OPTIMIZATION OF INJECTION MOULDING PROCESS PARAMETERS FOR RECYCLED HIGH DENSITY POLYETHYLENE (RHDPE) USING THE TAGUCHI METHOD

[1]JAMALUDDIN ABDULLAH, [2]LIAU WAI SHAN, [3]HANAFI ISMAIL

[1,2]School of Mechanical Engineering, Universiti Sains Malaysia, Engineering Campus, 14300 Nibong Tebal, Seberang Perai Selatan, Pulau Pinang, Malaysia
[3]School of Materials and Mineral Resources Engineering, Universiti Sains Malaysia, Engineering Campus, 14300 Nibong Tebal, Seberang Perai Selatan, Pulau Pinang, Malaysia
E-mail: mejamal@usm.my, wsliau@gmail.com, ihanafi@usm.my

Abstract- In this work, recycled High Density Polyethylene (rHDPE) from the industry disposal is investigated as potential recycled plastic to substitute its virgin source for the injection moulding process. In particular, the study aims to determine the optimum process parameters for the rHDPE in the application of injection moulding process. Taguchi method is adopted to optimize the process parameter combination from the four controllable process parameters, namely the melting temperature, packing pressure, packing time and injection pressure. The effects of the process parameters are evaluated and benchmarked against the established mechanical properties and dimensional stability of the moulded plastic tray from virgin source. The result of the study reveals that the qualities of the moulded rHDPE plastic tray are good and optimized under the process combination of the melting temperature of 513.15 K, packing pressure of 70%, packing time of 30 s and injection pressure of 15 MPa for the shrinkage; meanwhile the combination of melting temperature of 518.15 K, packing pressure of 85%, packing time of 30 s and injection pressure of 15 MPa for the tensile strength and lastly, the combination of melting temperature of 518.15 K, packing pressure of 80%, packing time of 10 s and injection pressure of 14 MPa for the flexural strength. The feasibility to injection moulded rHDPE and optimize the process parameters shows huge potential of using rHDPE as sustainable alternative to virgin HDPE as the raw material for injection moulding process.

Index Terms- Recycled High Density Polyethylene, Taguchi Method, Injection moulding, Mechanical Properties, Shrinkage, Green Manufacturing

I. INTRODUCTION

The use of the plastics for the diverse household and industrial appliances has grown dramatically during the last few decades due to the versatile and unique properties of the plastic such as corrosion resistance, lightness, chemical inert and color fastness. Annual total consumption of plastic products in Western Europe was estimated at 98 kg per capita in 2003, almost doubling from 64 kg per capita in year 1993 [1]. From this total, thermoplastics contributed 73 wt.% of plastics consumed. The major type of thermoplastics included 17 wt.% of Low Density Polyethylene (LPDE), 11 wt.% of High Density Polyethylene (HDPE) and 16 wt.% of Polypropylene (PP) [1]. Such heavy consumption of plastic inevitably leads to the creation of the large quantities of solid plastic disposal as the plastic's product life cycle is comparatively short compare to metals and other materials. According to Yong Lei et al., a huge plastic waste stream of 24.7 million ton of plastic waste were recorded in the United States in year 2000 [2].

The disposed plastic is either non-biodegradable or if it decays, it takes long period to decay in the landfill due to their highly stable organic compound composition [3]. Consequently, this will fill-up the landfill and has now been recognized as serious worldwide environmental problem [4]. Owing to these reasons and the effort to support greening the earth, recycling, reprocessing and reuse the plastic wastes have become a central role in the today's plastic industry [5]. These activities are not just solving the landfill pollution problems but at the same time, reducing cumulative energy required for virgin plastic processing and dramatically minimizing the production cost of the raw plastic worldwide.

Cruz et al [6] and Pedrose et al [1] objected to the use of recycled plastics as raw material in injection moulding as the claims of the degradation of recycled plastic especially the mechanical properties due reprocessing and storing. They declared that this will constrained the application of the recycled plastic. Nevertheless, the claims have been overthrown by Papaspyrides et al. and other researchers [2]. They have proven that three largest plastic commodities in the world, which were the low density polyethylene (LDPE), high density polyethylene (HDPE) and polypropylene (PP) recycling models possess the similar tensile properties for the virgin polymers and the mechanically recycled polymers through the different solvents/non-solvents system at different weight percent and temperatures.

Among the processing techniques used for the plastic products, the injection moulding process is the most commonly used technique in the plastic industry especially for the mass production of the products [7, 8]. Although the injection moulding is low cost and high production single step manufacturing process, the controlling and monitoring the injection moulding process parameters for both virgin and recycled plastics requires skills and knowledge. Inappropriate and ineffective selections of the process parameters

will alter the effects of other parameters as each of these parameters is dependent on each other and consequently adversely degrade the moulded product quality, which contributed to costly high product reject rate. In the literatures, few researches have studied and optimize the effect of the injection moulding process parameters with the aid of the statistical optimization approaches. Zahid et.al. [9] used the combined grey relational and principal component analyses to examine and optimize the significance of process parameters towards the tensile, compression and flexural properties of the moulded HDPE product. At the same time, Nik et al. [10] studied the parameters affect on the flexural and compressive behavior of the mixture of virgin and recycled PP product by using the Taguchi method. Oktem et al, Chang and Fashion and Mirigul A. studied the effects of the process parameters toward the shrinkage behavior of the moulded product by using Taguchi method [10, 11]. These works illustrated the practically and feasibility of the application of statistical optimization approaches such as Taguchi Method in the study to optimize the process parameters.

In this paper we studied the effect of the four injection moulding process parameters, namely melting temperature, packing pressure, packing time and injection pressure on the mechanical properties (tensile strength and flexural strength) and shrinkage of the rHDPE product from industrial waste. Taguchi method is adopted to study the effects of the process parameters toward the mechanical properties and shrinkage of the product and subsequently determine the optimum process parameters combinations for the mechanical properties and shrinkage respectively. This work contributed to the knowledge on optimizing injection moulding parameters of rHDPE direct from plastics industry production rejects which usually contain unknown polymer blends. The uncertainty of the blends of industrial plastic waste make it even more important to study the suitable processing parameters of the recyclates.

II. EXPERIMENTAL PROCEDURES

A. Sample Source

This study focused on the research of the rHDPE that was produced from post-industrial disposal. The sample source is illustrated in the Fig. 1. Such sample source was mechanically recycled in which the scrap and defect HDPE products were collected from the plant and then processed into a recyclate via the melt extruder process. This sample source was a non-homogenous plastic as it is a mix of different grades of HDPE industrial disposals. The sample source also contain unknown metal impurities, which is the residual of post-industrial products. Material properties of the rHPDE were determined through a series of material testing and characterisation. The results revealed that the rHDPE has the melting temperature at 401.75 K with the latent heat of fusion of 195.6 J/kg and the degradation point of rHDPE at 788.49 K.



Fig.1: rHDPE from industrial waste

B. Experimental Design

The product to be studied was the plastic tray with the dimension of L (204.5 mm) x W (102.5 mm) x H (23.6 mm) as shown in Fig. 2. The function of this plastic tray is to hold the toolkit inside a tool box. The tensile strength and flexural strength are crucial for the plastic tray to maintain its form when load is applied. The tensile strength and flexural strength were therefore considered as the quality characteristics of the plastic tray. In addition, the dimensional tolerance of the plastic tray is also important to ensure that the plastic tray is perfectly fitted inside the partition of the toolbox. Shrinkage which may contribute to dimensional changes of the moulded products was thus chosen as another quality characteristic of the plastic tray.

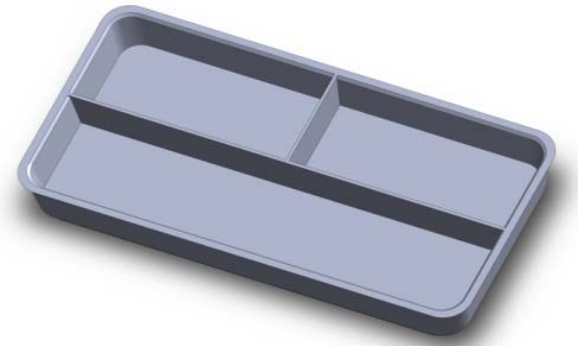


Fig.2: CAD drawing of plastic tray

Four controllable three-level injection process parameters were selected in order to evaluate their performances on the three quality characteristics of the plastic tray respectively. The optimum process parameters were then obtained in accordance to the analysis results. The four controllable process parameters were melting temperature, packing pressure, packing time and injection pressure. Their levels were listed at Table 1 respectively. Other process parameters, such as mould temperature (303.15 K equivalents to 30 □C), injection time (3.33 s), stroke distance (150 mm) and cooling time (55 s) were kept at constant throughout the study. These working range of these process parameters were obtained and revised with the aid of the Simpoeworks simulation software.

Table 1: Injection moulding process parameters and levels

Process Parameters	Level 1	Level 2	Level 3
A: Melting temperature (K)	508.15	513.15	518.15
B: Packing pressure (%)	70	80	85
C: Packing time (s)	10	20	30
D: Injection pressure (MPa)	14	15	16

The orthogonal array (OA) of the Taguchi method was adopted to simplify into a few experiments, which otherwise need 81 runs using full factorial design [12, 13]. By using the L_9 OA, only nine experiments were conducted and the experimental combinations were listed in Table 2.

Table 2: L_9 Orthogonal Array

Run	A: Melting Temp (K)	B: Packing pressure (%)	C: Packing time (s)	D: Injection pressure (MPa)
1	508.15	70	10	14
2	508.15	80	20	15
3	508.15	85	30	16
4	513.15	70	20	16
5	513.15	80	30	14
6	513.15	85	10	15
7	518.15	70	30	15
8	518.15	80	10	16
9	518.15	85	20	14

Battenfeld TM750/210 injection moulding machine were utilized to produce the rHDPE plastic trays with the experimental combinations listed in Table 2. Each of the combinations were repeated twice for each particular quality characteristics, giving a total of six injection moulded rHDPE plastic trays from three quality characteristics to be evaluated.

Prior to the injection moulding process, the rHDPE sample was granulated into smaller pieces by using the granulator to enable to flow through at the hopper. The crushed rHDPE pellets then were poured into the hopper and preheated at temperature of 353.15 K for two hours to vaporize the moisture contents inside the pellets to prevent air bubbles being trapped in the moulded plastic tray. The preheat process is crucial for all the recycling plastics as the moisture contents inside the recyclates are much higher than the virgin plastic. Once the preheat process was completed, the injection molding process parameters were set in accordance to the experimental combinations as shown in Table 2 respectively.

In-mold shrinkage is measured on the molded product by measuring linear dimension just after moulding and again after 48 hours at room temperature [14]. The term of the shrinkage was used and referred to the in-mold shrinkage in the subsequent discussion of the paper. The shrinkage testing was conducted in accordance to ASTM D955-10 standard. The plastic trays were placed under condition with the room temperature of (296.15 ± 275.15) K which equivalents to (23 ± 2) □C and 50% relative humidity upon the ejection of molded part. The trays were recommended to cool in a horizontal position by placing them on the low thermal conductivity surface to minimize the warpage. The transverse dimension of plastic trays were then taken at three difference testing sections as shown in Fig. 3 using the analog vernier caliper, after 48 hours upon the ejection of the plastic tray from the mould.

The shrinkage was then calculated by using Eq. (1):

$$Sw = (Wm - Ws)x\ 100\%\ /Wm \quad (1)$$

where Sw is the shrinkage perpendicular to flow (%), Wm is the mold dimension perpendicular to flow, which equal to 101.7 mm and Ws is the specimen dimension perpendicular to flow (mm).

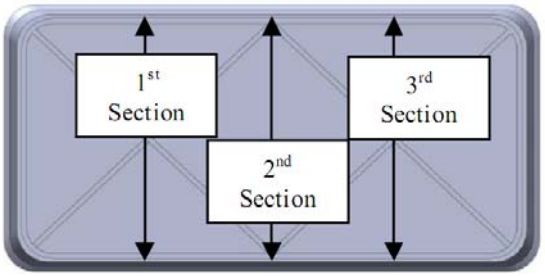


Fig.3: Test section on plastic tray

The remaing plastic trays were cut into four sections with the dimension of L (170 mm) x W (20 mm) X (T 2.65 mm) for each by using the steel saw and then they were piled with the file and sand paper to remove the burr of the cutting prior to the mechincical properties testing.

The tensile strength is defined as the maximum of the stress that material can withstand before the necking starts [15] and it was tested with Instron Table Mounted Universal Testing Machine (UTM) of the model of 3367 in accordance to ASTM D638-10 standard. The testing was conducted at the room temperature of 296.15 K and 50% relative humdity. Each of the specimen was marked for the gauge length of 100 mm from the center to sides of the specimens. The testing was performed with the crosshead speed of 5 mm/min and the sampling rate of 2 points/sec until the specimen ruptured

On the contrary, the flexural strength is defined as the maximum stress that material can withstand before it starts to bend or deform [16]. In this study, the method of three-points bending was used for the flexural strength testing and it was performed with the same UTM mentioned previsouly in accordance to ASTM D790-10 standard. The testing was conducted under the same condition and gauge length of 100 mm. The data sampling rate of 10 points/sec and the crosshead speed of 6.29 mm/min were specified in the testing. The testing was terminated when the maximum strain of 5.0% was reached. The obtained shrinkage, tensile strength and flexural strength results were then

analyzed using the Signal-to-Noise (S/N) ratios and Analyses of Variance (ANOVA) to determine the optimum process parameters combinations for each specified quality characteristics of the plastic tray.

III. RESULTS

A. Signal to Noise ratio

In this study, the smaller the better approach was chosen for the shrinkage testing results as the lesser the shrinkage, the better dimensional stability of the moulded rHDPE plastic tray. Whilst the bigger the better approach was selected for the mechanical properties testing results as the higher the mechanical strength, the stronger the rHDPE plastic tray would withstand load without being bend or deform.

S/N ratio of quality characteristic can be determined by three approached, namely "the smaller the better", "the nominal the better" and "the bigger the better" and it is calculated using Eq. (2)

$$\frac{S}{N}\text{ratio} = -10\log_{10}(\text{MSD}) \quad (2)$$

where MSD is the mean squared deviation from targeted value of quality characteristic and is expressed in the following equations.

For "the smaller the better",

$$\text{MSD} = \frac{y_1^2+y_2^2+y_3^2+\cdots}{n} \quad (3)$$

For "the nominal the better",

$$\text{MSD} = \frac{(y_1-m)^2+(y_2-m)^2+(3-m)^2+\cdots}{n} \quad (4)$$

For "the bigger the better",

$$\text{MSD} = (1/y_1^2 + 1/y_2^2 + 1/y_3^2 + \cdots)/n \quad (5)$$

where y_i =is results of experiment, m is the targeted results and n is number of repetitions.

B. Main Effect Analysis

Upon the obtaining of S/N ratios for the results of three quality characteristics respectively, the main effect of each process parameters is determined by computing the average values of the S/N ratio of four process parameters correspondingly using the eq. (6). The main effect graphs are then plotted in accordance with the average values against the controllable process parameters.

$$\overline{A} = \frac{y_1+y_2+y_3+\cdots}{n} \quad (6)$$

where $\overline{A}$ is average value of S/N ratio for the parameter, y_i = is S/N ratio of i level and n is number of levels.

C. Analysis of Variance (ANOVA)

The ANOVA of Taguchi method is applied to determine the significance of each process parameter towards performance of the quality characteristics in terms of relative percentage by comparing their relative variances. The ANOVA analysis is performed by the computation of Degree of Freedom (f), Sum of Squares (S), Variance (V), F-ratio (F) and Percentage of Contribution (P) sequentially as expressed in the following equations.

D. Verification Test for Optimum Variables

The verification test was conducted by producing the plastic trays with the optimum process parameter combinations from the L_9 orthogonal array run. The shrinkage testing, tensile strength testing and flexural strength testing were then performed respectively. The results obtained from each testing would be compared with the projection results.

The accuracy of the optimum process parameters was justified based on the computed percentage error. The projection of output of each quality characteristic for the optimum process parameter was computed using equation (6) and (7). Only the significant factors were taken into consideration meanwhile the pooled (non-significant) factors would be excluded for the projection results.

$$\text{Projection} = \overline{T} + (\overline{Y_1} - \overline{T}) + (\overline{Y_3} - \overline{T}) + \cdots \quad (6)$$

$$\overline{T} = \text{sum of results of all the experiments/ Total Number of Experiments} \quad (7)$$

IV. DISCUSSIONS OF RESULTS

In this study, the S/N ratios for the shrinkage, tensile strength and flexural strength testing are computed based on the smaller the better approach for the shrinkage and the bigger the better approach for the other two quality characteristics. The main effects of each particular quality characteristics are then obtained by computing the average means of the S/N ratios.

The graphs of the main effects of the controllable process parameters against their corresponded levels are plotted and demonstrated as shown in Fig. 4 to Fig. 6. These graphs are utilized to exploiting the main effect responses for the shrinkage, tensile strength and flexural strength of the rHDPE plastic trays.

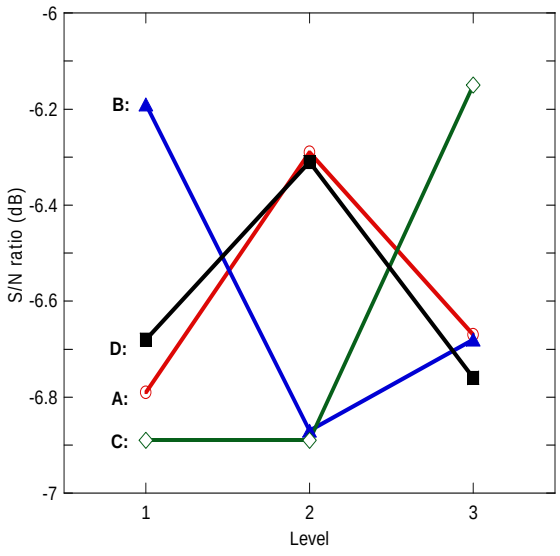


Fig.4: Main effects plot for shrinkage

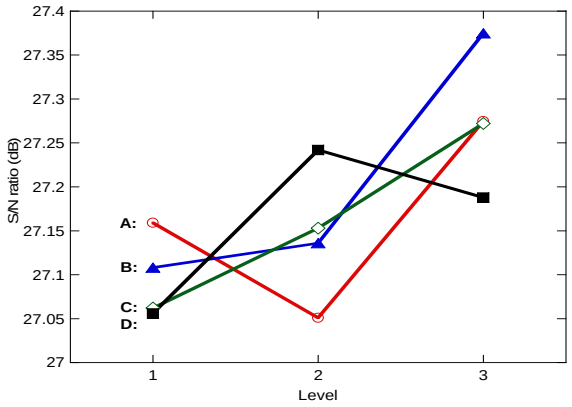


Fig.5: Main effects plot for tensile strength

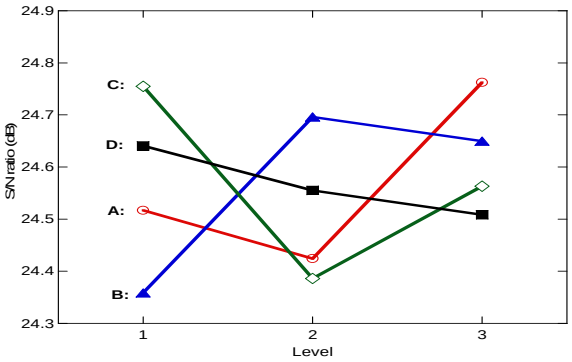


Fig.6: Main effects plot for flexural strength

Table 3 summarizes the optimum parameter combination following the execution of the L_9 experiment. The optimum process parameters combination for the shrinkage of the rHDPE plastic tray is identified as $A_2B_1C_3D_2$, which A_1 represents melting temperature at 513.15 K, B_1 represents packing pressure of 70%, C_3 represents packing time of 30 s and D_2 represents injection pressure at 15 MPa. The tensile strength is optimized by the combination of $A_3B_3C_3D_2$, which A_3 represents melting temperature at 518.15 K, B_3 represents packing pressure of 85%, C_3 represents packing time of 30 s and D_2 represents injection pressure at 15 MPa. The flexural strength meanwhile works at optimum condition under the $A_3B_2C_1D_1$ combination, which the A_3 represents melting temperature at 518.15 K, B_2 represents packing pressure of 80%, C_1 represents packing time of 10 s and D_1 represents injection pressure at 14 MPa. Table 4 shows the percentage errors of the verification test from the calculated values.

Table 3: Optimum parameter combinations

Quality Characteristics	Melting Temperature (K)	Packing Pressure (%)	Packing Time (s)	Injection Pressure (MPa)
Shrinkage	A_2 513.15	B_1 70	C_3 30	D_2 15
Tensile Strength	A_3 518.15	B_3 85	C_3 30	D_2 15
Flexural Strength	A_3 518.15	B_2 80	C_1 10	D_1 14

Table 4: Percentage error of verification test

Quality Characteristic	Optimum Parameter	Expected Value	Result from Verification Test	Error (%)
Shrinkage	$A_2B_1C_3D_2$	1.82	1.96	-7.14
Tensile Strength	$A_3B_3C_3D_2$	23.834	21.753	8.73
Flexural Strength	$A_3B_2C_1D_1$	17.9418	16.1994	9.71

CONCLUSIONS

In this study, the rHDPE is successfully employed to produce the plastic tray by using the injection molding process under the control of four process parameters, which are melting temperature, packing pressure, packing time and injection pressure. These parameters have the great impact on the shrinkage, tensile strength and flexural strength of the moulded rHDPE plastic tray. Experimental results show that any changes of these parameters will eventually improve or degrade performance of the shrinkage, tensile strength and flexural strength. By implementing the Taguchi method, the effects of process parameters are optimized using S/N ratios and main effect analysis. The process parameter level that possesses the highest S/N ratio results the least shrinkage and highest tensile and flexural strength and yields minimum variance. The optimum process parameters combinations are determined by obtained the highest S/N ratios of each process parameters. The optimum combinations for the shrinkage, tensile strength and flexural strength of the moulded rHDPE plastic tray are $A_2B_1C_3D_2$, $A_3B_3C_3D_2$ and $A_3B_2C_1D_1$ respectively. ANOVA approach of Taguchi method is also effectively employed to study the impacts of process parameters toward the quality characteristics of the rHDPE plastic tray. The packing time is acknowledged to play a significant role on the shrinkage and mechanical properties performances of the rHDPE plastic tray as it acquires the first ranking on impact of shrinkage and flexural strength along with the second ranking for the tensile strength. Besides that, the packing pressure is recognized as the process parameter that has a significant contribution to the shrinkage and flexural strength after the packing time. Meanwhile, the melting temperature is just playing a crucial role in the performance of tensile strength of rHDPE plastic tray by owning the first ranking among the others. In contrast, the effect of injection pressure is less significant since it owns the third or four ranking for the impacts of the shrinkage and tensile strength but it does not have any effect on the flexural strength of the plastic tray. The confirmation test conducted had successfully proved that the optimum process parameters for each quality characteristic of plastic tray have almost the similar behaviors with the

expected performances and the percentage of errors, which are less than 10%. Therefore, those optimum process parameters are applicable for the production of rHDPE with the injection molding.

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