AN INTEGRATION OF TAGUCHI METHOD AND GREY RELATIONAL ANALYSIS IN OPTIMIZING INJECTION MOULDING PROCESSING PARAMETER OF RECYCLED PLASTIC

by

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LIST OF ABBREVIATIONS

EPA	Environmental Protection Agency
OSHA	Occupational Safety and Health Administration
VOC	Volatile Organic Compound
CAAA	Clean Air Act Amendments
ABS	Acrylonitrile Butadiene Styrene
PA	Polyamide
FRP	Fiber Reinforced Polymer
FRC	Fiber Reinforced Composite
CAD	Computer Aided Design
POM	Polyoxymethylene
PS	Polystyrene
AGMA	American Gear Manufacturers Association
DOE	Design of Experiment
OA	Orthogonal Array
S/N	Signal-to-Noise
ANOVA	Analysis of Variance
PP	Polypropylene

CAE	Computer Aided Engineering
FEA	Finite Element Analysis
PC	Polycarbonate
PPE	Polyphenylene ether
AI	Artificial Intelligence
ANN	Artificial Neural Network
GA	Genetic Algorithm
SOM	Self-Organizing Map
BPNN	Back-Propagation Neural Network
RMSE	Root Mean Square Error
GRA	Grey Relational Analysis
HDPE	High Density Polyethylene
PA66-GF	Polyamide 66 Glass Fiber Filled
DOF	Degree of Freedom
MFI	Melt Flow Index
GRG	Grey Relational Grade

INTEGRASI KAEDAH TAGUCHI DAN ANALISIS HUBUNGAN GREY DALAM MENGOPTIMUMKAN PARAMETER PROSES PENGACUAN SUNTIKAN MENGGUNAKAN PLASTIK YANG DIKITAR SEMULA

ABSTRAK

Plastik merupakan salah satu kumpulan bahan yang terbesar di seluruh dunia dengan kadar pertumbuhan tinggi. Hari ini, pengeluar xilastic di seluruh dunia sangat bimbang dengan pengurusan sisa dan masalah alam sekitar yang disebabkan oleh sisa xilastic. Banyak usaha dan kajian telah dilakukan berkaitan dengan kitar semula xilastic untuk menyelesaikan masalah pelupusan xilastic. Dalam kajian ini, kesan pengadunan komposisi poliamida 66 yang mengandungi 33% gentian kaca yang dikitar semula, disiasat dan dinilai berdasarkan kestabilan dimensi, sifat mekanik dan reologi. Pengoptimuman parameter pengacuan suntikan untuk gear PA66-GF dibentangkan dengan mengintegrasikan analisis hubungan "Grey" dan kaedah Taguchi. Ciri-ciri kualiti gear PA66-GF seperti pengecutan bahan, kekuatan tegangan dan indeks aliran kecairan telah dipilih. Eksperimen awal telah dijalankan dengan menggunakan L_{18} susunan xilasticxial untuk menyaring parameter-parameter penting dalam proses acuan suntikan. Kemudian, parameter yang telah dikenal pasti optimum menggunakan tahap campuran L_{27} OA dengan interaksi, analisis kesan utama dan analisis varians bagi eksperimen pengoptimuman. Keputusan menyatakan bahawa kestabilan dimensi dan juga sifat-sifat mekanikal dan reologi bagi gear yang dikitar semula PA66-GF pada keadaan optimum telah bertambah baik sehingga ke tahap yang lebih kurang sama dengan PA66-GF tulen. Penemuan eksperimen menunjukkan keberkesanan kedua-dua kaedah bersepadu analisis hubungan "Grey" dan kaedah Taguchi untuk mengoptimumkan parameter-parameter proses pengacuan

suntikan dan meningkatkan kualiti pelbagai ciri bagi gear xiilastic dengan bilangan eksperimen dan kos peralatan yang minimum.

AN INTEGRATION OF TAGUCHI METHOD AND GREY RELATIONAL ANALYSIS IN OPTIMIZING INJECTION MOULDING PROCESSING PARAMETER OF RECYCLED PLASTIC

ABSTRACT

Plastics are material group with the largest growth rate worldwide. Today, plastic manufacturers all over the world are seriously anxious with the waste management and environmental problem caused by the plastic waste. Numerous efforts and studies have been done related to plastic recycling in order to solve the plastic disposal problem. In this research, the effect of blending compositions of recycled polyamide 66 with 33% glass fiber filled (PA66-GF) is investigated and evaluated based on the dimensional stability, mechanical and rheological properties. The optimization of the injection molding parameters for PA66-GF gear is presented by integrating grey relational analysis (GRA) with Taguchi method. The quality characteristics of the PA66-GF gear such as material shrinkage, tensile strength and melt flow index are selected. A screening experiment was conducted with an L_{18} orthogonal array (OA) to screen out significant parameters of the injection molding parameters. Later, an optimal parameter is identified using a mixed levels L_{27} OA with interaction, main effects analysis and ANOVA of the optimization experiment. The results depicted that the dimensional stability as well as mechanical and rheological properties of recycled PA66-GF at optimal conditions were improved up to a level close to the virgin PA66-GF. The experimental findings show the effectiveness of integrated both GRA and Taguchi method to optimize the processing parameters of injection molding and improve the multiple quality characteristic performances of the plastic gear with minimum number of experiments and tooling cost.

CHAPTER 1

INTRODUCTION

1.0 Research Background

The development of plastic was believed to have started around 1860s when John Wesley Hyatt introduced and patented the first plastic under the name of celluloid (McCrum et al. 1997). Over the next few decades, more and more plastic were introduced into plastic industry. It is hard to imagine a world without plastic because it serves many functions, satisfies many desires and quickly recedes into relative invisibility as long as it does its job well. Plastic has spread through the material world, moving from almost no presence at all to near ubiquity (Meikle 1995).

Unfortunately, rapid growth of plastic in worldwide has directly increased plastic waste. Plastic waste poses an environmental issue because of the problem associated with disposal management. In view of plastic waste management, there are various methods such as landfill, incineration and recycling to solve the plastic waste problem. However, the limitation of landfill capacity and non-biodegradable properties of plastic makes the landfill method avoidable since the plastic waste consumes a large space and a lot of time to decompose in landfill sites (Fei et al. 2013a). On the other hand, incineration of plastic emits hazardous gasses during disposal of plastic waste which affects the environment and human health (Martins and De Paoli 2002). Comprehending to these limitations of landfill and incineration, recycling or reusing plastic waste as a single resin or in combination with other plastics were being developed and considered as a necessity (Boronat et al. 2009; Guerrica-Echevarría et al. 1996).

However, plastic recycling is hindered by a wide range of barriers, including mistrust of the quality of the recycled plastics as well as restrictions imposed by standards and specifications. Most plastic manufacturers and consumers were reluctant to use recycled plastics because of the perception that recycled plastics are inferior to the virgin resin and more difficult to handle (Fei et al. 2013b). Apart from that, improvements of mechanical and material properties of the recycled plastic products are still possible. From manufacturing perspective, optimization of injection molding parameters is well known in improving the quality of the final product (Chen et al. 2008; Oktem et al. 2007). Optimization of injection molding process is an appealing approach in improving the quality of the recycled plastic products. Hence, basic knowledge of injection molding process is relevant.

Injection molding process is the most commonly used method in plastic processing industry (Gao and Wang 2009). Although injection molding is one of the most widely used processes in plastic manufacturing, the quality of the products are easily affected by different injection molding conditions. Material selection, part and mold design, and processing parameters play important roles in determining the quality of the final product (Lu and Khim 2001). In industrial practice, part and mold design are commonly assumed as fixed because any modification and alteration of part and mold design may lead to high production cost. Hence, processing parameters can be manipulated in order to improve the quality of the recycled product to a satisfactory level.

0.1 **Problem Statement**

Incorporated with plastic recycling issues, an effort is needed to prove that the recycled plastics are feasible and reliable to replace the virgin plastics. The usability of recycled plastic is still doubtful in term of its properties. This is due to the fact that recycling of plastic often leads to degrade the products inferior value (Kartalis et al. 1999). Recycled plastics will not behave similar as their virgin form in term of its mechanical and rheological properties. However, improvement can be done to upgrade the mechanical and rheological properties of the recycled plastics via blending technique in producing the products (Maspoch 2003). When incorporated with blending of recycled plastics, it is difficult to determine the appropriate amount of recycled material to be mixed with its virgin material so that the quality of recycled blend product behaves almost the same as the pure virgin product (Mehat and Kamaruddin 2011a).

Growing demands on the quality of injection molded plastic products as well as the reduction of costs in the production require fast and reliable control methods. The quality of the molded product fluctuates within a certain range due to the variation in the operating environment or the properties of materials. This situation raises a question of how the optimization method could be done effectively in the plastic injection molding industry. A reliable optimization method is needed for substituting the trial and error method, which requires tremendous time and works which leads to a high cost production.

1.2 Research Objectives

The objectives of this research are:

1. To study the effectiveness of the standalone Taguchi method in finding the most significant processing parameter affecting the dimensional stability and mechanical properties of injection molded gear.
2. To study the effectiveness of integrating mixed-levels Taguchi interaction method with grey relational analysis in determining the significant parameters and interaction for multi performance quality characteristics.
3. To optimize the quality of recycled plastic gear in terms of rheological and mechanical properties as well as dimensional stability by adopting the optimal combination parameters.
4. To study the feasibility and reliability of recycled material blending composition in terms of rheological and mechanical properties as well as dimensional stability compared to the virgin material.

1.3 Research Scope

Generally, plastic can be subdivided into two categories, namely thermoplastic and thermoset. Thermoplastic was used in this study over thermoset because thermoset cannot undergo reheating which is impossible for plastic recycling. Considering the end use of the product, polyamide 66 was chosen amongst the wide variety of thermoplastic groups. PA66 is one of the most commonly used thermoplastics in various applications, particularly in plastic gear industry (Düzcükoğlu 2009b). Furthermore, the specialty of PA66 which reinforced with glass fiber filler was found as an interesting subject to undergo plastic recycling (Rosato and Rosato 2004). To limit the study with the incompatibility issue of recycled material blends, the recycled material was prepared with homogenous material by recycling the virgin material scraps.

Considering the part geometry, injection molding process was selected. The effectiveness of the standalone Taguchi method in determining significant processing parameters of injection molding was investigated. Comprehending to the plastic recycling, the improvement of parts quality was considered relevant. The integration of Taguchi method with grey relational analysis was used to obtain a better analysis representing multiple quality responses. The rheological and mechanical properties as well as dimensional stability of the molded product represented the performance measure of virgin and recycled PA66-GF blended products simultaneously.

1.4 Thesis Outlines

The thesis begins with Chapter 1 which briefly introduces the research. The research background based on plastic development was introduced and the problems related to plastic waste management were discussed. The respective problem was solved by adopting plastic recycling. The problem statement and objectives of the research were also described in this chapter. The flow of this study continues by doing literature works as presented in Chapter 2. This chapter presents the work done by other researchers associated with the field of plastic, plastic recycling, plastic gear manufacturing process and improvement of parts quality from the optimization process. Then, Chapter 3 describes the methodology used in this research, including the details of experimental procedures involved and the analyses performed. Chapter 4 analyzes and discusses the results obtained according to the methodology stated in Chapter 3. Finally, Chapter 5 concludes the research work and suggests the appropriate future work for other researchers.

CHAPTER 2

LITERATURE REVIEW

0.1 Introduction

This chapter begins with brief information of plastic and its classifications. The next section briefly introduces plastic recycling for further development of plastic gear industry. An introduction of plastic gear was presented and manufacturing process of plastic gear was simply illustrated in the next section and further discussion was on the injection molding process. Factors affecting quality of plastic molded product were analyzed. Previous works employing Taguchi method and integration of Taguchi method with various approaches in minimizing and optimizing the quality of product were reviewed thoroughly in this study. Finally, the findings from the literature review were clearly stated at the end of this chapter.

2.1 Plastic Overview

A plastic is a type of synthetic or man-made polymer which similar in many ways to natural resins found in trees and other plants. A polymer is defined as any of various complex organic compounds produced by polymerization, capable of being molded, extruded, casted into various shapes and films, or drawn into filaments and then used as textile fibers (Mills 1986). In some cases, polymer is also referred as a synthetic compound such as polyethylene and polyester, consisting of large molecules which are chemically linked together with repeated monomers (Painter and Coleman 2008).

Plastic can be subdivided into two main categories; thermoplastics and thermosets. According to Mills (1986), thermoplastics consist of individual long chain molecules and in principle, any product can be reprocessed by chopping it up and feeding it back into the appropriate machine. On the other hand, thermosets contain an infinite three dimensional network which is only created when the product is in its final form, and cannot be broken down by reheating.

Plastics have some unique properties such as corrosion resistance, low density, very low thermal and electrical conductivities and low cost (Chung 2000). The cost advantage of plastics always comes from their excellent processibility in comparison to other types of materials. The properties of the plastic can be tailored to suit a specific application. Such examples; plastic eases the production of complex parts and has become a driving force in innovation in the fields of electronics, medicine, automobiles, household goods and construction. Because of their unique properties, plastics have replaced metallic components increasingly.

The unique properties of plastics have increased the usage of plastics directly. Plastic is a material group with the largest growth rate worldwide and industry has implemented plastic in a wide variety of products and applications. Industrial products made of plastics include food containers, packaging, house ware, medical instruments, paints, toys, electrical and electronic devices, and automobile components. Since 1950, plastics production has been increased by an average of almost 10% every year on a global basis. The total global production of plastics has grown from 1.3 million tonnes in 1950 to 230 million tonnes in 2005 (Plastics Europe 2007). World demand and plastics contained in municipal waste have derived an environmental and social concern on the plastic growth. Santos et al. (2002) have reported that in Brazil, there was an annual loss of 2.5 million tonnes of residues equivalent to US$ 4.6 billion per year, since only 20% of this potential was explored. The resistance of plastics to degrade, the great variety of types produced, the difficulty in separation of the different types due to similarities in physical characteristics, and the incompatibility between certain types if blended for re-use complicates their reprocessing (Richard et al. 2011). Moreover, the number of re-use cycles is limited and eventually the properties of the polymers start to deteriorate to the point when they cannot be used without further processing (Azapagic et al. 2003). This brings in another option for resource and waste management, which is recycling.

2.2 Plastic Recycling

According to Osswald et al. (2006), plastic recycling can be subdivided into two major categories; industrial and post-consumer plastic scrap recycling. Post-consumer plastic scrap recycling requires the material to go through a full life cycle prior to being reclaimed. This life cycle can be varied from a few days for a packaging material to several years for an electronic equipment used in housing materials. Mantia (2002) has stated that the recycling of post-consumer materials is an important challenge for the plastic industry. The post-consumer plastic scrap can come from commercial, agricultural and municipal wastes which are typically contaminated wastes.

As the amount of plastic waste is growing globally, due to the high environmental resistance, these plastic materials survive in the environment for a long time and give negative impact to the environment. Xiang et al. (2002) have stated with respect to recycling by reprocessing, environmental problems related to emissions have been a concern of the Environmental Protection Agency (EPA) and the Occupational Safety and Health Administration (OSHA). Emissions generated during processing can be as high as 5% of the annual tonnage of resins processed in the US. Among the different species generated during reprocessing, volatile organic compounds (VOCs) have received the most scrutinizes. They originate from devolatilization and degradation of additives such as plasticizers, stabilizers, and antioxidants (Touati et al. 2011). Many of these VOCs are hazardous air pollutants that also participate in photochemical reactions to form smog and ground-level ozone. Therefore, the Clean Air Act Amendments (CAAA) of 1990 regulates these VOCs, and the Title V of this Act established a permit program for their eventual reduction.

Martins and De Paoli (2002) found that reprocessing of scrap plastics may generate a significantly higher amount of VOCs emissions than virgin resins because they have a long thermal and mechanical exposure in oxidizing environments. Types and amounts of these emissions depend upon the material and the operating parameters. Thus, it is important to choose appropriate recycled material with suitable operating parameters to minimize the hazardous emission during recycling process. Beyond the environmental pressure, the recycling of plastics can be considered as an important economic tool because energy and material can be re-used (Lea 1996). Most of the work done by others emphasize on the sustainability of plastic recycling to the environmental issues.

Barriers to the use of recycled plastics also include the problem with quality, supply and cost as well as restrictions imposed by standards and specifications. There is a perception, which recycled resins are inferior to virgin resin and more difficult to handle (Fei et al. 2013c). Problems may include the inabilities of some recyclers to provide recycled resins that perform within a narrow specification range and to meet the specific requirements of the customer. However, this situation is changing as recycling companies improve their products and processes, adopt reliable quality systems and provide better customer service. Manufacturers now have a greater choice of recycled resins and compounds suitable for a huge range of applications.

Hence, industrial scrap is rather easy to recycle and re-introduce into the manufacturing stream, either within the same company as a regrind or sold to third parties as a homogeneous, reliable and uncontaminated source of resin. According to the fact that industrial wastes are relatively clean and uncontaminated, they are currently recycled more than postconsumer waste (Fletcher and Mackay 1996). Therefore, researchers are more focused on to maximize the potential of plastic recycling from the industrial waste perspective.

Boronat et al. (2009) in their studies stated that the increase of demand of new products and waste suggests the importance of using recycled plastics. The study emphasized the importance of studying the recycling of ABS as an aid to reduce economical, environmental and energy issues. Aurrekoetxea et al. (2003) also stated that recycling of plastic materials is strategically very important for the environmental policy of industry. As environmental issues become a priority, this study will be focused on the sustainability aspect of recyclable materials from the industrial waste perspective particularly for plastic gear.

2.3 Plastic Gear

More than two millennia, gear have received special attention from the technical community because of their unique contribution to the operation of so many machines and mechanical devices. Drago (1988) in his book stated that the existences of gears begin with the invention of rotating machinery. Early gears were made from wood. However, during industrial revolution in Britain in the eighteenth century saw an explosion in the use of metal gearing. The science of gear design and manufacture rapidly developed through the nineteenth century.

Today, new developments in gear technology, particularly from the materials point of view have become more significant. Modern metallurgy has greatly increased the uses of industrial and automotive gears as well as in consumer electronic devices, which have driven plastic gearing to a new levels of lubricant-free and quiet operation gears (Lin and Kuang 2008).

Plastic gears are continuously being developed to replace metal gears in various applications ranging from automotive components to micro- and nano-scale electronic devices (Hakimian and Sulong 2012). Previously, plastic gears were not considered to be able to transmit power and motion. However, improved materials with higher load capacities and advancement in mold design and molding technology led to successful and increased the use of plastic material for both motion carrying gears and power transmission gears (İmrek 2009; Kim 2006; Ikegami et al. 1986).

According to Düzcükoğlu (2009a) and Mendi et al. (2006), plastic gears have some advantages, such as silent operation durability against corrosion, low weight, easy and quick production, and working without lubrication. However, one of their main limitations is their low allowed operational temperature and load (Lin and Kuang 2008). Because of the poor heat conductance of plastic gears, the material accumulates heat and softens quickly. As a result, the plastic gear contact surface temperature becomes high enough to increase the likelihood of local softening and surface wear dramatically (Breeds et al. 1993). Over the past few decades, a considerable number of studies have been conducted on the performance and quality of plastic gears and such work was carried out by (Kurokawa et al. 2000; Düzcükoğlu 2009b; Mao 2007).

Design standards for plastics gears do exist, but they have been adapted from those from metal gears with a very little modification (Drago 1988). Sufficient experimental data do not yet exist to make a confident prediction about the behavior of plastics gears over the full range of operating conditions. The data which do exist throw doubts on the validity of the present design standards. Therefore, sufficient experimental data are needed to validate the predictions about the behavior of plastic gear over a certain range of operating conditions and applications. Before further discussions on the designing of plastic gear, the following section will briefly introduce some commonly used materials in the plastic gear industry.

2.3.1 Material Composition

This section will briefly review some of the commonly used plastics for plastic gears. The plastic gear material used can be in an unmodified condition or modified with various additives to produce a wide variety of gear configurations. Davis (2005) in his book stated that selection of a plastic gear material does not only depend on its properties, but also on the manufacturing process used, part and shape size or design, shrinkage rates, moisture absorption and processing variables. Some common materials used in the plastic gear manufacturing are as follows;

- **Nylons (Polyamides, PA)**

For plastic gear application, thermoplastics are the most commonly used considering the properties of the material. According to İmrek (2009), nylons (polyamides, PA) and acetals are the most commonly used thermoplastics for plastic gear application. Nylons; which come in unmodified, toughened, and reinforced conditions, exhibit outstanding toughness and wear resistance, low coefficients of friction, excellent electrical properties and chemical resistance. Senthilvelan and Gnanamoorthy (2008) and Düzcükoğlu (2009b) have used nylons spur gear in their research and studied the gear performances. However, some nylons are hygroscopic which means absorb moisture and this is a negative effect on their strength. Despite this limitation, nylons is still a considerably used material for gear manufacturing process either in machining or molding (Letzelter et al. 2010).

- **Acetals**

Acetals have a relatively low water absorption rate compared to nylons. Therefore, it is more stable after machining or molding process. Acetals, which come in unmodified, toughened, reinforced, and internally lubricated conditions, are strong, resistant to creep and fatigue, low coefficient of friction, and resistant to abrasion and chemicals. Breeds et al. (1993) have studied the wear behavior of acetals gear in details. It was found that the wear of acetals gear is a complex process. The limitation of the use of acetals as a gear material was also considered in their studies where at low torque, life of acetals gear was limited by wear and at high loads the maximum permissible surface temperature was a limiting factor.

- **Reinforced material**

  Fillers are intentionally placed in polymers to make them stronger, lighter, electrically conductive, or cheaper. Any filler will affect the mechanical behavior of a polymeric material. According to Osswald et al. (2006), reinforced plastics whose properties have been enhanced by introducing a reinforcement or fibers of higher stiffness and strength are usually called as a fiber reinforced polymer (FRP) or a fiber reinforced composite (FRC). The purpose of introducing a fiber into a matrix is to transfer the load from the weaker material to the stronger one.

Ikegami et al. (1986) investigated the strength of fiber reinforced gears with various material constitutions. The effects of fiber reinforcements were experimentally evaluated by both static and dynamic tests. A method to reinforce gear teeth with glass or carbon roving cloths along the tooth profile was proposed to improve the bending strength. The study has shown that fiber reinforcement is useful to improve the strength of plastic gears. Whereas, Senthilvelan and Gnanamoorthy (2008) studied the effect of reinforcement material on gear metrology. The orientations of the fibers in injection molded gear were observed and compared with unreinforced injection molded gears. It was found that the fiber orientation has influenced on part shrinkage behavior of the injection molded gear's quality.

According to Wright and Kukureka (2001), gear materials are chosen on cost or simple performance grounds; such as heat deflection temperature. Aspects of the performance of polymeric gears have yet been studied systematically. The study has explained the comparative methods of measurement of various polymer matrix composite gear materials which related to the gear performance. Despite gear materials, advance knowledge of the plastic gear manufacturing process is prerequisite to the successful improvement of the plastic gear quality. Hence, the next section will further discuss on the plastic gear manufacturing process.

2.4 Manufacturing Process of Plastic Gear

Plastic gears are manufactured either by machining or injection molding. Machining of plastic gears is performed by most of the same processes used in the machining of metal gears. Machining may be selected over molding as the plastic gear manufacturing process for several reasons; the small quantities are needed to justify the tooling cost for molding, special design feature or accuracy may be too difficult for molding, desired plastic material may not be suited to precision molding (Davis 2005).

However, machining invariably leaves the gear teeth made from the core material, which generally has different strengths, wear resistances and chemical resistances which make injection molding more preferable method to manufacture plastic gears. In addition, machining may expose to void in the stock. Therefore, injection molding was considered as the plastic gear manufacturing process for this study. Understanding the injection molding process is crucial in finding the root causes of quality problems and improving the process. The following section will further discuss the fundamental issues of injection molding process.

2.4.1 Injection Molding Process

Plastic injection molding is the most commonly used method in plastic processing (Gao and Wang 2009). More than one third of all thermoplastic materials were injection molded (Shen et al. 2007). Injection molding provides products with high dimensional steadiness, low manufacturing cycles and low costs (Chen et al. 2009a). Generally, injection molding is carried out in three phases: filling, packing and cooling. Galantucci and Spina (2003), Kumar et al. (2002) and Pantani et al. (2005) have briefly described the fundamental principle of injection molding process.

Basically, in injection molding process, plastic materials in the form of granules or pellets are put into a hopper and passed into a barrel where they are heated until they become soft. Then, the pellets are melt and form molten plastic due to the heat generated by the friction between the barrel wall and the screw. The screw is pushed forward and the molten plastic flows through the nozzle, the sprues and the runner system into a mold cavity. As the cavity is completely filled, a hold pressure is applied. The cooling phase starts and the mold cools the plastic. After the plastic is cooled and solidified, the product is ejected. During these phases, interactions between material properties, machine parameters and process variables increase the complexity of the fabrication process.

Due to the complexity of injection molding process, an effort is needed to keep the quality of the final product under control. The quality characteristics of injection molded products can be characterized in terms of dimensional stability, appearance and mechanical properties (Galantucci and Spina 2003). Dimensional stability often refers to the thickness, part length, shrinkage or warpage. Whereas, for aesthetics appearance quality characteristic, weld lines and sink marks are some examples. Finally, quality characteristics in term of mechanical properties are such as tensile strength, impact strength, elongation at break and modulus elasticity of the final product.

According to Chang et al. (2000), injection molding has many advantages, such as a short product cycle, excellent surface of the product and easily molded complicated shapes. Presently, it is well used in the plastic industries. Although injection molding is one of the most widely used processes in plastic manufacturing, the characteristics of the products are easily affected by the flow type of the melt, the effect of heat transfer, the material properties and the specific geometry of the mold. Thus, different injection molding conditions will induce different quality characteristics of final products. Furthermore, there are many other factors which may lead to the occurrence of defects on the injection molded products. If the root cause of the defects is identified, the quality of injection molded products can be improved by elimination and optimization of all possible root causes of the defects.

2.4.2 Factors Affecting Product Quality in Injection Molding

Tjantelé (1991) stated that there are two types of factors which influence the quality characteristics of a product. First are controllable factors such as temperature, pressure, raw material, additives, etc. Second are uncontrollable factors which are difficult or costly to control including ambient temperature, humidity, impurity of material, dimensional tolerances, etc. These quality characteristics can be classified into three main categories. As for injection molding process, material selection, part and mold design, and processing parameters play important roles to determine the quality of the final product. The inappropriate combination of these factors may lead to numerous production problems such as high production cost, lots of scraps and defects, etc. For a better understanding on how the factors influence the product quality and the occurrence of the defects, further elaborations were discussed in the next section.

- **Material selection**

  There are many different ideas on how the materials selection for a product should be performed. Beiter et al. (1993) mentioned that the selection of a material for plastic parts is a challenging task. However, the principles are rather similar. When choosing among different types of materials for a certain product it is interesting to notice that there are more than thousand different types of materials to choose among and the number of materials are increasing rather rapidly. Ljungberg (2003) described some important criteria for the selection of a material based on some aspects: production methods, function, user demands, design, total price and environmental aspects.

On the other hand Dowlatshahi (2000) presented a conceptual framework for material selection and product safety using a medicine manufacturing company as a case study. The author came out with general rules for comparison and selection of materials as a guideline. The demands for improved quality of extruded products measured by their surface quality and mechanical properties require better understanding of material response to the process parameter (Kazanowski et al. 2005). Today, such selection process is made easier with the use of material data banks such as CAMPUS, which does not only eliminate tedious searches through catalogs and material data sheets printed by the resin suppliers, but also facilitates a fair comparison between the materials since all their properties are measured using the same standardized testing techniques.

During the material selection process, the designer searches for the suitable candidate in term of the properties and the impact strength of the material. Comprehending to this matter, Beiter et al. (1993) have developed a program that can help engineers in material selection process which is HyperQ/Plastics program. The program gives detailed information concerning materials, properties and design guidelines. In addition, the program has reduced the time taken for a material selection from two days via manual searching through material handbooks to less than one hour by using the program. In view of plastic recycling, the properties of recycled material may differ from its virgin in affecting the quality of molded products. Comprehending to this fact, recycled material behavior is another issue to be considered in the material selection process.

- **Part and Mold Design**

As known, plastic injection molding is one of the most important polymer processing operations in the plastic industry. However, lack of skill in mold making and injection molding machine control lead to defective plastic product (Huang and Fu 2001). In the study of Tang et al. (2007), it has clearly shown that the relationship of mold design and machine settings may affect the quality of molded products by reducing warpage problem. The result shows that the most effective factor on the warpage problem was melting temperature. The filling time only influenced the warpage problem slightly. The optimum parameters that can minimize the warpage defect were melting temperature of 240 ◦C, filling time of 0.5 s, 90% of packing pressure and packing time of 0.6 s.

In another study, Chen et al. (2009b) proposed a gas-assisted heating system combined with water cooling for different mold designs to achieve dynamic mold surface temperature control. The effects of mold design as well as heating conditions were studied. Results showed that as hot gas temperature and gas flow capacity were increased, the heating times and the mold surface temperature were also increased significantly. The study found that fan shaped gas channel design exhibits better mold surface temperature distribution uniformity than tube shaped gas channel design. In addition, under specified heating conditions and using the best composite mold designs, the heating rate can reach up to 30 °C/s, a rate which is well-suited to industrial applications.

In gear application, Düzcükoğlu (2009a) affirmed that when analyzing gear designs, breakage at the tooth root, thermal damage, pitting, and wear should be considered. Kansal et al. (2001) have developed a thermal analysis for injection molding process using computer aided design (CAD) system. The temperature distribution and thermal residual stresses which were developed due to the non-uniform cooling of the molten plastic inside the mold cavity in the injection molded polystyrene gear were studied. This study optimized a cooling channel design inside the mold cavity since temperature distribution profiles were known.

- **Processing Parameters**

Tool and machine selection is one of the most important activities in a process planning (Chung and Peng 2004). Qualitative and quantitative criteria such as power, ram speed, screw speed, machine size and machine cost, die design and die geometry, raw material, barrel temperature, pressure, etc. are evaluated for machine selection of respective plastic processing (Schmid and Kalpakjian 2006).

Many researchers such as Chen et al. (2008) and Oktem et al. (2007) have found that injection molding processing parameters have crucial effects on the quality of final products. Postawa and Koszkul (2005) stated that factors connected with injection molding machine such as design of mold, processing conditions and processed polymer may affect the physical state of molded products. However, this study was focused more on the effect of processing parameters on the shrinkage problem of injection molded semi-crystalline polymer polyoxymethylene (POM) and amorphous polystyrene (PS). A design of experiment of 27 runs with five factors; mold temperature, injection temperature, cooling time, hold pressure and injection speed, were studied. As for POM, the clamp pressure was found to be the most significant factor, while for PS, injection temperature and mold temperatures were much more affecting factors of the shrinkage problem.

In another study, Tsai et al. (2009) determined the effects of processing parameters on optical quality of lenses during injection molding. This study has identified that the most significant processing parameters affecting surface waviness were the melting temperature, followed by mold temperature, injection pressure and packing pressure, whereas injection molding processing parameters were found to have a slightly less effect on the light transmission and surface finish of lenses produced.

Injection molding process has been used to produce plastic gears since 1950s. American Gear Manufacturers Association (AGMA) has set the quality levels ranging from 6 to 8 which can be obtained for plastic gear via injection molding process. Senthilvelan and Gnanamoorthy (2008) in their studies stated that manufacturing process may influence the accuracy and quality of gears being produced. The study has found that material shrinkage behavior affects the quality of injection molded gear significantly. In addition, Breeds et al. (1993) in their studies stated that injection molded plastic gears will change in size if alterations were made to the material specifications or to the molding conditions. They also tend to have geometric imperfections of fairly large magnitude, such as overall eccentricity and tooth form errors.

Therefore, determining an optimum setting of injection molding process is a great concern for the plastic industry in order to produce plastic products with a good quality. Researchers have attempted various approaches in the determination of processing parameters in injection molding process to obtain consistent and better quality of molded products. The following section expands more on optimization of injection molding process to improve the quality of molded products.

2.5 Optimization Technique

In the previous section, injection molding process was discussed as a complicated process and numerous studies have been done related to the factors affecting the quality of the final product. Improper material selection, part and mold design, and inappropriate processing parameter setup could have a negative impact on the quality of the final product as discussed previously.

Kamoun et al. (2009) adopted the sequential simplex method to optimize on-line the levels of the parameters of injection molding process in order to minimize the process cycle time and to reduce the rejects. Nine processing parameters were selected to conduct the optimization experiment; screw rotation speed, back pressure, injection rate, injection pressure, cooling time, holding pressure, holding time, nozzle temperature and opening stroke. Optimum conditions were achieved using 17 experiments and the results clearly showed that the process cycle time was very sensitive to the effect of two parameters: cooling time and holding pressure.

Therefore, it is important to control all potential factors in the plastic injection molding process that may disturb and affect the quality of the final product. A reliable optimization method is needed for substituting the trial and error method, which requires tremendous time and work which can lead to a high cost production. Nowadays, optimization processes have gained interest and attention among researchers as they can minimize cost and defects as well as improve production efficiency (Ibrahim et al. 2010). Taguchi's design of experiment is one of the most commonly used optimization process in the plastic injection molding industries.

Design of experiments (DOE) is a statistical technique introduced by Sir R. A. Fisher in England in the early 1920s (Roy 2001). His primary goal was to determine the optimum conditions needed to produce the best crop in an agricultural field (Dowlatshahi 2004). Using the DOE technique, Fisher was able to lay out all combinations which were also called trial conditions of factors in the experimental study. The trial conditions were interpreted using a matrix which allowed each factor an equal number of test conditions. Generally, traditional DOE method can be divided into a full factorial design and fractional design (Park and Ahn 2004).

Full factorial design is used to identify all possible combinations for a given set of factors. Comprehending to this fact, most industries may prefer full factorial design since it evaluates all possible combinations. Consequently, a large number of experiments is needed which are very costly and time consuming (Farkas et al. 2007). Hence, fractional factorial design is another option for a design of experiment. Fractional factorial design is applied by selecting a limited number of experiments from all the possibilities generated from most information and reduces the number of experimental work. However, the complexity and inadequate guideline of performing and analyzing such experiments are major drawback for researchers in applying the fractional factorial design (Rao et al. 2008).

Hence, in 1940s, a Japanese scientist called Dr. Genichi Taguchi who spent much of his life for researching ways to improve the quality of manufactured products proposed a quality engineering method called Taguchi method by utilizing former DOE technique. According to Maghsoodloo et al. (2004), Taguchi's major contributions on developing the method are by listing and describing the method in a systematic and analytical manner. The concepts of Taguchi method utilize orthogonal array (OA), signal-to-noise (S/N) ratios, main effects and analysis of variance (ANOVA).

The Oas provide a set of well-balanced experiments which satisfy the minimum experimental design needed and a modification of the Oas became necessary when mixed levels and interactions are present. The determination of the appropriate size of an orthogonal array is very important in Taguchi method to minimize the number of trial runs. Taguchi has prescribed proper guidelines regarding this matter. The size of an orthogonal array mainly depends on the number of processing parameters and their factor levels.

In analyzing the experimental results, Taguchi method uses a signal to noise ratio instead of normal average value by converting the trial results data into a value for the characteristic in the optimum setting analysis. Taguchi's S/N ratio measures the sensitivity of the quality characteristic and serves as objective functions for the optimization depends on the experimental viz; the smaller the better, the nominal is the best or the higher the better. A high value of S/N ratio implies better quality characteristic. Therefore, the S/N ratio is adopted in analyzing the main effects and ANOVA. The main effects visualize the optimal condition of the processing parameters at a specific level with the highest response and ANOVA determined the significance of the selected parameters affecting the product quality. For better understanding of the Taguchi method concept, Roy (1990) can be referred.

2.5.1 Standalone Taguchi Method

Various industries have employed the Taguchi method over the years to improve products or manufacturing processes (Chen et al. 2009a). It is a powerful and effective method to solve challenging quality problems. The DOE method has been used quite successfully in several industrial applications like in optimizing manufacturing processes or designing electrical or mechanical components (Puertas and Luis 2004; Tong et al. 2004). According to Chen and Chen (2007), Taguchi approach enables a comprehensive understanding of the individual and combined effects of various design parameters to be obtained from a minimum number of experimental trials. Kim et al. (2003) concluded that the aim of the Taguchi design method is to optimize manufacturing parameters.

The quality of an injection molded parts greatly depends on material selection, part and mold design as well as processing parameters. Numerous studies have been done by employing Taguchi method as optimization technique and applied successfully for parametric analysis of various polymeric systems (Mehat and Kamaruddin 2011b; Ozcelik 2011; Erzurumlu and Ozcelik 2006). From the review