fibres. *Progress in Polymer Science*, 24, pp.221–274.

Boitout, F., Agassant, J.F. & Vincent, M., 1995. Elastic calculation of residual stresses in injection molding - influence of mold deformation and pressure in the liquid. *International Polymer Processing*, 10, pp.237–242.

Burgstaller, C., 2014. A comparison of processing and performance for lignocellulosic reinforced polypropylene for injection moulding applications. *Composites Part B: Engineering*, 67, pp.192–198.

Bushko, W.C. & Stokes, V.K., 1996. Solidification of thermoviscoelastic melts. Part 3: Effects of mold surface temperature differences on warpage and residual stresses. *Polymer Engineering & Science*, 36(3), pp.322–335.

Carroll, D.R., Stone, R.B., Sirignano, A.M., Saindon, A.M., Gose, S.C. & Friedman, M.A., 2001. Structural properties of recycled plastic/sawdust lumber decking planks. *Resources, Conservation and Recycling*, 31(3), pp.241–251.

Chang, T.C. & Faison, E., 2001. Shrinkage behavior and optimization of injection molded parts studied by the taguchi method. *Polymer Engineering & Science*, 41(5), pp.703–710.

Chen, C.-P., Chuang, M.T., Hsiao, Y.H., Yang, Y.K. & Tsai, C.H., 2009. Simulation and experimental study in determining injection molding process parameters for thin-shell plastic parts via design of experiments analysis. *Expert Systems with Applications*, 36(7), pp.10752–10759.

Chen, C.-S., Chen, T.J., Chien, R.D. & Chen, S.C., 2007. Investigation on the weldline strength of thin-wall injection molded ABS parts. *International Communications in Heat and Mass Transfer*, 34(4), pp.448–455.

Chen, D.C., Chen T.H., Lin G.F., Wang Y.K. & Chang Y.C., 2014. Experimental Investigation into Suitable Process Conditions for Plastic Injection Molding of Thin-Sheet Parts. International Journal of Engineering and Technology Innovation, 4(2), pp.107–116.

Chen, H.-L., Chen S.C., Liao W.H., Chien R.D. & Lin Y.T., 2013. Effects of insert film on asymmetric mold temperature and associated part warpage during in-mold decoration injection molding of PP parts. *International Communications in Heat and Mass Transfer*, 41, pp.34–40.

Chen, X., Lam, Y.C. & Li, D.Q., 2000. Analysis of thermal residual stress in plastic injection molding. *Journal of Materials Processing Technology*, 101(1-3), pp.275–280.

Cheng, X.M., Zhou, L., Sheng, N.Y. & Wu, Y.D., 2009. Injection Molding and Warpage of Thin-walled Parts Based on Simulated Deformation. *IEEE*, (2006), pp.3–6.

Chiang, K.-T., 2007. The optimal process conditions of an injection-molded thermoplastic part with a thin shell feature using grey-fuzzy logic: A case study on machining the PC/ABS cell phone shell. *Materials & Design*, 28(6), pp.1851–1860.

Chiang, K.-T. & Chang, F.-P., 2007. Analysis of shrinkage and warpage in an injection-molded part with a thin shell feature using the response surface methodology. *The International Journal of Advanced Manufacturing Technology*, 35(5-6), pp.468–479.

Chiang, K.-T. & Chang, F.-P., 2006. Application of grey-fuzzy logic on the optimal process design of an injection-molded part with a thin shell feature. *International Communications in Heat and Mass Transfer*, 33(1), pp.94–101.

Chiang, Y. C, Cheng, H.C., Huang, C. F., Lee, J. L., Lin, Y. & Shen, Y. K., 2011. Warpage phenomenon of thin-wall injection molding. , 55, pp.517–526.

Choi, D. & Im, Y., 1999. Prediction of shrinkage and warpage in consideration of residual stress in integrated simulation of injection molding. *Composite Structures*, 47, pp.655–665.

Chris, S., 2014a. Roctool claims thin wall gains in electronics. *Injection World by Applied Market Information Ltd*, p.47.

Chris, S., 2014b. Xiaomi adopts LNP compounds for ultra-slim smartphone. *Injection World by Applied Market Information Ltd*, p.46.

Coutinho, F.M.B., Costa, T.H.S. & Carvalho, D.L., 1997. Polypropylene – Wood Fiber Composites : Effect of Treatment. *Journal of Applied Polymer Science*, 65(6), pp.1227–1235.

Eichhorn, S.J., Dufresne, A., Aranguren, M., Marcovich, N.E., Capadona, J.R., Rowan, S.J., Weder, C., Thielemans, W., Roman, M., Renneckar, S., Gindl, W., Veigel, S., Keckes, J., Yano, H., Abe, K., Nogi, M., Nakagaito, A.N., Mangalam, A., Simonsen, J., Benight, A.S., Bismarck, A., Berglund, L.A. & Peijs, T., 2009. *Review: current international research into cellulose nanofibres and nanocomposites*. *Journal of Materials Science*, 45(1), pp.1-33.

Erzurumlu, T. & Ozcelik, B., 2006. Minimization of warpage and sink index in injection-molded thermoplastic parts using Taguchi optimization method. *Materials & Design*, 27(10), pp.853–861.

Fahy, E.J., 1998. Modeling Warpage in Reinforced Polymer Disks. *Polymer Engineering and Science*, 38(7), pp.1072–1084.

Fischer, J.M., 2003. Handbook of Molded Part Shrinkage and Warpage, Plastics Design Library.

Gatenholm, P., Bertilsson, H. & Mathiasson, A., 1993. Effect of chemical composition of interphase on dispersion of cellulose fibers in polymers. I. PVC-coated cellulose in polystyrene. *Journal of Applied Polymer Science*, 49(2), pp.197–208.

Giboz, J., Copponnex, T. & Mélé, P., 2007. Microinjection molding of thermoplastic polymers: a review. *Journal of Micromechanics and Microengineering*, 17(6), pp.R96–R109.

Gould, P., 2002. Exploiting spider's silk. *Materialstoday*, (December), pp.42–47.

Gu, Y., Li, H. & Shen, C., 2001. Numerical Simulation of Thermally Induced Stress and Warpage in Injection-Molded Thermoplastics. *Advances in Polymer Technology*, 20(1), pp.14–21.

Hakimian, E. & Sulong, A.B., 2012. Analysis of warpage and shrinkage properties of injection-molded micro gears polymer composites using numerical simulations assisted by the Taguchi method. *Materials & Design*, 42, pp.62–71.

Hastenberg, C.H.V., Wildervanck, P.C. & Leenen, A.J.H., 1992. The measurement of thermal stress distribution along the flow path in injection-molded flat plates. *Polymer Engineering and Science*, 32, pp.506–515.

Huang, M.-C. & Tai, C.-C., 2001. The effective factors in the warpage problem of an injection-molded part with a thin shell feature. *Journal of Materials Processing Technology*, 110(1), pp.1–9.

Hubbe, M.A., Rojas, O.J., Lucia, L.A. & Sain, M., 2008. Cellulosic nanocomposites: a review. *BioResources*, 3(3), pp.929–980.

Huda, M.S., Mohanty,A.K., Drzal, L.T., Schut, E. & Misra, M., 2005. " Green " composites from recycled cellulose and poly (lactic acid): Physico-mechanical. *Journal of Materials Science*, (40), pp.4221–4229.

Isayev, A.I. & Crouthamel, D.L., 1984. Residual stress development in the injection moldings of polymers. *Polymer Plastics Technology and Engineering*, 22, pp.177–232.

Isayev, A.I., Shyu, G.D. & Li, C.T., 2006. Residual stresses and birefringence in injection molding of amorphous polymers: Simulation and comparison with experiment. *Journal of Polymer Science Part B: Polymer Physics*, 44(3), pp.622–639.

Ishak, Z.A.M., Aminullah, A., Ismail, H. & Rozman, H.D., 1998. Effect of Silane-Based Coupling Agents and Acrylic Acid Based Compatibilizers on Mechanical Properties of Oil Palm Empty Fruit Bunch Filled High-Density Polyethylene Composites. *Journal of Applied Polymer Science*, 68, pp.2189–2203.

Jacques, M.S., 1982. An Analysis of Thermal Warpage in Injection Molded at Parts Due to Unbalanced Cooling. *Polym. Eng. Sci*, 22, pp.241–245.

Jansen, K.M.B., Van Dijk, D.J. & Husselman, M.H., 1998. Effect of processing conditions on shrinkage in injection molding. *Polymer Engineering & Science*, 38(5), pp.838–846.

Joseph, K., James, B., Thomas, S. & Carvalho L.H.D., 1999. A Review on Sisal Fiber Reinforced Polymer. *R. Bras. Eng. Agríc. Ambiental, Campina Grande*, 3(3), pp.367–379.

Kabanemi, K.K. & Crochet, M.J., 1992. Thermoviscoelastic calculation of residual stresses and residual shapes of injection molded parts. *International Polymer Processing*, 7, pp.60–70.

Kamal, M.R., Lai-Fook, R.A. & Hernandez-Aguilar, J.R., 2002. Residual thermal stresses in injection moldings of thermoplastics: A theoretical and experimental study. *Polymer Engineering & Science*, 42(5), pp.1098–1114.

Kansal, G., Rao, P.N. & Atreya, S.K., 2001. Study: temperature and residual stress in an injection moulded gear. *Journal of Materials Processing Technology*, 108(3), pp.328–337.

Kdlik N., 1991. Thin wall technique. In *Inject. Molding*. p. 89.

Khalina, A., Jalaluddin, H., Martin, P.A., Khairul, Z.M.D., Rimfiel, J. & Nor Azowa, I., 2009. Mechanical and rheology properties of injection moulded short oil palm fibre reinforced polymer composite. In S. M. Sapuan, ed. *Research on Natural Fibre Reinforced Polymer Composite*. Universiti Putra Malaysia Publishers.

Khan, R.M. & Acharya, G., 2015. Optimization Of Thin Walled Plastic Product Through Simulation And Statistical Tools. I*nternational Journal of Scientific Research and Engineering Studies* , 2(1), pp.10–16.

Kim, C.H. & Youn, J.R., 2007. Determination of residual stresses in injection-moulded flat plate: Simulation and experiments. *Polymer Testing*, 26(7), pp.862–868.

Kim, K.H., Isayev, A.I., Kwon, K. & van Sweden, C., 2005. Modeling and experimental study of birefringence in injection molding of semicrystalline polymers. *Polymer*, 46(12), pp.4183–4203.

Kim, S.K., Lee, S.W. & Youn, J.R., 2002. Measurement of residual stresses in injection molded short fiber composites considering anisotropy and modulus variation. *Korea-Australia Rheology Journal*, 14(3), pp.107–114.

Kozlowski, R. et al., 2005. Application of fibrous plants with a special reference to composite and paper. In *Biofiber Industry Advancement Workhop*.

Kuo, P., Wang, S.Y., Chen, J.H., Hsueh, H.C. & Tsai, M.J., 2009. Effects of material compositions on the mechanical properties of wood – plastic composites manufactured by injection molding. *Materials and Design*, 30(9), pp.3489–3496.

Kwiatkowski, D., Gnatowski, A. & Nabialek, J., 2011. Numerical Analysis of Residual Stresses and Deformation of Injection Moulded Parts Manufactured From Polymeric. *Kompozyty*, 4, pp.294–298.

Larpsuriyakul, P. & Fritz, H.-G., 2011. Warpage and countermeasure for injection-molded in-mold labeling parts. *Polymer Engineering & Science*, 51(3), pp.411–418.

Lee, S.-H. & Wang, S., 2006. Biodegradable polymers/bamboo fiber biocomposite with bio-based coupling agent. *Composites Part A: Applied Science and Manufacturing*, 37(1), pp.80–91.

Lee, Y.B., Kwon, T.H. & Yoon, K., 2002a. Numerical Prediction of Residual Stresses and Birefringence in Injection/Compression Molded Center-Gated Disk. Part I: Basic Modeling and Results for Injection Molding. *Polymer Engineering and Science*, 42(11), pp.2246–2272.

Lee, Y.B., Kwon, T.H. & Yoon, K., 2002b. Numerical Prediction of Residual Stresses and Birefringence in Injection/Compression Molded Center-Gated Disk. Part II: Effects of Processing Conditions. *Polymer Engineering and Science*, 42(11), pp.2273–2292.

Li, T.Q., Ng, C.N. & Li, R.K.Y., 2001. Impact Behavior of Sawdust / Recycled – PP Composites. *Journal of Applied Polymer Science*, 81, pp.1420–1428.

Li, T.Q. & Wolcott, M.P., 2004. Rheology of HDPE–wood composites. I. Steady state shear and extensional flow. *Composites Part A: Applied Science and Manufacturing*, 35(3), pp.303–311.

Li, X., Tabil, L.G. & Panigrahi, S., 2007. Chemical Treatments of Natural Fiber for Use in Natural Fiber-Reinforced Composites: A Review. *Journal of Polymers and the Environment*, 15(1), pp.25–33.

Liao, S.J., Chang, D.Y., Chen, H.J., Tsou, L.S., Ho, J.R., Yau, H.T., Hsieh, W.H., Wang, J.T & Su, Y.C., 2004. Optimal process conditions of shrinkage and warpage of thin-wall parts. *Polymer Engineering and Science*, 44(5), pp.917–928.

Liao, S.J., Hsieh, W.H., Wang, J.T. & Su Y.C., 2004. Shrinkage and warpage prediction of injection-molded thin-wall parts using artificial neural networks. *Polymer Engineering and Science*, 44(11), pp.2029–2040.

Lin, C.-W., 1987. A Statistical Analysis Tool for Variation Simulation Modeling. *Proceedings of the 9th Annual Conference on Computers & Industrial Engineering*, 13, pp.386–391.

Liu, S.-J., 1996. Modeling and simulation of thermally induced stress and warpage in injection molded thermoplastics. *Polymer Engineering & Science*, 36(6), pp.807–818.

Lodha, P. & Netravali, A.N., 2002. Characterization of interfacial and mechanical properties of “ green ” composites with soy protein isolate and ramie fiber. *Journal of Materials Science*, 37, pp.3657–3665.

Lotti, C., Ueki, M.M. & Bretas, R.E.S., 2002. Prediction of the shrinkage of injection molded iPP plaques using artificial neural networks. *Journal of Injection Molding Technology*, 6, pp.157–176.

Lu, X. & Khim, L.S., 2001. A statistical experimental study of the injection molding of optical lenses. *Journal of Materials Processing Technology*, 113(1-3), pp.189–195.

Maldas, D. & Kokta, B.V., 1992. Performance of surface modified nutshell flour in HDPE composites. *Intern. J. Polymer Mater*, 17, pp.1–16.

Malloy, R.A., 1994. *Plastic part design for injection molding – an introduction*, New York: Hanser Publisher.

La Mantia, F.P. & Morreale, M., 2011. Green composites: A brief review. *Composites Part A: Applied Science and Manufacturing*, 42(6), pp.579–588.

Marsh, G., 2003. Next step for automotive materials. *Materialstoday*, (April 2003), pp.36–43.

Maxwell, A.S., 2005. Measurement of Residual Stress in Plastics. *DEPC (MN) 027*.

Michaeli, W. & Potsch, G., 1995. Injection Molding: An Introduction. In New York.: Hanser Publishers.

Mohanty, A.K., Misra, M., Drzal, L.T., Selke, S.E., Harte, B.R. & Hinrichsen, G., 2005. Natural fibres, biopolymers and biocomposites: an introduction. In A. K. Mohanty, M. Misra, & L. T. Drzal, eds. *Natural Fibres, Biopolymers and Biocomposites 2005*. Boca Raton: Tylor and Francis.

Mohanty, A.K., Misra, M. & Hinrichsen, G., 2000. Biofibres, biodegradable polymers and biocomposites: An overview. *Macromolecular Materials and Engineering*, 276-277(1), pp.1–24.

Morreale, M., Scaffaro, R., Maio, A. & La Mantia, .P., 2008a. Effect of adding wood flour to the physical properties of a biodegradable polymer. *Composites Part A: Applied Science and Manufacturing*, 39(3), pp.503–513.

Morreale, M., Scaffaro, R., Maio, A. & La Mantia, .P., 2008b. Mechanical behaviour of Mater-Bi®/wood flour composites: A statistical approach. *Composites Part A: Applied Science and Manufacturing*, 39(9), pp.1537–1546.

Naurah, M.I., 2006. *Injection Molding Process Parameter and Performance Analysis of Column End Cap Based on RHPE Composite*. Universiti Teknologi Malaysia.

Netravali, A.N. & Chabba, S., 2003. Composites get greener. *Materialstoday*, (April), pp.22–29.

Nian, S.-C., Wu, C.-Y. & Huang, M.-S., 2015. Warpage control of thin-walled injection molding using local mold temperatures. *International Communications in Heat and Mass Transfer*, 61, pp.102–110.

Nickel, J. & Riedel, U., 2003. Activities in biocomposites. *Materialstoday*, (April), pp.44–48.

Nishino, T., Hirao, K., Kotera, M., Nakamae, K. & Inagaki, H., 2003. Kenaf reinforced biodegradable composite. *Composites Science and Technology*, 63(9), pp.1281–1286.

Nita, A. & Oanta, E., 2010. Improving the quality of the molded polymeric parts by reducing the residual stress. In *Proceedings of the 2nd international* *conference on manufacturing engineering, quality and production systems*. pp. 77–82.

Nörnberg, B., Borchardt E., Luinstra G. & Fromm J., 2014. Wood plastic composites from poly(propylene carbonate) and poplar wood flour – Mechanical, thermal and morphological properties. *European Polymer Journal*, 51, pp.167–176.

Nourbakhsh, A., Hosseinzadeh, A. & Basiji, F., 2011. Effects of Filler Content and Compatibilizing Agents on Mechanical Behavior of the Particle-Reinforced Composites. *Journal of Polymers and the Environment*, 19(4), pp.908–911.

Oktem, H., Erzurumlu, T. & Uzman, I., 2007. Application of Taguchi optimization technique in determining plastic injection molding process parameters for a thin-shell part. *Materials & Design*, 28(4), pp.1271–1278.

Olesen, P.O. & Plackett, D., 1999. Perspectives on the performance of natural plant fibres. In *Natural Fibers Performance Forum*. Copenhagen.

Ozcelik, B. & Erzurumlu, T., 2006. Comparison of the warpage optimization in the plastic injection molding using ANOVA, neural network model and genetic algorithm. *Journal of Materials Processing Technology*, 171(3), pp.437–445.

Ozcelik, B. & Sonat, I., 2009. Warpage and structural analysis of thin shell plastic in the plastic injection molding. *Materials & Design*, 30(2), pp.367–375.

Park, K., Kim, B. & Yao, D., 2006. Numerical Simulation for Injection Molding with a Rapidly Heated Mold, Part II: Birefringence Prediction. *Polymer-Plastics Technology and Engineering*, 45(8), pp.903–909.

Plackett, D., Løgstrup Andersen, T., Batsberg Pedersen, W. & Nielsen, L., 2003. Biodegradable composites based on l-polylactide and jute fibres. *Composites Science and Technology*, 63(9), pp.1287–1296.

Postawa, P. & Kwiatkowski, D., 2006. Residual stress distribution in injection molded parts. *Journal of Achievements in Materials and Manufacturing Engineering*, 18(1), pp.171–174.

Powell, C.P. & Housz, I.J.A., 1998. *Engineering with Polymers*, London: Stanley Thornas Publishers.

Rahman, W., Sin, L.T. & Rahmat, A.R., 2008. Injection moulding simulation analysis of natural fiber composite window frame. , 7, pp.22–30.

Rahman, W.A.W.A., Sin, L.T., Rahmat, A.R., Isa, N.M., Salleh, M.S.N. & Mokhtar, M., 2010. Comparison of rice husk-filled polyethylene composite and natural wood under weathering effects.

Rangaprasad, R., 2003. Wood Plastic Composites – an overview. In *IPI Seminar on Synthetic Wood*.

Rials, T.G., Wolcott, M.P. & Nassar, J.M., 2001. Interfacial Contributions in Lignocellulosic Fiber-Reinforced Polyurethane Composites. *Journal of Applied Polymer Science*, 80, pp.546–555.

Rosa, S.M.L., Santos, E.F., Ferreira, C.A. & Nachtigall, S.M.B., 2009. Studies on the Properties of Rice-Husk-Filled-PP Composites – Effect of Maleated PP 2 . Experimental Procedures. , 12(3), pp.333–338.

Rotheiser, J.I., 2002. Controlling Warpage for the Decorating and Assembly of Plastic Parts. In *ANTEC, Annual Technical Conference Proceedings, Conference 60*. pp. 3020–3023.

Rowell, R.M., 2008. Natural fibres: types and properties. In K. L. Pickering, ed. *Properties and Performance of Natural-Fibre Composites*. Cambridge England: Woodhead Publishing Limited., pp. 3–66.

Rowell, R.M., Young, R.A. & J.K. Rowell, 1997. *Paper and Composites from Agro-Based Resources*, New York: Lewis Publishers.

Rozman, H.D., Tan, K.W., Kumar, R.N., Abubakar, A., Mohd Ishak, Z.A. & Ismail, H., 2000. The effect of lignin as a compatibilizer on the physical properties of coconut fiber-polypropylene composites. *European Polymer Journal*, 36, pp.1483–1494.

Rozman, H.D., Peng, G.B. & Mohd. Ishak, Z.A., 1998. The effect of compounding techniques on the mechanical properties of oil palm empty fruit bunch-polypropylene composites. *Journal of Applied Polymer Science*, 70(13), pp.2647–2655.

Rozman, H.D. & Wan Daud, W.R., 1999. Developments of oil palm based lignocellulosic polymer blend. In G. O. Shonaike & G. P. Simon, eds. *Polymer Blends*. New York: Marcel Dekker, p. 719.

Samir, M.A.S.A., Alloin, F. & Dufresne, A., 2005. Review of recent research into cellulosic whiskers, their properties and their application in nanocomposite field. *Biomacromolecules*, 6(2), pp.612–26.

Sanadi, A., Caulfield, D.F. & Rowell, R.M., 1998. Lignocellulosic/Plastic Composites. *Technology Summaries*, pp.8–13.

Scaffaro, R., Morreale, M., Lo Re, G. & La Mantia, F.P., 2009. Effect of the Processing Techniques on the Properties of Ecocomposites Based on Vegetable Oil-Derived Mater-Bi and Wood Flour. *Journal of Applied Polymer Science*, 114, pp.2855–2863.

Sen, A. & Bhattacharya, M., 2000. Residual stresses and density gradient in injection molded starch/synthetic polymer blends. *Polymer*, 41(26), pp.9177–9190.

Šercer, M., Raos, P. & Rujnić-Sokele, M., 2009. Processing of wood-thermoplastic composites. *International Journal of Material Forming*, 2(S1), pp.721–724.

Shen, C.-Y. & Li, H.-M., 2003. Numerical Simulation for Effects of Injection Mold Cooling on Warpage and Residual Stresses. *Polymer-Plastics Technology and Engineering*, 42(5), pp.971–982.

Shen, Y.-K., Wu, C.W., Yu, Y.F. & Chung, H.W., 2008. Analysis for optimal gate design of thin-walled injection molding. *International Communications in Heat and Mass Transfer*, 35(6), pp.728–734.

Shen, Y.K., Yeh, P.H. & Wu, J.S., 2001. Numerical simulation for thin wall injection molding of fiber-reinforced thermoplastics. *International Communications in Heat and Mass Transfer*, 28(8), pp.1035–1042.

Shoemaker, J., 2006. *Moldflow Design Guide (A Resource for Plastic Engineer)*, Hanser Publisher.

Slaviero, C., Weiss, K. & Woodman, D., 2001. Thinwall Injection Molding for Instrument Panels. In *SAE Technical Paper Series*.

Song, M.C., Liu, Z., Wang, M.J., Yu, T.M. & Zhao, D.Y., 2007. Research on effects of injection process parameters on the molding process for ultra-thin wall plastic parts. *Journal of Materials Processing Technology*, 187-188, pp.668–671.

Struik, L.C.E., 1978. Orientation Effects and Cooling Stresses in Amorphous Polymers. *Polymer Engineering and Science*, 18, pp.799–811.

Subramanian, N.R., Tingyu (Leon), L. & Seng, Y.A., 2005. Optimizing warpage analysis for an optical housing. *Mechatronics*, 15(1), pp.111–127.

Tang, S.H., Tan, Y.J., Sapuan, S.M., Sulaiman, S., Ismail, N. & Samin, R., 2007. The use of Taguchi method in the design of plastic injection mould for reducing warpage. *Journal of Materials Processing Technology*, 182(1-3), pp.418–426.

Timothy, A.P., 2001. Specializes Molding Techniques. In H.-P. Heim & H. Potente, eds. *10 Common Pitfalls in Thin Wall Plastic Part Design*. Norwich: Plastic Design Library, p. 107.

Touzé, C. & Thomas, O., 2006. Non-linear behaviour of free-edge shallow spherical shells: Effect of the geometry. *International Journal of Non-Linear Mechanics*, 41(5), pp.678–692.

Wang, T.-H. & Young, W.-B., 2005. Study on residual stresses of thin-walled injection molding. *European Polymer Journal*, 41(10), pp.2511–2517.

Wang, T.H., Young, W.B. & Wang, J.T., 2002b. T. *Intern. Polymer Processing XVII*, 2, p.146.

Wang, X., Zhao, G. & Wang, G., 2013. Research on the reduction of sink mark and warpage of the molded part in rapid heat cycle molding process. *Materials & Design*, 47, pp.779–792.

Weng, C., 2010. *Modelling and simulation of residual stresses and birefringence in the precision injection moulding of microlens arrays*, The Hong Kong Polytechnic University: UMI Dissertation Publishing.

Willett, J.L., 1994. Mechanical properties of LDPE/granular starch composites. *Journal of Applied Polymer Science*, 54, pp.1685–1695.

Williams, J.G., 1981. On the prediction of residual stresses in polymers. *Plastics and rubber processing and applications*, 1, pp.369–377.

Wu, H., Zhao, Z. & Sha, J., 2009. Experiments and prediction of in-cavity stress for injection molded part. *Mechanics of Time-Dependent Materials*, 13(3), pp.233–244.

Xie, P. Guo, F., Jiao, Z., Ding, Y. & Yang, W., 2014. Effect of gate size on the melt filling behavior and residual stress of injection molded parts. Materials & Design, 53, pp.366–372.

Xu, Q.J. & Yu, S., 1998. Calculation of residual stress in injection molded production molded products for polymer materials. *Chinese J Theor Appl Mech*, 30, pp.157–167.

Young, W.-B., 2004. Residual stress induced by solidification of thermoviscoelastic melts in the postfilling stage. *Journal of Materials Processing Technology*, 145(3), pp.317–324.

Zhang, X., Cheng, X., Stelson, K.A., Bhattacharya, M., Sen, A. & Voller, V.R., 2002. Approximate Model of Thermal Residual Stress in an Injection Molded Part. *Journal of Thermal Stresses*, 25(6), pp.523–538.

Zheng, R., Kennedy, P., Phan-Thien, N. & Fan, X.-J., 1999. Thermoviscoelastic simulation of thermally and pressure-induced stresses in injection moulding for the prediction of shrinkage and warpage for fibre-reinforced thermoplastics. , 84, pp.159–190.

Zhou, H. & Li, D., 2005a. Numerical Simulation and Experimental Study of Warpage of Injection-Molded Parts. *Polymer-Plastics Technology and Engineering*, 44(4), pp.603–617.

Zhou, H. & Li, D., 2005b. Residual stress analysis of the post-filling stage in injection moulding. *The International Journal of Advanced Manufacturing Technology*, 25(7-8), pp.700–704.

Zhou, H., Xi, G. & Liu, F., 2008. Residual Stress Simulation of Injection Molding. *Journal of Materials Engineering and Performance*, 17(3), pp.422–427.

Zini, E. & Scandola, M., 2011. Green Composites : An Overview. *Polymer Composites*, 32, pp.1905–1915.

Ziran, L., Gongxuan, C. & Haihong, W., 2010. The Simulation of Internal Stresses of Injection Molded Crystalline Polymers during Cooling Stage. *2010 International Conference on Computing, Control and Industrial Engineering*, (4), pp.136–140.

Zoetelief, W.F., Douven, L.F.A. & Housz, A.J.I., 1996. Residual thermal stresses in injection molded products. *Polymer Engineering & Science*, 36(14), pp.1886–1896.