AN INTEGRATION OF TAGUCHI METHOD AND RESPONSE SURFACE METHODOLOGY (RSM) ON INJECTION MOULDED PP GEARS FOR PARAMETERS OPTIMIZATION

by

AMIRUL ALIFF BIN JAMALUDIN

Thesis submitted in fulfillment of the requirements

for the degree of

Master of Science

February 2015

Acknowledgement

In humbleness, thank you Allah for allowed me to complete this dissertation. I dedicated this work to my beloved parents; Mr. Jamaludin Bin Musa and Madam Kamariah Binti Ismail who always, support and motivate me in many ways.

First of all, I would like to express my deep gratitude and sincere thanks to my supervisor, Assc. Prof. Dr. Shahrul Bin Kamaruddin for his thoughtful supervision, steady support, guidance, critics and comments to improve the dissertation and the content of the research work. Without him, I would not be able to complete my research in such an efficient manner.

Apart from that, I would like to express my appreciation to Miss Nik Mizamzul Mehat, Mr. Shawal Faizal, Mr. Fakruruzi Fadzil and others School of Mechanical Engineering technical support team for their continuous support and assistance in this research.

Finally, I would like to express my appreciation to Ministy of Higher Education, for funding my tuition fees, Universiti Sains Malaysia research grant for providing me subsistence allowances and all those who helped me to complete this research.

Amirul Aliff Bin Jamaludin
February 2015

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

LIST OF ABBREVIATIONS

ABS	Acrylonitrile Butadiene Styrene
AGMA	American Gears Manufacturers Association
ANOVA	Analysis of Variance
Au/Pd	Gold/Palladium
CAD	Computer Aided Design
CCD	Central Composite Design
DOE	Design of Experiment
DOF	Degree of Freedom
DSC	Differential Scanning Calorimetry
LDPE	Low Density Polyethylene
MFR	Melt Flow Rate
MSW	Municipal Solid Waste
MW	Molecular Weight
MWD	Molecular Weight Distribution
OA	Orthogonal Array
PIW	Post-Industrial Wastes
PA	Polyamide
PA6	Polyamide 6
PA12	Polyamide 12
PA46	Polyamide 46
PA66	Polyamide 66
PC	Polycarbonate
PE	Polyethylene

PP	Polypropylene
PS	Polystyrene
PSW	Plastic Solid Waste
PTFE	Polytetrafluoroethylene
RSM	Response Surface Methodology
SEM	Scanning Electron Microscopy
SMA	Styrene Maleic Anhydride
S/N	Signal-to-Noise
SS	Sum of Square
TGA	Thermo Gravimetric Analysis
T_c	Degree of Crystallinity
T_m	Melt Temperature
T_{max}	Maximum Thermal Degradation Temperature
T_{od}	Onset Thermal Degradation Temperature

PENYATUAN KAEDAH TAGUCHI DAN KAEDAH GERAK BALAS PERMUKAAN DALAM MENGOPTIMUMKAN PARAMETER PENGACUAN SUNTIKAN GEAR PP

ABSTRAK

Sejak kebelakangan ini, terlalu banyak perhatian diberikan kepada kitar semula bahan plastik, yang mana ianya mempamerkan banyak kelebihan jika dibandingkan dengan proses yang lain. Oleh itu, proses kitar semula diaplikasikan secara meluas dalam penggunaan semula bahan buangan semasa pemprosesan bahan plastik di industri. Walau bagaimanapun, perubahan sifat semasa proses kitar semula adalah masih sukar untuk difahami, misalnya untuk menjangka prestasi kualiti produk yang dihasilkan dari plastik yang dikitar semula. Dalam kajian ini, kebolehgunaan polipropilena (PP) yang dikitar semula sehingga 15 kitaran untuk digunakan sebagai pengganti bagi PP dara dikaji dengan menilai pengaruh parameter pemprosesan terhadap sifat-sifat pengecutan dan mekanikal. Sebuah pendekatan gabungan antara kaedah Taguchi dan kaedah gerak balas permukaan telah digunakan untuk mengoptimumkan sifat-sifat kualiti gear suntikan acuan. Mengambil kira fungsi dan aplikasi produk, ketebalan gigi, pengecutan bulatan adendum, pengecutan bulatan dedendum, kekuatan tegangan terakhir, modulus Young dan pemanjangan semasa patah dipilih sebagai penilaian prestasi bagi gear yang dihasilkan. Dalam kajian ini, eksperimen telah dijalankan dengan mengunakan L_{18} susunan ortogo untuk mengenal pasti parameter yang bererti. Hasil dari eksperimen pemeriksaan dengan menggunakan kaedah Taguchi, menunjukkan bahawa suhu pencairan, suhu acuan, tekanan suntikan, masa suntikan dan masa pengepakan adalah sangat mempengaruhi sifat-sifat pengecutan dan mekanikal gear PP. Dengan mempertimbangkan kesan interaksi di antara parameter-parameter bererti tersebut, sebuah model matematik telah dibangunkan untuk menyiasat kesan parameter pemprosesan terhadap kualiti gear yang dihasilkan. Akhir sekali, analisa fungsi keboleh-inginan dilakukan untuk meningkatkan sifat pengecutan dan mekanikal gear di bawah satu set keadaan proses parameter yang optimum. Hasil dari optimasi respon berganda, suhu pencairan telah ditetapkan 220.03 ºC, suhu acuan telah ditetapkan 40 ºC, tekanan suntikan telah ditetapkan 99.98 bar, masa suntikan telah ditetapkan 3s dan masa pengepakan telah ditetapkan 14.83s dengan tujuan untuk mengoptimumkan sifat-sifat pengecutan dan mekanikal gear PP. Hasil dari kajian ini dapat memberi manfaat yang besar kepada penguji kaji dalam mengoptimumkan sifat-sifat pengecutan dan mekanikal gear PP suntikan acuan dengan bilangan eksperimen dan kos pemprosesan yang minimum.

AN INTEGRATION OF TAGUCHI METHOD AND RESPONSE SURFACE METHODOLOGY (RSM) ON INJECTION MOULDED PP GEARS FOR PARAMETERS OPTIMIZATION

ABSTRACT

Recent years, much attention has been paid to material recycling of plastics, which exhibits many advantages as compared to other kind of processes. Thus, the plastic recycling is widely utilized in the reuse of waste during the industrial processing of plastics. However, the changes in properties during recycling process still remain unclear, for instance, to anticipate the performance of products made of recycled plastics. In this research, usability of reprocessed polypropylene (PP) up to 15 cycles as substitute for virgin PP is investigated by evaluating the influence of processing parameters on shrinkage and mechanical properties. An integrated optimization approach based on Taguchi method and response surface methodology (RSM) analysis was utilized to optimize the quality properties of injection molded gears. Considering the functionality and application of the product, tooth thickness shrinkage, addendum circle shrinkage, dedendum circle shrinkage, ultimate strength, Young’s modulus and elongation at break are selected as the performance measured of moulded gear. In this research, the experiments have been conducted by using L_{18} Taguchi’s experimental orthogonal arrays design to identify only on the significant factors. As a result of Taguchi’s screening experiment, melt temperature, mould temperature, injection pressure, injection time and packing time was identified as significant processing parameters that have a great influence on PP gear shrinkage and mechanical properties of PP gear. Considering the interaction effect between the significant processing parameters, a mathematical model has been established in

order to investigate the influence of processing parameters on produced gear's quality properties. Finally, the desirability function analysis is performed with an intention to simultaneously enhance both of shrinkage and mechanical properties of produced gears under one set of optimal processing parameters setting. Results of the optimal multi-response optimization show that the melt temperature was set to 220.03 ºC, mould temperature was set to 40 ºC, injection pressure was set to 99.98 bar, injection time was set to 3s and packing time was set to 14.83 s in order to get both of optimal PP gear's shrinkage and mechanical properties. The results drawn through this study can be of great significance to the practitioners, in optimization of shrinkage and mechanical properties of injection moulded PP gears with a minimum number of experiments trials and processing cost.

CHAPTER 1

INTRODUCTION

1.0 Overview

In this chapter, the introduction of the plastics and their production's impact on the environment together with the solution is be presented. At the end of this chapter, the problem statement is be highlighted together with the objectives, scopes and outlines of this thesis.

1.1 Research Background

Plastic, once hailed as a modern-day wonder, has attracted more attention in the literature for the past 100 years. The invention of plastic began in 1855 by Alexander Parkes, a British inventor and metallurgist who used chemical solvents and nitric acid in combination with natural cellulose makes a debut in plastics development to create a plastic that he has patented as "Parkesine" (Ferdous and Das, 2013). Moreover, in 1907, Leo Baekeland, a Belgian-born American chemist introduced a synthetic plastic called as "Bakelite", which came to be used in television and radio casings, toys and even kitchenware (Hirano and Asami, 2013). Since the early 1950s, the continual development, modification and refinement of materials make plastics experience a rapid growth in world's major industry.

Plastics have formed a significant role in modern world and transformed the quality of life. There is no exaggeration to say that our daily life activities will be impossible without plastics. Plastic applications are unlimited in our daily life from clothing to shelter, from entertainment to health care and from transportation to communication. The versatility of attractive properties such as high strength, lightweight, cost effectiveness and ease of processing make plastic materials one of the most important materials needed by men. As a consequence, the worldwide demand and production of plastics has increased substantially over the last 100 years from around 0.5 million tons in 1950's to over 260 million tons today and this figure is expected to increase up to 19 billion tons by the year 2025 (Bari et al., 2012).

1.2 Impacts of Plastic Production

Over the last 60 years plastic plays lots of important roles in our life and day after day our planet is threatened by the tsunami of plastic waste. Environmentally, plastic is a growing disaster and the widespread production of plastic leads to the depletion of our natural resources. Most of plastic are made from petroleum or natural gas and production of plastics has a great impact on oil consumption. According to British Petroleum Statistical Review of World Energy (2014), the world's total oil consumption in 2013 was 91.331 million barrels per day and the total proved reserves of global oil at the end of 2013 are estimated around 1.688 trillion barrels. It is estimated that around 8 percent of the world's oil production are being consumed to make a plastic where 4 percent from that figure is used in energy consumption during their production (Plastic Oceans, 2010). The 8 percent of the total global oil production consume to produce plastics is a significant figure and our oil reserves estimated to be lasted only 50 years before they are completely depleted. Besides, there is a challenge in disposing of the waste created by plastics.

Limited resources, an exponent growing of population, rapid urbanization and worldwide industrialization have contributed to global challenges for plastic solid waste (PSW) management (Hazra and Goel, 2009). According to Das et al. (1998), more than 90 percent of the PSW generated all over the world is directly disposed on land in an unsatisfactory manner. Therefore, various options such as landfill, incineration and recycling are introduced in order to solve this dumping PSW issue. However, lack of landfill capacity has become a serious problem in PSW management efficiency due to their recalcitrant to microbial degradation. Besides, another alternative for PSW disposal is incineration. According to Al-Salem et al. (2009), the incineration of PSW results in the reduction of landfill dependency up to 90-99 percent. However, the incineration approach is difficult to be implemented due to dangerous emission of fumes that could be harmful to the environment and human health. Thus, plastic recycling alternative is more favorable in nowadays society due to the advantages of efficient fossil energy saving, landfill capacity declining as well as air pollution abatement.

1.3 Plastic Recycling

Plastic recycling is a recent technology, which is considered to be the most effective environmental friendly method and it has become an urgent necessity alternative to deal with waste disposal problem. While, there are many different ways to classify the approximately 20,000 plastic materials available today, the first classification is usually the one that defines the material as either thermoplastic or thermoset. Thermoplastic materials can be defined as a plastic material which when heated, undergoes a physical change. It can be reheated, and reformed, over and over again. On the other hand, thermoset materials can be defined as a plastic material which when heated, undergoes a chemical change and "cures". It cannot be reformed, and reheating only degrades it. Therefore, the focus of this thesis is thermoplastic materials because of their current popularity (approximately 88 percent of all plastic products today are made from thermoplastic materials) (RecycledPlastic, 2014). The adaptation of plastic recycling has attracted considerable attention in reduction of global crude oil consumption and become a major task for researchers and industries. Moreover, the application of recycled plastic to make new product can preserve up to 70 percent of energy loss compare to the production of virgin resins (Santos and Pezzin, 2003). Thus, the plastic recycling has drawn attention along with growing environmental concerns, as well as the potential of economic benefits by establishing a waste reduction.

Still, the demand for recycled plastics is hindered by the general uncertainty of the quality issues, especially when they are being used for high-grade plastic product applications. This is due to the impression that recycled materials are suffering from degradation mechanism during their reprocessing cycle, which has a great influence in product's service life reliability and durability (Karlsson, 2004) and this factor has been cited as the main barriers faced by plastics recycling industry. In fact, the structure and morphology of materials deeply can be changed by mechano-oxidative and thermo-oxidative degradation during plastic recycling process (Saikaew and Sripaya, 2009). In this thesis, the quality improvement of injection moulded recycled plastic gear has became the main consideration. The quality properties of recycled plastic gear should be as reliable as a replacement for virgin plastic gear. Thus, the improvements of recycled materials as well as injection moulding process might be necessary in producing recycled plastic gear with satisfactory quality.

1.4 Quality Enhancement of Recycled Plastics

A good balance between reprocess ability and properties of recycled material is absolutely necessary in producing a satisfactory product quality. A lot of efforts have been done by the researchers to enhance the performance and properties of the recycled plastic, such as blending with virgin resins, blending with other plastics, addition of additive and stabilizer, and so on. However, due to the high cost required, it has become a constraint for the aforementioned approaches to be implemented in an industrial scale compared to the cost of using virgin resin.

As a consequence, most of plastic manufacturers start to look for the possibility of manufacturing perspective improvement by optimization of injection moulding processing parameters. Considering no extra processing cost is required, this processing parameters optimization could be an effective approach to enhance the recycled plastic products quality.

The processing parameters in injection moulding process can be categorized into four main groups: temperature, pressure, time and distance. Control of distances is critical to producing high quality products at reasonable cost. This is primarily because excessive distance requires excessive time, and time is money (Bryce, 1996). Besides, the improper adjustment of other processing parameters could negatively influence the final quality of recycled plastic products either on the physical properties, or aesthetic properties. In fact, the optimum quality properties of recycled plastic are impossible to be achieved and become meaningless without optimum processing parameters. In order to enhance the quality of recycled plastic, the processing parameters can be manipulated with the solid knowledge of the relationship between processing parameters and part properties.

1.5 Problem Statement

A diligent effort should be done to convince the community that recycled plastic have a great potential and reliable for virgin plastics replacement. As mentioned previously, recycled materials are exposed to mechano-oxidative and thermo-oxidative degradation that responsible to alter their mechanical and rheological properties, followed by deterioration of product's functional quality (Vilaplana and Karlsson, 2008). Therefore, the improvement of recycling and product development system need to be established in order to make recycled materials can be used to compete with virgin resins performance (Strömberg and Karlsson, 2008). Improvement can be done via the optimization of processing parameters, in order to produce recycled plastic products with satisfactory quality.

To date, injection moulding processes faced increasing requirements for lower cost and higher quality part. From the viewpoint of processing parameters, there are numerous processing parameter settings that have great influences on product quality. Therefore, the optimization of parameter design problems is routinely performed in the plastics industry, especially for final optimal process parameters setting (Mok and Kwong, 2002). According to Shen et al. (2007), determination of injection moulding optimal processing parameter settings is recognized as one of the most important steps to improve the quality of moulded products. However, it has raised a question on how the processing parameters optimization could be done effectively. Previously, the determination of optimal processing parameter settings involves a trial-and-error approach and relies heavily on operator's experience and intuition. Nevertheless, the trial-and-error approach is costly and time consuming, and not suitable for complex manufacturing process (Lam et. al, 2004). Thus, a reliable and effective processing parameters optimization approach with the purpose to enhance the product quality of recycled plastics is proposed in this study.

1.6 Research Objectives

The objectives of this research can be enumerated as follow:

1. To determine the most significant processing parameter that influencing the injection moulded product properties by using standalone Taguchi method.
2. To determine the optimal processing parameters and to identify the interaction effect on multi-response quality characteristics enhancement by using response surface methodology (RSM).
3. To determine the changes of rheological, morphological, thermal behavior and thermal stability properties of recycled plastic caused by mechano-oxidative and thermo-oxidative degradation during multiple injection moulding process.

1.7 Research Scope

In general, plastic materials can be categorized into two types based on chemical properties classification: thermoplastic and thermosetting. In this research, thermoplastic material is given the important consideration due to their ability to be recycled, over and over again compared to thermoset materials. Out of all types of thermoplastic, polypropylene (PP) is proposed as the raw material in this study due to its durability and reliability in producing high quality of plastic parts.

Plastic wastes can be categorized as post-industrial scrap and post-consumer products. In order to avoid compatibility issue, post-industrial scraps are being used as a source of recycled materials since they comprise clean plastic waste with similar type of production process material.

Aiming on the improvement of the part quality for recycled plastics, the Taguchi approach is used as an experimental design method to figure out the significant processing parameters in injection moulding. The results obtained from Taguchi method was integrated with response surface methodology (RSM) to make a better analysis for plastic gear multi-response quality properties optimization. The shrinkage and mechanical properties will represent the performance measures for virgin and recycled PP gear.

1.8 Thesis Outlines

This thesis is divided into five chapters. Chapter 1 in this thesis briefly introduces the research and covers the rest of works in context. A succinct introduction to plastics, their production and the environmental matters associated with them are explained thoroughly. A solution has been solved by adopting plastic recycling. The problem statements, objective and scopes of this research also are presented in this chapter. Chapter 2 consists of literature review related to this study. In this chapter, the latest knowledge and previous works conducted by other researchers relating to the plastics, plastics recycling, plastic gear manufacturing process and the enhancement of parts quality through the optimization process will be presented. Chapter 3 will focus on the detailed steps of methodology used in this research. In this chapter, every experiment procedures and analysis techniques are explained in details. All the results obtained from the methodology conducted in

Chapter 3 are analyzed and discussed in Chapter 4. Finally in Chapter 5, the conclusion on this research work will be presented together with the recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

2.0 Overview

This chapter starts with a brief discussion on the consumption of plastic materials. Latter, the following section introduced the classification of plastic recycling used to overcome the environmental issues cause by plastic wastes. The constraints on the usage of recycled plastic also are highlighted in this chapter. Subsequently, several of plastic gear processing technique was introduced and injection moulding will be the main focus in this thesis. The influences of material selection, part and mould designs and processing parameters on injection moulding process are analyzed thoroughly to investigate their significance in influencing the quality of plastic gear. Besides, the previous works on the Taguchi method and integration of Taguchi method with response surface analysis (RSM) will be reviewed thoroughly. Finally, the findings from the literature review will be discussed at the end of this chapter.

2.1 Plastics Overview

"The greatest innovations of the millennium", that is the suitable depiction that can be endowed to plastics (Panda et al., 2009). In general, plastics are derived from organic products such as crude oil and natural gas. Heavy crude oil is separated into fine groups, called monomer via distillation process. Latter, the polymerization of monomers will link them together to produce a new substance called plastics (PlasticsEurope, 2010). Different kinds of monomer combination will produce different kinds of plastics (Halden, 2010). Various attractive characteristics and properties of plastics make them a convenient choice for wide applications in industry.

Over the past three decades, plastics expeditiously evolved into our daily life due to their versatility properties (Derraik, 2002) and can be said that our life is incomplete without plastics. Lightweight, durable, cost competitive and convenient for product design applications has resulted in the rapid growth of plastics consumption (Richard et al., 2011) that represent significant advantages as substitution for several other non-renewable resource materials. The versatility and how the plastics play role in our modern living cause them became a fundamental of sustainability determination (Geiser, 2001).

Plastics have step-changed in our lifestyles in every stage of our society (Andrady and Neal, 2009). According to Richard et al. (2011), there was about 260 million tons of global plastics consist of 88 percent thermoplastic and 12 percent of thermoset (Reference for Business, 2015) was consumed for various applications, where 4 percent to 8percent of that figure represents global oil consumption for plastics raw materials production. Recent year, there are great volumes of plastics consumed by industry and most of them are consumed in packaging (30 percent), construction (28 percent), industrial equipment (25 percent), furniture (7 percent), appliances (6 percent), medications (1 percent) and toys and recreation (1 percent) (Mulder, 1998). Improvement of our life-quality in-line with plastics consumption has caused the piling of the plastics waste stream. Based on statistical data, USA generates almost 13.2 million metric tons of plastics waste in 1998 that contributes about 8 percent of total global plastic solid waste (PSW) disposal (Shent, 1999). Conscious on the impact of plastics waste on the environment, finding the proper way for PSW disposal become the main priority of most researchers (Vasudevan, 2012).

Due to non-biodegradability and high visibility in the waste stream, the growth of plastics waste disposal has a great influence in PSW landfilling and incineration management. Landfilling and incineration method are not a proper way to permanently dispose the waste since both of them just contribute to land and air pollution respectively (Vasudevan, 2012). Nevertheless, plastic recycling offers the best alternative solution to overcome both of landfill and incineration drawbacks and should be applied in the PSW management (Shent, 1999).

2.2 Classification of Plastic Recycling Process

Due to the insistence of environment and regulatory issue, the plastic manufacturers need to shift to the green production where efforts are aimed at facilitating the plastic recycling to a greater extent complies with ISO 14001. Generally, plastic waste can be categorized as municipal solid waste (MSW) and post-industrial wastes (PIW) where both of them show different qualities, properties and subjected to different management strategies (Demirbas, 2004). MSW generally refers to plastic wastes which are produced by the household, office and retail consumer. However, the recycling process of MSW seems to be a difficult process because of contamination presence and difficulties in separation cause by complex and mixed nature of the waste. In contrast, PIW refers to scrap plastic waste generated during the manufacturing of plastic products. In fact, PIW is preferable to be recycled and extensively carried out in recycling process compare to MSW since they are compromised with free of contamination, consist of single and identified polymer type that can avoid the incompatibility problem.

In principle, the treatment and recycling process for PSW can be classified into four categories: primary, secondary, tertiary and quaternary (Mastellone, 1999).

Primary Recycling

Primary recycling is a reprocessing of single and identified PSW in order to re-produce the products with similar features to the original product (Al-Salem et al., 2009). In fact, this primary recycling is carried out extensively in plastic industry since they are focused on clean, uncontaminated and single type plastics scrap that can minimize material immiscible issues during processing.

Secondary Recycling

Secondary recycling is known as recycling of PSW into materials that produce the features less demanding compared to the original material. Furthermore, this recycling type allows for a higher mixture of plastic level combination. The material compatibility and low properties issue may be arise and these are the reason why they are suitable for less demanding product features.

Tertiary Recycling

Tertiary recycling is known as advance recycling technologies where the basic chemical and fuels are generated by converting back the plastics to their basic monomers through pyrolysis and hydrolysis processing (Kumar et al., 2011). However, this process is very complicated and costly to be implemented due to complicated chemical reaction (Rebeiz and Craft, 1995).

Quaternary Recycling

Quaternary recycling comprises the utilization of plastic wastes as an energy source through direct incineration process (Dodbiba et al., 2008). This process is the most common and widely used in recycling because the high temperature heating of plastic waste can reduce the plastic weight and volume to 80 percent and 90 percent respectively. Nevertheless, among the recycling technique, quaternary recycling meets great society opposition due to the emission of harmful gases that may contribute to the air pollution issue.

2.3 Constraints on the Use of Recycled Plastics

Most of recycled plastics can be used in almost of applications as prime plastics. The application of these recycled plastics is not restricted to light industries such as packaging, but their application was spread to heavy industries such as construction and automobiles. Nevertheless, there are a lot of issues associated with the inferior properties of recycled plastics compared with virgin plastic, such as low mechanical strength, low ageing durability, etc. (Hopewell et al., 2009). In fact, the quality of plastics will be degraded after experience the recycling process and this limits the demand for application of recycled plastics as a raw material in many types of manufacturing (Turner, 2010).

In plastic waste streams, the recycled plastics may come in contact with other non-polymeric and other polymeric contamination that can cause the presence of impurities and so on degraded the product performance. Karlsson (2004) claimed that the presence of impurities can reduce the mechanical and ageing resistance properties of recycled plastics. The different degree of impurities level can give different rheological, mechanical and thermal properties in recycled plastics, thus makes them ideal only for particular application (Liang and Gupta, 2001). Moreover, Mantia (2002) affirmed that the blending of polymers with different polymeric mixture will form heterogeneous blends that results in weak adhesion properties between components. Therefore, high purity and high compatibility properties of mixtures is a crucial issue that should be considered in order to make the recycled plastic can satisfactorily meet the product requirement.

Even there are a primary recycling that focused on clean and uncontaminated plastics scrap processing, the recyclates still exposed to thermo-mechanical degradation when they are subjected to multiple reprocessing. The high level of heat and shear stress can deeply alter the rheology and morphology structure of recycled plastics during the recycling process (Canevarolo, 2000). In fact, thermo-mechanical degradation reduced the performance of recycled plastic by the alteration of molecular weight (MW), molecular weight distribution (MWD) and the viscosity of molten recyclates (Mantia, 1991). Thus, plastic waste cannot be recycled endlessly as it leads to the degradation and restricts the number of recurrent plastic cycles (InHabitat, 2015).

The use of recycled plastics as a raw material is inexpensive compared to virgin materials, even there are a lot of difficulties in their processing. Theoretically, the recycled plastics can be re-grinded, melted and reused without degradation as soon as advance knowledge should be applied properly during their processing method. Based on a survey conducted by ReTAP (1999) on injection and extrusion moulder, they claimed that there is wide potential of recycled plastic to be used in plastics manufacturing industries. Furthermore, many works have been done on the properties improvement of recycled plastics product and this study will be focused on the aspect of reliability and sustainability of recycled PIW for plastic gear production.

2.4 Plastic Gear

In the history of the world, gear can be regarded as the oldest basic components in a machine application. There are many industries that grow in line with the progress of the world and gears are identified as popular basic elements that generated power and motion transfer in every machine and equipment (Fuxing et al., 1985). Figure 2.1 show the schematic of typical gear tooth nomenclature. In the present development of gear technology, the materials selections for gear manufacturing have become more significant and plastics have expanded the uses of gear over the full range of operating conditions (Mallesh et al., 2009). In fact, plastic gears are widely continued to replace metal gears in every emergence of new applications due to their unique characteristics such as lubricant-free, silent operation, lightweight and easy to produce (Letzelter et al., 2010). Expected, the application of plastic gear would give a major impact in many applications as well as in heavy engineering applications (İmrek, 2009).

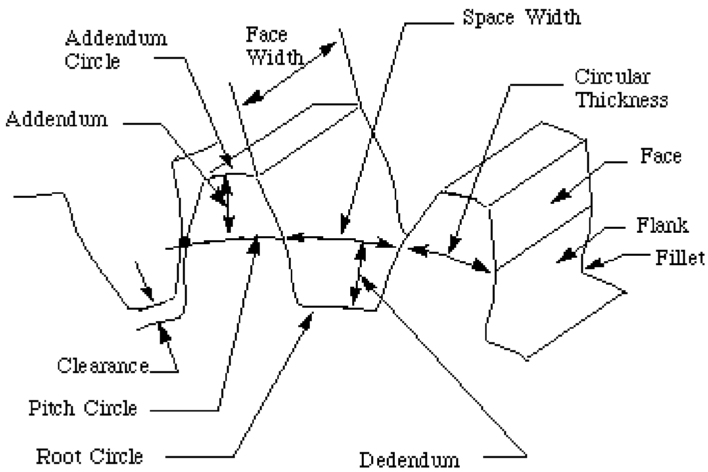

Figure 2.1: Schematic of Typical Gear Tooth Nomenclature.(Source: Nomenclature, Teardown, Exploded Diagram, 2007)

As metal gears, plastic gears also exhibit a variety of failure mechanisms such as tooth fatigue, creep, excessive wear, fatigue and deformation. Plastic gears indeed well-known with their poor mechanical strength, poor thermal resistance, low load-carrying capacity, a short service life and low elasticity modulus compared to metal gears (Senthilvelan and Gnanamoorthy, 2007). Lately, a few studies have been performed to observe the source of failure mechanism in plastic gears operation. Kukureka et al. (1999) observed the removal of thin surface layer on nylon 66 gear causes by melting effect on gear surface. Meanwhile, Hooke et al. (1993) studied the wear behavior of acetal gears and found that the wear rate increases upon the increasing of torque due to excessive heat generation.

In another part of research, there are a lot of studies have been done to improve the performance of plastic gear functionality. Düzcükoğlu (2009a) was conducted a study to delay the formation of thermal damage on PA 66 gear by increasing the tooth width surface area under different loads and rotation rates. In other work, Düzcükoğlu (2009b) has drilled the cooling holes at different location of gear part in order to distribute the generated heat on the polyamide gear tooth surface and he found that the modification successfully decreased tooth surface temperature. Moreover, there are some experimental studies have been done on the engagement of different gear materials. Yakut et al. (2009) investigated the gear damage by using different polymer-polymer meshing and found that PC/ABS spurs gear meshing can withstand rather higher load capability compare to PC/PC and ABS/ABS meshing combination. Not only that, the study on a material point of view also has been done for this improvement purpose. Ikegami et al. (1986) ran an experimental study to investigate the mechanical strength of glass and carbon roving clothes reinforcement plastic gear. Their finding shows that glass reinforcement is significant to improve the bending strength of plastic gears. Besides, Senthilvelan and Gnanamoorthy (2008) studied the effect of material composition on nylon 6/6 spur gear and found that the addition of glass fiber reduces the shrinkage behavior compared to unreinforced gears.

Many works have been reported on design modification as well as material composition improvement of plastic gear performance. However the effect of the manufacturing process on plastic gear production is not reported. Apart of design modification and material selection, Akata et al. (2004) claimed that advanced knowledge regarding manufacturing process is very crucial to plastic gear performance improvement. In the following section, the process of plastic gear manufacturing will be the fundamental issue to be explored.

2.5 Manufacturing Process of Plastic Gear

Generally, plastic gear manufacturing processes can be divided into two main categories namely machining that involved material removing process and forming that involved the tooth-forming process using mould or die. Figure 2.2 briefly shows the process involved in both machining and forming processes.

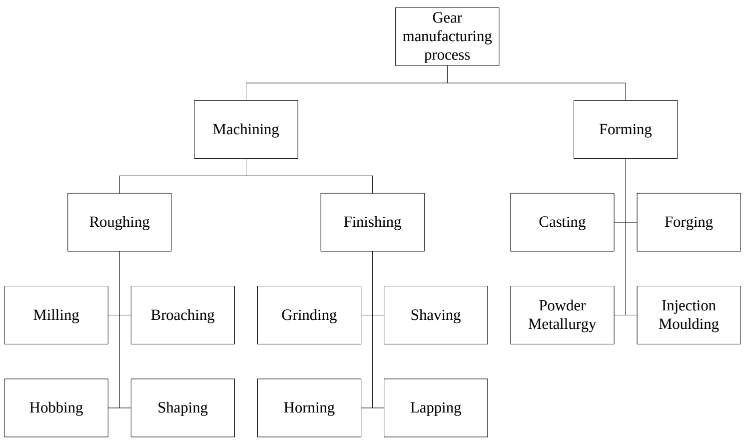

Figure 2.2: Plastic Gear Manufacturing Process

In fact, the machining process of plastic gears is performed in the same way as metal gears machining process. In machining, roughing can be described as blank gears cutting processes, whilst finishing are described as a process to improve previously roughing blank gears accuracy and surface finish. Each process that applicable to gear manufacturing has an advantage and suited for specific type of gear manufacturing. For example, milling process is an operation that involved cutting method to form the gear teeth and commonly used to produce spur or helical gears (Davis, 1995). Broaching process is suitable to generate an internal and external part features such as internal helical gears (Sutherland et al., 1997). Hobbing process uses a cutting tool that have a spiral spaced cutting teeth that revolved with work pieces and become the most popular process in cylindrical gears manufacturing due to their rapid and economical features (Gerth et al., 2009). With similar principle with hobbing, shaping process involves two pinion type of cutter with the same pitch diameter that meshed together and applicable to generate high-quality external and internal cylindrical gear (Srinivasan and Shunmugam, 1983). As mentioned previously, grinding, shaving, honing and lapping are the final operation after machining processes in order to ensure a better and consistent tooth profile surface finish.

In contrast to the machining process, forming does not involve any material removal process where it makes use of the tooth-forming process utilizing mould or die. Casting is a process where the molten materials are poured into a mould and harden to desired shapes, despite economical, the produce gears resulting rough surface finish and poor dimensional accuracy. Furthermore, forging is a gear manufacturing method that involving the shaping of blank gear using localized compressive forces that are commonly used to produce lightweight gear with high mechanical and dynamical strength (Behren and Odening, 2011). According to Cedergren et al. (2005), powder metallurgy consists of compacting of plastic powder within a desired shape die followed by a heating process at elevated temperature and widely used in high-volume small gear production. In recent years, injection moulding becomes the most important process in gear manufacturing due to the demand for lighter, faster, durable and low sliding friction plastic gear (Mendi et al., 2006). Therefore, the overview about injection moulding process will be further elaborated in the next section and become the main focus in this research.

2.5.1 Injection Moulding Process

Plastic injection moulding process is a nonlinear and multivariable process that ideally suitable for mass-production of complex shape parts that requires precise dimension (Wang et al., 2010). Injection moulding is the most common process for plastic parts manufacturing. Some important parts of an injection moulding machine are the hopper, barrel, screw, and mould. The hopper contains the raw plastic material before it has been processed. There are several steps that comprise the injection moulding process: feeding, melting, injecting, cooling, and ejecting. In the feeding step, the injection moulding machine rotates the screw, drop the plastic pellets from the hopper towards the front of the barrel, creating a reservoir of melted plastic. During screw rotation, heat and friction from electric barrel melt the plastic pellets. Next, in the injection phase, the screw moves forward, pushing the molten plastic into the mould. The cooling water in the mould draws away the plastic's heat during the cooling phase. After the plastic has been held long enough to solidify, the injection moulding machine opens the mould and ejects the newly formed plastic part. Further information about injection moulding can be found in Rosato et al. (2000).

The shorter manufacturing lead times, dimensional precision, and others advance features make an injection moulding became an important and most exploited method in plastic manufacturing process (Dimla et al., 2005; Tang et al., 2007). The superiority of performance, dependability, flexibility, low cost and high quality of produced parts has lead the injection moulding process to become a key competitive among plastic industries (Yeung et al., 1997). The applications of the injection moulding are not only limited to bigger parts, but also suitable for high precision components such as optical lenses, medicinal devices, pharmaceutical devices, micro-machines, prosthetics, solar-energy system, sensor and other electronic devices (Gerber et al., 2006). Therefore, the injection moulding process is very promising in term of high-value-added products manufacturing (Kumar et al., 2002).

Despite of becoming the most popular processing methods in plastic industry, the injection moulding still have a lot of deficiencies in term of maintaining the produced parts quality properties (Yamazaki et al., 1994) due to a lot of processing parameter and interaction exists between them (Dubay, 2002). Stated by Bharti (2010) and Min (2003), appearance, dimensional stability and structural integrity are the term that can be considered as injection moulding part quality. The good appearance refers to product cosmetics that are free from any splay marks, sink marks, voids, weld lines, poor surface finish, air traps and burn marks. Moreover, dimensional stability is the term that depicted the size and shape of moulded part against the shrinkage and warpage (DePolo, 2005). In other hand, the structural integrity properties that commonly considered in injection moulding parts are stress and strain, modulus of elasticity, Poisson’s Ratio, impact strength, fatigue endurance and so on (Bryce, 1997).

Since injection moulding is drawing the attention as one of the most important technology in today's plastic industry, the prediction and improvement of final part quality are necessary in order to satisfy the customer demands. As noted by Chen et al. (2008), there are many factors that contribute to the occurrence of defects in produced parts quality. Therefore, by analyzing the root cause of the defects, the process control improvement can be done accordingly.

2.5.2 Factors Affecting the Product Quality in Injection Moulding

Products made by a plastic injection moulding process can experience various defects that are caused by several factors. Among of the common defects that occur in plastic injection moulding products are black specks, flash, short shots, packing, sink marks, voids, warpage and dimensional changes. Bharti (2010) claimed that material selection, part and mould design, and processing parameters are the main factors that cause the defect in injection moulded products. For better understanding, following section will elaborate in details on how the material selection, part and mould design, and processing parameters can influence the part quality and the occurrence of the defects.

(a) Material Selection

The fundamental knowledge of material selection has a substantial impact on injection moulding parts quality. According to statistical data collected by Stress Engineering Services (2012), they stated that poor material selection cause about 45 percent of product failure, poor design by 20 percent, 20 percent of poor processing condition and abuse factor for 15 percent (Figure 2.3). Therefore, the designers need to select a material with specific attributes that can guarantee optimum performance of product quality. Recommendation to the right type and grade of resin used depends on the product's application, where all characteristics need to be carefully weighed before a selection can be made. A lot of criteria such product sustainability, process performance, mechanical properties, physical properties, thermal properties, cost, performance and impact on the environment should be considered for materials selection (Jahan et al., 2010).

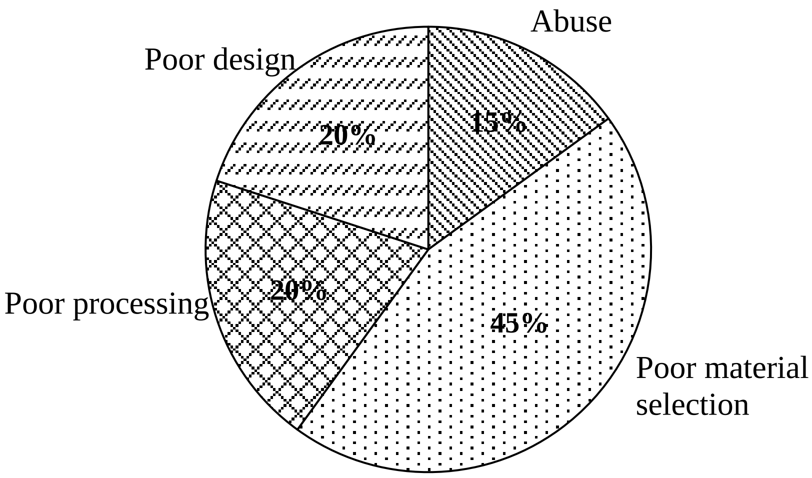

Figure 2.3: Cause of Products Defect [Stress Engineering Services, 2012]

A few studies have been conducted to provide a theoretical base for material selection procedures. Sancin et al. (2010) studied the influences of different materials selection on dryer machine knob quality characteristic. They used four types of material, including polyamide (PA), polypropylene (PP), polyethylene (PE) and acrylonitrile butadiene styrene (ABS). Results from their study show that PA has the highest fracture toughness value, while PP has the lowest one. Despite having the lowest fracture toughness, PP is observed to be tougher than ABS. In another field of manufacturing, Girubha and Vinodh (2012) performed a case study with an aim to select a proper material for an automotive instrument panel manufacturing. There are four materials suggested, namely styrene maleic anhydride (SMA) and polycarbonate (PC), PP and ABS. All these four materials are chosen based on structural integrity performance, economically, environmental friendly and society beneficial aspects. From their finding, it is suggested to use PP due to its satisfying mechanical performance, high material procurement, high end-of-life besides contribute to lesser environmental impact compare to other materials.

Besides, the right selection of material is very crucial in plastic gear manufacturing process. Many studies have been extensively conducted to investigate the influence of material used on plastic gear durability and endurance. Mao et al. (2009) conduct an experiment to investigate both of acetal and nylon gear friction and wear behavior. Under specific load applied, it was found that acetal gear exhibit surface wear failure mechanism while nylon gear shows root and pitch fractures. The finding is clearly shown that types of material used will induce to different failure mechanism. In another study, by concerning on the composite material application, Kurokawa et al. (2003) conduct an experiment to investigate the gear performance on four types of carbon fiber reinforced polyamide material: polyamide 12 (PA12), polyamide 6 (PA6), polyamide 66 (PA66), and polyamide 46 (PA46). It was found that reinforced PA12 shows an excellent wear property, highest load capability, excellent noiseless property, and the lowest water absorption among all polyamides investigated.

(b) Part and Mould Design

Apart of the material selection and processing parameters, parts and mould designs are considered as the main factor that affecting the final quality of injection moulded parts quality (Deng et al., 2008). According to (Chin and Wong, 1996), there are close relationship existed between both of parts and mould designs which interact each other. Therefore, the functional requirement of the parts, including its