OPTIMIZATION OF INJECTION MOULDING PROCESS FOR HDPE MOULDED GEAR

by

MOHD SYAHIR BIN MOHD KASSIM

A Thesis Submitted in Partial Fulfilment of the Requirement for the Degree of Master of Science

JULY 2015

ACKNOWLEDGEMENT

Alhamdulillah, through His Blessing and Dignity of Allah s.w.t. allowed me complete this thesis. I express my sincere gratitude to my supervisor, Assoc. Prof Dr. Shahrul B. Kamaruddin, for their endless guidance, support and encouragement towards completion of this research. Without his guidance and motivation, I could not have finished this dissertation.

The assistance from my colleagues; Nik Mizamzul Bt Mehat and Amirul Aliff Bin Jamaluddin is valuable for their help on perfecting my experiment plan and solving many related problems. Also special appreciation to all staff in Mechanical Engineering Department, USM for their help and support at work especially Mr. Syawal Faizal for his machine and mould setup.

I express my heartfelt gratitude to my beloved family mainly my father Mohd Kassim Shaik Mohd who give me moral support and inspiration. Finally, I would like to express my appreciation to Ministry of Higher Education, Mybrain15, for funding my tuition fees as well as USM research grant that providing me allowances during my study.

Mohd Syahir Bin Mohd Kassim
JULY 2015

TABLE OF CONTENTS

Contents

LIST OF TABLES

Page

LIST OF FIGURES

Page

LIST OF ABBREVIATIONS

AGMA	American Gears Manufacturers Association
ANOVA	Analysis of Variance
CAD	Computer-Aided Engineering
CRS	Conventional Runner Systems
DOE	Design of Experiment
DOF	Degree of Freedom
DSC	Differential Scanning Calorimeter
EPDM	Ethylene–Propylene–Diene Terpolymer
HDPE	High Density Polyethylene
HRS	Hot Runner System
LDPE	Low Density Polyethylene
MPI	Multi Performance Index
MQCI	Multiple Quality Characteristics Index
MSW	Municipal Solid Waste
OA	Orthogonal Array
PA	Polyamide
PCA	Principle Component Analysis
PIW	Post-Industrial Wastes
PP	Polypropylene
S/N	Signal-to-Noise
SAW	Submerge Arc Weld
SRT	Scrap Rubber Tires
T_{dec}	Decompose Temperature
TGA	Thermal Gravimetric Analysis

T_{onset}	Onset Temperature
WPCA	Weighted Principle Component Analysis

PENGOPTIMUMAN PROSES SUNTIKAN ACUAN TERHADAP HDPE GEAR

ABSTRAK

Pada masa kini, penggunaan plastik seluruh dunia meningkat secara mendadak dalam pelbagai applikasi produk. Berikutan permintaan, pengeluaran yang pantas diperlukan untuk menampung keperluan pasaran. Oleh kerana itu, semua pengilang plastik berusaha keras untuk mengekalkan kualiti produk dan pengilang juga dibebani dengan masalah pengurusan sisa plastik yang berkaitan dengan perlupusan sisa post-industri yang cekap. Pelbagai usaha telah dilakukan untuk memudahkan kitar semula plastik ke tahap yang lebih bagus dalam menyelesaikan isu pelupusan plastik serta peningkatan kualiti produk. Dalam kajian ini, kebolehlaksanaan proses berkala kitar semula HDPE dikaji berdasarkan ciri-ciri kestabilan dimensi, sifat mekanikal dan reologi bahan. Pengoptimuman proses parameter acuan suntikan terhadap gear HDPE telah dilaksanakan melalui kaedah integrasi Taguchi dan prinsipal komponen analisis (PCA). Penilaian prestasi mengambil kira fungsi pada gear plastik, kadar pengecutan dan sifat pemanjangan bahan. Eksperimen saringan telah dilakukan dengan susunan ortogon L_{18} untuk proses penyaringan parameter beerti yang terlibat. Kemudian, parameter yang optimal dan kesan interaksi parameter telah dikenal pasti melalui pengoptimuman eksperimen dengan menggunakan L_{27} OA, PCA, analisis kesan utama dan analisis varians (ANOVA). Keputusan mendapati, kadar pengecutan dan sifat tegangan pada gear HDPE dapat dioptimumkan secara serentak. Akhir sekali, parameter optimum yang diperolehi telah digunakan dalam eksperimen kebolehlaksaan untuk penilaian prestasi kitar semula berkala untuk HDPE. Keputusan mendapati bahawa pemprosesan kitar semula berkala pada peringkat ke-3 hingga ke-7 mempunyai prestasi yang optimum

di mana prestasi ia hampir sama dengan prestasi HDPE yang asal. Hasil daripada penyelidikan ini menunjukan bahawa keberkesanan integrasi kaedah Taguchi dengan PCA telah terbukti dalam pengoptimumam proses parameter dan pelbagai kualiti dalam HDPE gear telah dapat ditingkatkan secara serentak dengan bilangan nombor eksperimen yang rendah.

OPTIMIZATION OF INJECTION MOULDING PROCESS FOR HDPE MOULDED GEAR

ABSTRACT

Nowadays, the world's plastic usage has drastically increased in various applications of product. As demand, a high speed production is requires to sustain the market needs. Consequently, all plastic manufacturers are struggling to maintain the quality of moulded product and they are also burdened with plastic waste management issues related to the efficient disposal of the post-industrial waste. Numerous efforts have been done to facilitate the plastic recycling to a greater extent in solving the plastic disposal issues as well as quality improvement of moulded product. In this research, the feasibility of multiple recycle HDPE is investigated based on their dimensional stability, mechanical and rheological properties. The optimization of the injection moulding processing parameters for HDPE gear is presented via integration of Taguchi method with principal component analysis (PCA). Considering the functionality of the plastic gear, the shrinkage rate (tooth thickness, addendum and dedendum circle) and tensile properties (ultimate strength, Modulus Young, and elongation at maximum load) are selected as the performance response. A screening experiment was conducted with an L_{18} orthogonal array (OA) to screen out the significant parameters involved. Later, the optimal parameters and interaction effect is identified via optimization experiment with the used of L_{27} OA, PCA, main effect analysis and analysis of variances (ANOVA). As a result, the shrinkage characteristics and tensile properties of moulded gear are optimized simultaneously. Finally, the obtained optimal parameter settings were used in feasibility experiment in order to evaluate the performance of multiple recycle HDPE. The results depict

that reprocess cycle at 3rd to 7th have the optimal condition which closes to virgin HDPE performance. The experimental findings show the effectiveness of the integration Taguchi method with PCA in optimizing parameter settings has proved and also improve the multiple quality characteristics of HDPE moulded gear simultaneously with minimum number of experiment.

CHAPTER 1

INTRODUCTION

1.0 Overview

This chapter describes the research background including the plastic recycling injection moulding and the problem statement. Subsequently, the research objectives and scope has been explained. Finally, the thesis outline has been discussed in this chapter.

1.1 Research Background

The revolution of the industrial plastic is believed to have started around 1800s and it has attracted more attention of researchers in plastic development since it was introduced. In 1856, the first plastic was patented as 'Parkesine' by Alexander Parkes, a British metallurgist who introduced an organic material cellulose treated with solvent of nitric acid to create plastic (Fenichell, 1996). Later, an American researcher, John Wesley Hyatt has successfully created plastic in year 1869 with celluloid, where it has derived from cellulose and alcoholized camphor (McCord, 1964). Over a few decades, plastic material has been modified chemically for improvement and finally it was derived into synthetic material or known as modern plastic.

The development of plastic offers more benefits to human life in various applications of product because of their natural properties such as lightweight, durability and versatility. Due to these characteristics, plastic demand has increased drastically around the world to replace other materials to fulfil market needs from

simple product such as storage container, to sophisticated product such as heart replacement valve. In fact, with a wide range of properties with low cost of raw material, the global plastic production is significantly increased over 260 million tons by today. The quantities of plastics have been estimated will be reach at least 19 billion tons annually by 2025 (Yoshizawa et al., 2004). However, the excessive plastic product usage has directly increased the plastic waste. Additionally, inefficient plastic waste management has contributed to environmental issues in our life. Various approaches have been applied in plastic waste management such as recycling, landfill and incineration to overcome the plastic waste issue (Lazarevic et al., 2010). Due to limited space of landfill and non biodegradable plastic waste, landfill method is not really efficient to solve the problem of plastic waste, which takes a long period to decompose. Besides, incineration of plastic waste will release hazardous gasses that will affect the environmental and also human health. Realizing of these limitations of landfill and incineration method, recycling approach is considered to be used to solve plastic waste issues.

1.2 Plastic Recycling

Currently, the plastic waste management has been considered as a vital issue for Malaysian government due to the increasing population and the Malaysian lifestyle that contributes to environmental issues. Various efforts have been done to give awareness of the public about plastic recycling. Plastic recycling is the most effective method to manage plastic waste compared to the landfill and incineration waste disposal methods. Many studies have proven that plastic recycle products highly beneficial to the society, economic and environment as well (Ahmad & Mayamin, 2012).

The application of recycled plastic significantly can reduce the consumption of petroleum and preserve the limited resources. In fact, most of plastics are produced from fossil fuel or natural gas. The production of plastics needs 8% of the world's annual oil production as a feedstock, where 4% from that amount is used in energy consumption of plastic process (Plastic Ocean, 2010). Besides, the recycled plastic material can saved up to 70% of energy consumed in the process plant in terms of electricity or fuel compared to virgin resins production (Santos & Prezzin, 2003). If all these factors are considered, the recycling of plastic waste would be efficient.

To date, the government authority has restricted the environment regulations to all plastic manufacturers in order to comply the ISO14001 in preventing pollution. Manufacturers need to considering the green productions in order to facilitate the plastic recycle process to a greater extent. Nevertheless, a large scale of recycled plastic has been doubted to be good replacement of virgin plastics. The changes of material properties in plastic recycling such as mechanical and rheological properties have created a bad perception that plastic recycling has produced low quality products. Therefore, most of manufacturers prefer a virgin resin plastic in their production rather than recycled resin plastic. Indeed, the properties of recycled plastic tend to decrease after several reprocessing cycles (Balart et al., 2005). However, the improvement quality of recycled plastic product could be made via optimization processing parameters in order to find optimal performance with satisfactory quality.

1.3 Injection Moulding

Injection moulding is one of the common methods used in plastic manufacturing process for fabrication of plastic part with a great dimensional tolerance; vary size product and complexity. Growing demands on plastic product requires high speed production line to sustain market needs. The quality product will be the first priority in manufacturing process to avoid rejected part and loss of profit. To achieve a good quality product, several factors needs to be considered in term of materials, injection machine, mould design and process parameter setting.

In view of process control, processing parameters of injection moulding can be classified into four groups; temperature, time, pressure and distance. The quality of moulded part fluctuates within a particular range due to incompatible input parameters setting (Alireza & Mohammad, 2011). Moreover, the interaction effect analysis of particular parameters is required in determining the relationship between the parameters. Therefore, finding the optimized parameters is most desirable in injection moulding process in order to achieve a good quality performance of moulded parts.

1.4 Problem Statement

In the injection moulding industry, the processing parameter setting significantly influences the quality of moulded product. Previously, trial and error method is used in determining the optimal parameters settings. However, this method is not systematic and it involves high cost of operation. The optimization process parameter requires multidisciplinary knowledge and more systematic method to replace the trial and error method which causes consuming time, high cost and needs extra works. This issue has been raised among plastic manufacturers to find

out an efficient optimization approach which has the ability to optimize multiple quality characteristics of moulded parts. Therefore, this study proposes an efficient optimization method of injection moulding process parameter.

Regarding the plastic recycle issues, many plastic manufacturers have interest to utilize plastic recycle material into their plastic fabrication in order to reduce production cost. Usually the plastic recycle properties have improved via blending method, either blending with virgin material or other different materials. However, is it possible for multiple recycles of polymer to be able to provide a good quality of moulded part? Hence, an alternative effort has been done in this study to investigate the feasibility and quality finished product of multiple reprocessing of HDPE plastic material toward optimize processing parameter.

1.5 Research Objectives

The objectives of this research can be describes as;

1. To optimize the processing parameters of injection moulding in order to achieve the optimal quality performance of moulded gear.
2. To study the effectiveness of integrated Taguchi method with Principal Component Analysis in optimizing multiple quality characteristics of moulded part.
3. To investigate the feasibility and quality finished product of multiple recycle plastic towards optimized processing parameter.

1.6 Research Scope

In view of plastic waste management, there are two types of plastic waste that can be classified; post-consumer waste and post-industrial waste. In this study, the post-industrial waste is preferred due to its purity of material and the possibility of contamination material is less. Additionally, plastic type is restricted to thermoplastic because of their recyclable properties, which has the ability to undergo the reheating process. Considering the common thermoplastic material, High Density Polyethylene (HDPE) is selected as the main material for fabricating moulded gear. To limit scope of study, the recycle material is prepared from virgin material scraps and it is used repeatable for 15 reprocessing cycles.

Considering the application of plastic gear, the dimensional stability and mechanical properties of gear have been selected to be analyzed for quality improvement. Due to the complexity of geometry, the injection moulding process is used to produce the moulded gear via numerous parameters settings. The significant processing parameter of injection moulding is analyzed in order to obtain the optimal performance of quality characteristic moulded gear. The integrated of Taguchi method and principal component analysis (PCA) were utilized in the optimization process of multiple quality characteristics performance.

1.7 Thesis Outline

This thesis covers five chapters which include introduction, literature review, methodology, result and discussion, and conclusion. Chapter 1 in briefly discusses the research background which is related to plastic development, the issue of plastic waste management, injection moulding, plastic product quality and processing parameter. Moreover, the problem statement and objectives of this research are also mentioned in this chapter. Chapter 2 discussed the current knowledge and studies from other researchers that are related to fundamental of plastic, plastic recycling, injection moulding process, improvement quality of moulded plastic and optimization of process parameter. Chapter 3 describes the methodology used in this research where the procedure is explained in detail including the screening, optimization and feasibility of experiment. Chapter 4 analyses and discusses the result obtained from experiments based on optimization of processing parameters toward quality moulded gear. The feasibility experiment analyzes the effect of recycles material toward the quality of moulded gear. Finally, chapter 5 highlights the conclusion of research work in this chapter and ends with recommendations for future work.

CHAPTER 2

LITERITURE REVIEW

2.0 Overview

This chapter begins with a brief discussion about plastic material, their consumption and their impact on environmental issues. Later, the following sub-section described the matters on plastic recycling including the limitation on the uses of recycled plastic. Considering the gear as a main subject to be pertinent with plastic applications, the details on plastic gear will be review thoroughly on subsequent sub-section. An introduction to numerous of plastic gear's processing method is presented and the injection moulding process is highlighted as a main focus to be discussed in this study. Subsequently, the influences of material selection, mould and product shapes design as well as processing parameters in affecting the quality of produced parts has been reviewed. Previous work relating with standalone Taguchi method and integration of Taguchi method with principle component analysis (PCA) will be reviewed thoroughly. Finally, the findings from the literature review will be concluded at the end of this chapter.

2.1 Plastic Overview

"Plastic" was defined as a type of high molecular mass synthetic polymers (American Chemistry Council, 2012). Generally, plastics are formed from the organic natural resources originated from the synthesis of plants or petrochemicals substances and it can be classified into two types: thermosetting and thermoplastic. Thermosets is a synthetic polymer that cannot be reprocessed once it was used during

manufacturing process. However, thermoplastic has a contra characteristic with thermoset material. Thermoplastic is a synthetic polymers that can be recurrently reheated over and over against without undergoes any substantial chemical change. The variability and versatility of plastic materials have allowed themselves to meet specific technical requirements for particular applications.

Plastic's product manufacturing is one of the most growth industries in the world. The unique characteristics of plastics, such as durable, lightweight and inexpensive are very attractive to be used as a daily consumer's product. Plastics application has highly penetrated into multi-purpose application such as in producing the electric and electronic parts, household, packaging material, automotive part, construction material, medical tool and many more. According to Jose (2012), Global Industry Analysts Incorporation has reported that the global plastic consumption will reach approximately 297.5 million tons by 2015. Moreover, it was expected that the global plastics consumption will grow for 4% per year from 2010 to 2016. Obviously, the aforementioned statistic has figured out that plastics have become an important material in our daily life application.

Unfortunately, the huge amount of plastics consumption has raised a critical issues related to the environmental conservation problems. The non-biodegradability properties of plastic materials lead to the increasing amount of plastic wastes and become a major threat particularly on land pollution problems since it probably takes a decade to completely decompose. According to U.S. Environmental Protection Agency (2014), there are 32 million tons of plastic waste were generated in 2012, which accounts for 12.7% of total municipal solid waste (MSW) where 14 million tons of plastics are packaging and containers, 11 million tons are durable goods and 7

million tons are nondurable goods. It is very difficult and costly to manage such a huge amount of plastic wastes.

Hence, there is necessary to find the best solution for a sustainable plastic waste management strategy to properly manage the huge amount of plastic materials that piled in the waste stream. At present, the landfill disposal method and incineration method is not more relevant due to the limitation of land filling space availability and an emission of dangerous gaseous that can harm human health. Therefore recycling is identified as the best solution for plastic wastes management with the advantage in pollution reduction as well as effective reduction of fossil energy consumption.

2.2 Plastics Recycling

Since plastic was introduced in 1940s, the plastic's production and consumption was increase drastically due to high demands all around the world for various applications in order to fulfil the current needs. Consequently, plastic solid wastes disposal has increased instantly. Thus, the plastic recycling approach has promise a best solution in reducing the rate of plastic wastes disposal, reduces the issues on the landfill's space problem as well as reduction in the emission of harmful gaseous through incineration process. According to Fei (2013), plastic wastes can be divided into two categories consist of post-consumer wastes and post-industrial wastes. Post-consumer waste can be referred as the wastes that generated by surrounding consumers especially by the peoples in residential area. Generally, post-consumer plastic wastes are contaminated with other foreign materials and need to be segregated before the recycling process can be performed (Takoungsakdakun & Pongstabodee, 2007). On the other hand, post-industrial wastes are referred as the

process scrap parts such as sprues, runners and defect parts that are not contributing into production. In contrary to post-consumer plastic wastes, the post-industrial plastic wastes are relatively clean since it consists of homogenous materials type. Therefore, the compatibility problem should not be an issue in this post-industrial plastic wastes recycling process.

Generally, plastic recycling process can be divided into four major categories; primary, secondary, tertiary and quaternary. Each category provides a particular benefit and advantage for specific requirement.

i. Primary recycling

Primary recycling is known as a closed loop recycling method. The disposed polymers such as drinking bottle and oil container is collected and reprocessed to their original use with similar properties (Al-Salem 2009). However, the plastic wastes should be properly segregated since this primary recycling only compromise for clean and homogenous plastics type.

ii. Secondary recycling

Secondary recycling process is referred to an open loop recycling process that involved the altering of mechanical or physical properties of new produced products (Mastellone, 1999). In fact, the wastes used in this secondary process consist of heterogeneous plastics type that commonly contaminated with other post-consumers materials. Therefore, the recycled product's performance is downgraded due to the existences of impurities and incompatibility issues.

iii. Tertiary recycling

Tertiary recycling process is knows as feedstock or commonly known as chemical recycling. This type of recycling process involve an advance processing approach by converting polymer wastes into low molecular weight, monomers or valuable chemical for petrochemical stock (Cardona & Corma, 2000). Common process involved for tertiary recycling process is chemical depolymerisation and thermal decomposition reaction. However, it is very costly and limited to be applied for commercial purpose due to economical consideration.

iv. Quaternary recycling

Quaternary recycling or energetic recycling is a process that involved the energy recovery by plastic wastes combustion as a source to generate electricity (Ha & Kyung, 2012). However, the plastic that is derived from crude oil may contain a very high calorific composition and it will release several of harmful gaseous such as dibenzofurans which irritated to human and environment health. Although it offers several advantages for energy recovery purpose, this quaternary recycling process is considered as the last method option for plastic wastes annihilation due to health and safety issues.

The classification of recycling process is clearly discussed in this section and it is very useful to recognize the type of recycling process that is involved in this study. Besides, the recycling material has several limitation in order to maintain the performance of quality material same as virgin material. This issue will discuss in the next section.

2.3 Limitations of Recycled Plastic

The biggest challenge of recycling process is to maintain the polymer performance within levels, which allow the material reuse in the same or other particular purpose. Almost all established plastic industry are preferred the virgin plastic resin to ensure and secure the properties of the material meet their product requirement especially in food packaging sector, medical tool and for baby product (Eureka Recycling, 2009). Although plastic waste undergoes several recycle process and a comprehensive treatments is needed to ensure it as pure as possible.

Basically the properties of recycled plastic have changes after recycling process particularly on physical properties such as material purity, thermal and mechanical properties. This phenomenon occur during reprocessing operation that is caused degradation effect and directly change the molecular structure where it gives side effect on the mechanical performance and on the rheological characteristics (Scaffaro, 2012).

Contamination with impurities material often appears on recycling plastic because uncontrolled waste material during segregation process. The contamination recycled plastic are referred in various form such as dirt, partially oxidized polymers, printing inks, paper, pesticides, metals, additives and so on (Scheirs 1996). Normally it happens to post-consumer waste because they are not classified the plastic waste properly follow their type and mixed with other element. Ruifeng and Rakesh (2001) were claimed in their study that 1% impurity of polymeric have enough to decrease certain mechanical properties. It means more than 99% purity of polymer is needed to sustain their originality of material properties. In addition, the blending of difference types of polymer could be treated as impurity because the microstructure

it formed, incompatible each other and contribute the fraction in microstructure. Mathew and Thomas (2003) has proved in their study that incompatible blending polymer can induces the poor adhesion of microstructure and the polymeric fraction which influences the performance of material properties.

Thermal degradation is also one of the effects in polymer recycling process. Generally, thermal degradation occurred when the polymer is overheated exceeding the service temperature until the primary chemical bonding are separated or known as molecular scission (Van & Klass, 2009). Once the microstructure of the polymer is changes due to thermal degradation, there has some effect are induced on their important mechanical properties such as stiffness, tensile strength and impact resistance (Moeller, 2008). Vilapna et al. (2006) discovered in their study that multi recycle polymer will alter the oxidative stability in polymer, hence it significantly influence the elongation properties of material. Besides, Karahaloiu and Tarantili (2009) also agreed that thermal degradation occur during reprocessing polymer will induced the microstructure chain scission and influences the mechanical and rheological performance of material.

2.4 Plastic Gear

The term 'gear' can be considered as a basic component of machine in human's life application. The revolution of gears application is begins since the invention of rotating machinery that used in generating power and motion transfer (Drago, 1998). The gear applications have received a special attention around the world due to their unique features in term of technical operation. At the beginning of creation, the gears have been made from wood. In eighteenth century, during the British industrial revolution, the metal gear design and manufacturing is rapidly

developed. Indeed, the development of gear technology is keep expanding till today especially in materials and design improvement. Modern metallurgy is significantly contributed to the variety of gear application; i.e. in the automotive industry as well as electric and electronic devices (Mallesh et al., 2009).

Currently, the performance of plastic gear have achieved a new level in developing process to replace the metal gears in various application from large component to micro and nano-scales of electronic devices (Hakimian & Sulong, 2012). Most of technical community are prefer the plastic gear in machine applications due to several features, such as lubricant-free, silent operation and lightweight properties (Lin & Kuang, 2008). The advances of materials and moulding technology have successfully lead the better performance of plastic gear in carrying load motion and power transmission (Kim, 2006).

According to Mendi et al. (2006), the failure mechanisms of plastic gear have been exhibited similar to metal gear, for example an excessive wear, creep, tooth fatigue and deformation. However, the limitations of plastic gear and metal gear are able distinguished through their performance. In facts, the plastic gears have poor properties in term of mechanical, thermal resistance, load-carrying capacity, service life and modulus elasticity compared to metal gear (Senthilvelan & Gnanamoorthy, 2006). Due to these properties, the plastic gear applications are limit and unable to sustain a high load capacity and accumulated heat.

Over a few decades, a numbers of studies have been conducted to analyse the quality of material and failure mechanisms of plastic gear during operation. Ikegami et al. (1986) studied the plastic gear material performance on mechanical strength of glass and carbon roving clothes reinforcement. The finding shows the glass

reinforcement is significantly improved the bending strength of plastic gears. Otherwise, Yakut et al. (2009) investigated the capabilities of plastic gear in resisting load through a meshing method. As a result, the meshing gears of different polymer PC/ABS can resist a high load capacity compared to homogeneous polymer PC/PC and ABS/ABS. Moreover, the modification of plastic gear has been made to improve the gear performance. Düzcükoğlu (2009) investigated the thermal distribution on tooth surface of polyamide gear. The cooling holes were drilled at different location on tooth surface for the purpose of distributing the generated heat. The results showed, the modified design is successful to decrease the temperature of tooth surface and wear resistance has been improved. In other works, İmrek (2009) modified the teeth width of Nylon6 spur gear in order to investigate the gear damage. From this study, the author found that modified Nylon 6 gears exhibited lower tooth temperatures and decreased in wear rate.

Most of study was reported on performance of material and gear design modification (Wright & Kukureka, 2001). However, the study about effect of manufacturing process in gear making is rarely done. In obtaining a good quality of plastic gear, advances knowledge of manufacturing process is required. Therefore, this study emphasized the manufacturing process of plastic gear for better improvement and it will further discuss in next section.

2.5 Plastic Gear Manufacture

Generally, plastic gears are able to be manufactured via two main methods; either machining (removal process) or injection moulding (forming process). The machining process of plastic gear is done similarly to process used in machining of metal gears. According to Davis (2005), there are several reason to be considered

machining process over moulding as the manufacturing process of plastic gear; the small quantities of produced gear is required to justify the tooling cost for moulding process, complex gear design with a high dimensional tolerance may be too difficult for moulding, unsuitable plastic materials for moulding process.

However, the produced plastic gear of machining process invariably leave gear teeth with different strengths, wear resistance and chemical resistance. For these reasons, the injection moulding is more preferable method in manufacturing of plastic gear. Besides, the material used in machining process may expose to void especially for fibrous material such as glass or carbon fibre, when it is used as additives in moulded gears. The additives may be removed during machining process and the surface of material will leave openings. Comprehending to these facts, the injection moulding method is selected process in this study for plastic gear manufacturing process. Understanding the injection moulding process is needed in finding the solution related to the quality problems of plastic gear. Therefore, the fundamental issues of injection moulding will be reviewed in the next section.

2.5.1 Injection Moulding Process

Injection moulding is very common method used in plastic manufacturing process, especially in producing complex parts and various sizes of mass production. In facts, more than one third of all thermoplastic materials are manufactured in injection moulding (Shen et al., 2007). According to Hill (1996), injection moulding process can be defined as a forcing operation of hot molten polymer into the mould system. Technically, the main parts of injection moulding machine are consists of hopper, barrel, screw and mould. In view of injection moulding process, it can divided into four phase; filling, packing, cooling and ejection (Bozdana &

Eyercioğlu, 2002). The beginning of process, the pellet or plastic granular from hopper is dragged into the hot barrel. The plastic granular is melted due to heat on barrel surface and the friction of the screw rotation. The reservoir of molten plastic is accumulated in the barrel. Then, the molten plastic is injected by force pressure rapidly through a nozzle into a mould cavity. Once the mould cavity is filled, packing pressure is applied. The moulded part is solidified gradually in cooling stage. When the product has reached a temperature below the solidification point, the mould is opened and finally, the product instantly ejected by pusher.

Many of plastic manufacturers preferred the injection moulding method due to the capability of machine running is continuous with low operating cost and also provide a high quality product (Tsai et al., 2009). The credibility of injection moulding method has proven in various plastic manufacturing products such as medical equipment, electric-electronic devices, and automotive parts, which exhibited an excellent dimension accuracy and good finished surface as well (Wong et al., 2008). Therefore, injection moulding is reliable manufacturing method in producing complex product like plastic gear.

Similar to any manufacturing process, there are some limitations associated with injection moulding. An intensive effort is required in controlling the parameter settings of injection moulding in order to achieve a good quality product. Galantucci and Spina (2003) stated that quality of injection moulded product can be evaluated based on dimensional stability, appearance and mechanical properties performance. The dimensional stability is referring to size and shape of moulded part against the shrinkage and warpage. Moreover, the product appearance is evaluated based on aesthetics values of moulded part which free from any burn marks, weld lines, poor

surface finish, air traps and sink marks. Lastly, the mechanical properties of moulded part can be tested in term of tensile strength, impact strength, elongation and modulus elasticity.

The consistency quality of moulded part is a crucial aspect in manufacturing process to satisfy the customer needs. However, there are many influence factors that contribute to the occurrence of defect product. In facts, the different condition of injection moulding process may lead a different condition of quality product. Comprehending to these facts, the root cause of the product defect need to be studied for further improvement and also optimize all possible defects as well.

2.5.2 Influential Factors on Injection Moulded Quality

According to Chang and Faison (2001), there are several factors need to be considered in producing a good quality of plastic moulded product; material selection, mould and product design, and processing parameters. The compatible settings of material selection, mould design and processing parameters could be reduces the percentage of defect in production. The explanation on how the factors are contributes to the occurrence of defect will further discussed in next section.

a) Material Selection

Material selection is a crucial stage in designing the injection moulded product. Based on statistic survey by Stress Engineering Services (2012), poor material selection contributes 45% of product failures and it's give a substantial impact on product's quality performance. There are many factors need to be considered in selecting the material for product design. Jahan et al. (2010) emphasis the selection of material is based on various aspect including function of product,

material properties, processability, cost, constraint, environmental aspects and aesthetics.

A few studies have been done to present the fundamental and theoretical for selection procedure of material. Da Costa et al. (2006) analyzed the impact strength on mixtures of ground scrap rubber tires (SRT) and polypropylene (PP); ethylene–propylene–diene terpolymer (EPDM) and PP; and, ground SRT, PP and EPDM. The finding shows, no major change on impact strength of mixed ground scrap rubber tires (SRT), even it worse then unmixed condition. This is happened due to a poor adhesion and large rubber particle size. Based on this study, the incompatibility of material mixed may lead worse material performance.

Moreover, Kurokawa et al. (2003) studied the gear performance on four different types of carbon fiber reinforced polyamide material; polyamide 12 (PA12), polyamide 6 (PA6), polyamide 66 (PA66), and polyamide 46 (PA46). As a result, the author found that material reinforced PA12 of gear shows a great performance in sustaining high load capacity, noiseless operation and low water absorption. Furthermore, Moa, et al. (2009) investigated the failure mechanism of gear friction and wear behaviour. Two different materials, acetal and nylon were used and tested under a same constant load. The results showed that acetal gear experienced worn on tooth surface, whereas nylon gear has fractured at root and pitch. From this study, the different material selection is clearly showing the different performance of product.

Often, the material selection is done manually. It is very complicated and expensive process due to various available materials is introduced every years and the decision maker required a high knowledge and experiences. Today, the material

selection is not an issue anymore for manufacturer because the material information is available in material data bank such as computer-aided engineering (CAD) software and HyperQ/Plastics program (Beiter et al., 1993). The developed programme software has offered better flexibility in selecting the correct material.

b) Mould System and Product Design

As known, the mould system is a main part in supporting the injection moulding process. A bad design of mould system can lead to disastrous consequences on the quality of produced part. Barrière, et al. (2002) emphasized that mould and product design as well as injection parameter settings have a mutual influences and interact each other. Therefore, understanding the mould operating system includes its mouldablility of part geometry and parameter settings are required in order to improve the product quality.

In the study of Kim et al. (2003), the gate position in mould design significantly influence the flow pattern of injection molten plastic. The author observed the resin flow pattern and modified by varying four different gate locations of mould design in order to avoid the product failure such as short shots formed in injection process. From this study, the short shots defect has overcome and the molten plastic smoothly fills in the mould cavity. In another study, Demirer et al. (2007) conducted an experiment to investigate the effects of runner system on injection moulding process and properties of injected part. The author made a comparison for both conditions of mould system, between the conventional runner systems (CRS) and hot runner system (HRS). Findings of this study showed, the hot runner system required low injection pressure in producing high weight product. The

shrinkage and warpage decreased with decreasing process temperature, increased with decreasing injection pressure.

In view of product design, the performance and functionality of product can be influenced by modification of product's geometry. Düzcükoğlu (2009) conducted an experiment to observe the performance of modified and unmodified plastic gear tooth width. The different loads were applied on gear rotation. The results showed the wear damage on modified tooth gear has been delayed compared to unmodified gear. This study has proven that product design significantly influenced the performance of moulded product. Therefore, the plastic manufacturer must take into account and should not be underestimated the contribution factor of the product and mould design that affecting on the quality of moulded part.

c) Processing Parameters

Apart of material selection, mould and product design, parameter settings of injection moulding is considered as a main contribution factor that affecting the quality of moulded product. Due to the complexity of injection moulding process, the variation of defects could be occurred on product such as short shots, shrinkage, residual stress, warpage, burn mark and sink mark (Oktem et al., 2007). According to Bryce (1996), there are four basic groups of processing parameters involved in injection moulding; temperature, time, pressure and distance.

Many researches have been done to investigate the influence of injection moulding parameters on the quality of the moulded part. Mehat and Kamaruddin (2011) investigated the effects of injection moulding parameters on the mechanical properties of recycled plastic toolbox tray. By considering six processing parameters, the preliminary experiment was conducted via Moldflow Plastic Insight integrated

with the L_{18} Taguchi orthogonal array (OA). Subsequently, the significant parameters obtained from preliminary experiment were used to conduct a principal experiment via L_9 Taguchi OA. As a result, authors found that injection time is significantly influence the flexural modulus of a recycled toolbox tray by percentage contribution of 40.49% and the melting temperature is significantly influence the yield stress with percentage contribution of 43.34%. Zhil'tsova et al. (2009) studied the effect of filling rate, packing pressure, packing time and hot nozzle temperature of the mould on the dimensional stability of high density polyethylene (HDPE) acetabular cups. Findings showed the packing pressure is the most influential factor on dimensional stability of HDPE acetabular cups.

In other study, Chen et al., (2009) reduced the warpage of moulded thin shell plastic part. Four processing parameters were analysed via simulation and experiment. The results obtained from both analyses were compared side-by-side. As a result, authors found that melting temperature and packing pressure is the most significant factors in contributing warpage on thin shell. Moreover, Ozcelik (2011) optimized process parameters condition and weld line on the mechanical properties of polypropylene (PP) mouldings. Three processing parameters have been considered including melting temperature, packing pressure and injection pressure. The results showed the injection pressure and melt temperature are the most important parameters affecting the maximum tensile load and the extension at break.

In plastic gear making process, compatible injection parameter settings can improve the quality of moulded gear. Mehat et al., (2012) optimized the process parameter settings of injection moulding, in order to reduce the shrinkage of tooth thickness, addendum and dedendum circle of moulded PP. Finding showed that

packing pressure, cooling time and packing time is the most significant injection parameters that influenced the dimensional stability of moulded PP gear. In other study of Mehat et al., (2013), the effects of process parameters settings including melting temperature, packing pressure, packing time and cooling time have been studied on properties of elongation and ultimate strength of PA6 plastic gear. The results indicated that melting temperature, packing pressure, packing time and cooling time have contributed to the variation performance of elongation and ultimate strength of moulded PA6 gears.

Comprehending to case studies, the optimal processing parameter settings of injection moulding is an important factor need to be considered in producing a better quality moulded part. Therefore, a systematic optimization method is required to facilitate the parameter settings. For better understanding on the optimization method used in this research, detail explanation will further discuss in next section.

2.6 Optimization Method

As discussed in previous section, there are many influential factors that affecting the injection moulded quality product; including inappropriate material selection, poor mould and product design, and incompatible parameter settings. However, this study emphasized the optimization of parameter settings in injection moulding process in order to obtain the optimal performance of quality moulded product. Therefore, the effectiveness and a reliable optimization method must be applied to control the influential parameters and directly can improve the product's quality performance.

Design of experiment (DOE) is one of common method used in designing and optimizing the process control. In early 1920s, DOE was introduced by British