UNIVERSITI SAINS MALAYSIA

Laporan Akhir Projek Penyelidikan Jangka Pendek

Improvement of Quality Characteristics of an Injection Moulding Product Made From Recycle Plastic by Optimising the Injection Moulding Parameters Using Taguchi Method

By

Assoc. Prof. Dr. Shahrul Kamaruddin

Assoc. Prof. Dr. Zulkifli Mohamad Ariff

2013

UNIVERSITI SAINS MALAYSIA

Sila kemukakan laporan akhir ini melalui Jawatankuasa Penyelidikan di Pusat Pengajian dan Dekan/Pengarah/Ketua Jabatan kepada Pejabat Pelantar Penyelidikan

1. **Nama Ketua Penyelidik:** A.P. DR.SHAHRUL KAMARUDDIN
Name of Research Leader

☑ Profesor Madya/ *Assoc. Prof.*　☐ Dr./ *Dr.*　☐ Encik/Puan/Cik *Mr/Mrs/Ms*

2. **Pusat Tanggungjawab (PTJ):**
School/Department
School Of Mechanical Engineering

RECEIVED 03 SEP 2013 Pej. Pengarah RCMO

3. **Nama Penyelidik Bersama:** A.P Dr. Zulkifli Mohamad Ariff
Name of Co-Researcher

4. **Tajuk Projek:**
Title of Project
Improvement of Quality Characteristics of an Injection Moulding Product Made From Recycle Plastic by Optimising the Injection Moulding Parameters Using Taguchi Method

5. Ringkasan Penilaian/*Summary of Assessment*:	Tidak Mencukupi *Inadequate* 1	2	Boleh Diterima *Acceptable* 3	Sangat Baik *Very Good* 4	5
i) **Pencapaian objektif projek:** *Achievement of project objectives*	☐	☐	☐	√	☐
ii) **Kualiti output:** *Quality of outputs*	☐	☐	☐	√	☐
iii) **Kualiti impak:** *Quality of impacts*	☐	☐	☐	√	☐
iv) **Pemindahan teknologi/potensi pengkomersialan:** *Technology transfer/commercialization potential*	☐	☐	☐	√	☐
v) **Kualiti dan usahasama :** *Quality and intensity of collaboration*	☐	☐	☐	√	☐
vi) **Penilaian kepentingan secara keseluruhan:** *Overall assessment of benefits*	☐	☐	☐	√	☐

sebagai bahan mentah dalam pengeluaran produk. Selain itu, integrasi kaedah Taguchi dan simulasi berangka telah meningkatkan secara berkesan prestasi produk yang dihasilkan dari bahan kitra semula yang diproses semula dari pandgan sudut pembuatan menunjukkan bahawa objektif kajian ini telah tercapai.

7. Sila sediakan laporan teknikal lengkap yang menerangkan keseluruhan projek ini.
[Sila gunakan kertas berasingan]

Applicant is required to prepare a Comprehensive Technical Report explaining the project.
(This report must be appended separately)

Please Refer Attachment 1

Senaraikan kata kunci yang mencerminkan penyelidikan anda:
List the key words that reflects your research:

Bahasa Malaysia	*Bahasa Inggeris*
Penyemperitan Acuan	Injection Moulding
Plastik Kitar semula	Recycle Plastic
Kaedah Taguchi	Taguchi Method

8. Output dan Faedah Projek
Output and Benefits of Project

(a) * **Penerbitan Jurnal**
Publication of Journals
(Sila nyatakan jenis, tajuk, pengarang/editor, tahun terbitan dan di mana telah diterbit/diserah
(State type, title, author/editor, publication year and where it has been published/submitted)

1. Nik Mizamzul Mehat and Shahrul Kamaruddin, Investigating the Effects of Injection Molding Parameters on the Mechanical Properties of Recycled Plastic Parts Using the Taguchi Method, Materials and Manufacturing Processes, 2011, 26, 7
2. Nik Mizamzul Mehat and Shahrul Kamaruddin, Optimization of mechanical properties of recycled plastic products via optimal processing parameters using the Taguchi method , Journal of Materials Processing Technology, 2011, 211, 5
3. Nik Mizamzul Mehat & Shahrul Kamaruddin, Quality Control and design optimization of plastic product using Taguchi method: a comprehensive review, International Journal Plastic Technology, 2012, 2, 16
4. Ng Chin Fei, Shahrul Kamaruddin, Arshad N. Siddiquee, Zahid A. Khan, Experimental Investigation on the Alternative Use of Recycled Plastic and Application of the Taguchi Method for Optimization of Injection Moulding Process Parameters, International Journal of Mechanical and Materials Engineering, 2011, 6, 10

Komen Jawatankuasa Penyelidikan Pusat Pengajian/Pusat

Comments by the Research Committees of Schools/Centres

The researchers have successfully completed the research grant by conducting a very good research. The work carried out through the grant has produced a very good output range; 5 publications in ISI (cited) journals and 2 MSc students.

In addition, a comprehensive report has been prepared to include the details of the project. ~~for the~~

In general, it is a good project.

Tutup Geran.

5/9/13

DR. ABDUL RAHIM B. OTHMAN
Timbalan Dekan (Penyelidikan)
Pusat Pengajian Kejuruteraan Mekanik
Kampus Kejuruteraan
Universiti Sains Malaysia
14300 Nibong Tebal, Pulau Pinang.

TANDATANGAN PENGERUSI
JAWATANKUASA PENYELIDIKAN
PUSAT PENGAJIAN/PUSAT
Signature of Chairman
[Research Committee of School/Centre]

29/7/2013.
Tarikh
Date

EXECUTIVE SUMMARY

2.0 METHODOLOGY

EXECUTIVE SUMMARY

This research focused on the feasibility study of using ABS recyclates to replace virgin resins and optimization of processing parameters for improving the performance of ring stopper produced from reprocessed ABS. In the feasibility study, varying proportions of ABS recyclates (0–50%) obtained from the post-industrial wastes including sprues, gates, and runners, were mixed with virgin resin to investigate their effects on the mechanical, rheological, and morphological properties of the ring stopper. In addition, the ABS blends were subjected to 10 reprocessing cycles to evaluate the reprocessing ability of the ABS recyclates by monitoring the polymer degradation during multiple reprocessing. Subsequently, a systematic and effective approach was used to optimize the processing parameters by integrating Taguchi method and numerical simulation to enhance the hoop tensile strength and elongation at break as well as to reduce the shrinkage of the ring stopper. Numerous processing parameters were analyzed to determine their significance via a Taguchi-based simulation experiment and only the significant processing parameters were further optimized to enhance the performance of ring stopper produced from reprocessed ABS. The effect of blending composition and reprocessing cycle has been thoroughly analyzed and the experimental findings show that the performance of the ring stopper produced of 10-time-reprocessed ABS blend which consists of 40% recyclate after optimization is comparable and slightly better than the performance of the ring stopper produced of virgin resin. Therefore, the recycled ABS could potentially substitute the virgin ABS resin as the raw material in plastic production. Moreover, the integration of Taguchi method and numerical simulation has effectively improved the performance of ring stopper produced of reprocessed ABS from the manufacturing point of view, indicating that the objectives of this research have been achieved.

Thus, plastic recycling has drawn attention along with growing environmental concerns, as well as the potential of economic benefits by establishing a waste reduction and recycling policy.

Unfortunately, large scale plastic recycling is still hindered by a wide range of barriers in the industry. One of the problems is recycled plastics has been doubted to be a reliable replacement of virgin plastics. This is due to the belief that changes in mechanical and rheological properties have created a perception that recycled plastics have a low economical value. Hence, the manufacturers avoid using recycled materials that they believe would affect the product quality. In fact, the properties of plastics tend to decrease after several injection cycles according to the nature of the polymer subjected to multiple reprocessing. But still, improvements could be made from both mechanical and material perspectives concurrently to find the optimal point in producing recycled plastic products with satisfactory quality.

A good balance between properties and reprocessability of recycled plastic which ensures its reuse over long production runs is absolutely necessary. This subject has been the focus of many papers and part of the literature on recycled plastic especially for the multiple reprocessing is of academic rather than of commercial interest. Various approaches are proposed by the researchers to improve performance and properties of recycled plastic from the material perspective, such as blending with other plastics and the addition of filler and stabilizers. Nevertheless, high processing costs has become an obstacle for implementing the aforementioned approaches from a laboratory to an industrial scale compared to the price of using virgin resin. As a consequence, an interest existed in the industrial sector for looking into the possibility of optimizing the injection moulding process from the manufacturing perspective. It could be an appealing approach to improve the recycled plastic products considering no extra processing cost is required.

It is vital to understand the basic mechanisms of the injection moulding process prior the process optimization. The quality of the plastic products, either it is produced of virgin material or recycled material, depends on a large number of process variables. Factors that influencing the part quality can be classified into four categories: part design, mould design, machine performance, and processing conditions. In a currently running production process, the part design, mould design, and machine performance are commonly assumed as established and fixed. Any modification made would lead to higher cost of production. Optimization of processing parameters can be regarded as a virtue approach to offer significant property improvements to the recycled plastic products without making any major alteration in the production process.

The settings of processing parameters in injection moulding process can be categorized into four groups: temperature, pressure, time, and distance. Each parameters adjustment will have either a positive or a negative effect on the physical and aesthetic properties of the moulded product. Nevertheless, the interaction effect between the processing parameters cannot be neglected because all processing

1.4 Project Objectives

The objectives of this project can be enumerated as follows:

1. To study the relationship of the blending composition of virgin and recycled plastic resins towards the mechanical and material perspectives and to obtain the optimal blending composition to produce acceptable product quality with lower raw material cost.
2. To analyze the changes of mechanical, rheological and morphological properties of recycled plastic due to thermo-mechanical degradation during multiple reprocessing and to determine the appropriate reprocessing cycles to manufacture products with satisfactory quality.
3. To study the effectiveness and importance of the integrated approach using the Taguchi method and numerical simulation in determining the significant processing parameters out of the numerous injection moulding process variables.
4. To improve the tensile properties and dimensional stability of recycled plastic products by optimizing the processing parameters via Taguchi method.

The research work was collaborated with Blaupunkt Malaysia Sdn. Bhd. in Penang. This research is target towards implementing closed-loop recycling in the production to effectively handle the post-industrial plastic waste. It was performed in industrial settings to yield recycled plastic products with satisfactory quality which are commercially viable in the market. Nevertheless, there are some limitations in this research where no modification is allowed to be done on the designs of product and mould as it will affect the productivity.

Aiming at enhancing the part quality for recycled plastics, the highlight in this research is to investigate the effectiveness of Taguchi method as a design of experiment to optimize the processing conditions in injection moulding. Computer-aided engineering (CAE) simulation was integrated with Taguchi method to make better analysis in regards to parameters selection. The hoop tensile properties and shrinkage will represent the performance measures for the virgin and recycled ABS blend.

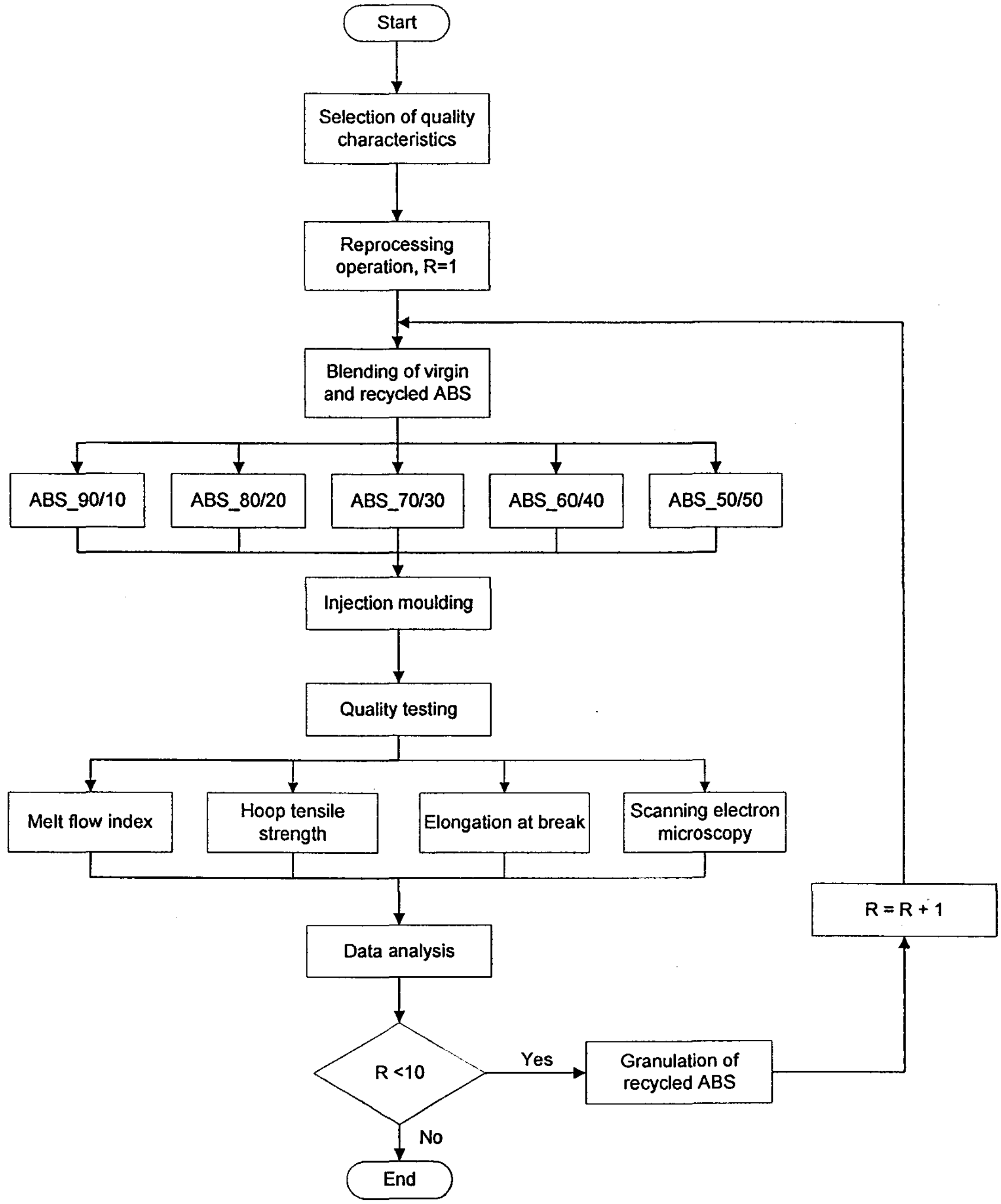

Figure 2.1: Flow chart of the feasibility study

2.2.2 Material Use Feasibility Study

The acrylonitrile butadiene styrene (ABS) material used in this work was an injection grade, denoted Novodur P2MT and supplied by Lanxess. The material was used as received. The general properties of the virgin ABS are shown in Table 2.1.

Table 2.1: General properties of ABS Novodur P2MT

Properties	
Density (g/cm^3)	1.04
Melt Flow Index (220°C/10 kg)	8
Ultimate Tensile Strength (MPa)	48
Tensile Strain (%)	2.4
Modulus of Elasticity (GPa)	2.5
Izod/RT, Notched (J/m)	220
Hardness (HK)	100

The recycled ABS pellets are the same grade as the virgin material where they were sourced by crushing the existed products and the post industrial scraps via a granulator. All the materials were vacuum dried in an oven at 80°C for two hours to remove moisture. Samples were prepared by mixing ratios of 10, 20, 30, 40, and 50% (by volume) of recycled and virgin material respectively via a proportional mixing valve, Motan Metromix 38. Details are shown in Table 2.2.

Table 2.2: Blending composition of virgin and recycled ABS

Sample Code	**Virgin ABS (%)**	**Recycled ABS (%)**
ABS_90/10	90	10
ABS_80/20	80	20
ABS_70/30	70	30
ABS_60/40	60	40
ABS_50/50	50	50

2.2.4 Quality Testing Feasibility Study

a. Melt Flow Index (MFI)Test

The MFI is a rheological property of polymer that is usually listed in grams per 10 minutes. It reflects the flow rate of plastic through a standard design orifice at a predetermined time by exerting a predetermined load on the plastic. MFI is commonly used in the recycling industries to measure its degradation on molecular weight of the final recycled material to monitor the reprocessing ability of the recyclates. The MFI value of virgin ABS was used as a reference of the relative MFI measurement to calculate the molecular weight of recycled ABS after each reprocessing cycle.

The specimens were grinded via a granulator and they were kept in an oven at 80 °C for four hours for drying purpose before the testing to ensure that there was no moisture within the samples. Appropriate quantity of each one of the polymer samples was packed properly in the barrel of the melt flow index machine to avoid formation of air pockets and preheated for 360 s before the MFI tests began. The tests were performed at 220 °C, at a weight of 10.0 kg, in accordance with Procedure A of the ASTM D1238-04, using a Dynisco Polymer Test LMI 4000 series melt flow indexer. Five measurements on the weight of each sample were taken and the average values and standard deviations were calculated.

b. Hoop Tensile Test

Due to the limitations of the dimension and shape of the component, the hoop tensile strength and elongation at break, were measured in accordance with ASTM D2290-04, using an Instron 3367 series table-mounted universal testing machine. A split-disc test fixture was fabricated accordingly, as shown in Figure 2.3. The test specimen was mounted on the test fixture where the reduced sections were placed at the side of split. This ensured that the specimen was centered on the line joining the fixture's points of attachment with the test machine. The crosshead speed was 2.54 mm/min and five specimens were tested for each reprocessing cycle. The hoop tensile strength at yield of the specimens was calculated using the appropriate equation as stated in ASTM D2290-04:

$$\sigma_a = P_b / (d_1 b_1 + d_2 b_2) \tag{2.2}$$

where: σ_a = hoop yield or ultimate tensile stress of the specimen, MPa

P_b = maximum or breaking load, N
d_1, d_2 = thickness at reduced or test section, mm
b_1, b_2 = width of reduced or test section, mm

2.3 Computer-Aided Engineering (CAE) Simulation

In this research, the main objective of the computer-aided engineering (CAE) simulation is to identify the significant processing parameters and to investigate their effects on the hoop tensile properties and dimensional stability of the injection-moulded ring stopper. With the advance of the CAE technology, an accurate prediction of the internal properties of plastic flow is made to forecast the final part quality. However, due to the complex dynamics of the injection moulding process, a large number of processing parameters that must be controlled and tremendous efforts are still required for the horde of simulation analysis. As a result, an integrated approach would a beneficial undertaking by introducing Taguchi method as it offers the advantages in reducing the number of simulation runs required by using an appropriate orthogonal array. Despite abridging the simulation experimentation, Taguchi method is still capable to give the accurate results. The procedures of the simulation runs are illustrated in Figure 2.4 and each stage of the simulation experimentation will be elaborated in detail.

2.3.1 CAE Model Preparation

The model preparation starts with the 3D geometry modelling using Solidworks 2009 software (Figure 2.5). The dimensions of the ring stopper are 40mm of outer diameter, 32mm of inner diameter and 9.3mm of length as referred to the part design. Despite the simulation is running for a mould of four cavities, only one 3D model is needed to be established as all the parts are identical. Subsequently, the 3D model is exported to the simulation software in stereo lithography (STL) format.

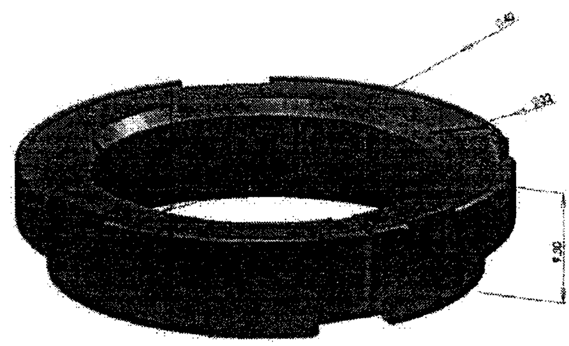

Figure 2.5: 3D model of the ring stopper

Cadmould 3D-F was employed to analyze the plastic flow simulation for a mould with four cavities of ring stopper (Figure 2.6). Prior the simulation, a runner system of rounded square shape was built in dimension of 3 mm in height and 1 mm in width based on the mould design. The runner system is crucial to the plastic processing because inappropriate design of runner system will lead to imbalance plastic flow and cause defects on the product. Subsequently, a gate location was defined as to connect the four 3D models to the runner system. Figure 2.7 illustrated the completed simulation model that consisted of the parts and the runner system.

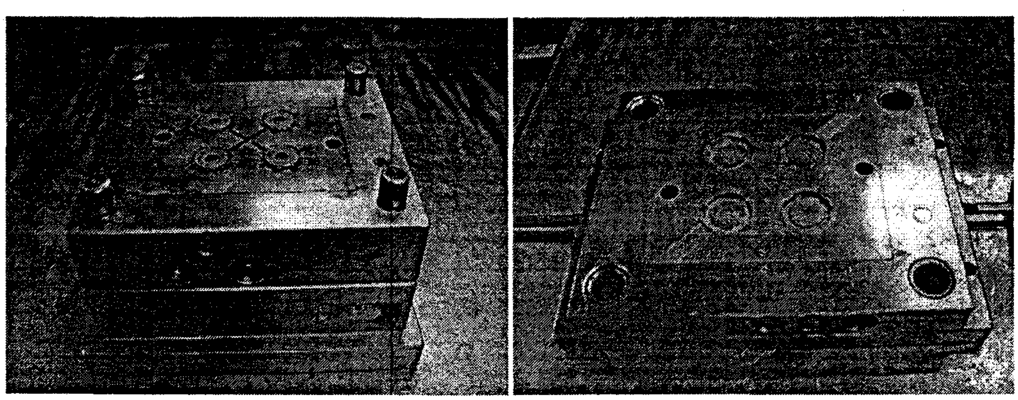

Figure 2.6: Mould design with four cavities of ring stopper

2.3.2 CAE Material Preparation

From the Cadmould 3D-F database, numerous types of plastic material with different grades, as well as from different suppliers were listed out in detail. All the information on the plastic materials including the details description, recommended processing conditions, mechanical, and material data are provided accordingly. Similar grade of ABS, type of Novodur P2MT as in the feasibility study was selected for the simulation runs. Table 2.3 summarized the properties and processing conditions of ABS Novodur P2MT.

Table 2.3: Material properties of ABS Novodur P2MT (LANXESS)

Properties	
Recommended cavity wall temperature (°C)	40-80
Recommended melting temperature (°C)	220-280
Solid density (g/cm^3)	1.04
Eject temperature (°C)	60-100
Thermal conductivity (W/mK)	0.129
Young's modulus (MPa)	3717.55
Poisson's ratio	0.35
Shrinkage factor (%)	0.5-0.7

2.3.3 CAE Determination of Quality Characteristics

Cadmould 3D-F is able to provide analyses on immeasurable quality characteristics in real practice of injection moulding such as shrinkage, warpage, weld line, air traps, pressure distribution, shear stress, sink index, fibre orientation, and etc. In this research, hoop tensile strength, elongation at break, and shrinkage are given the momentous priority to signify the quality characteristics of the ring stopper. Nevertheless, the hoop tensile strength and elongation at break of the part are not able to be analyzed via the simulation runs. Alternatively, the shear stress in the product was carefully selected as one of the quality characteristics due to its indirect influence on the mechanical properties, for the parts that are subjected to intense and local mechanical forces (Shi et al., 2003). Crack growth can be driven by excessive shear stress in the planes of high shear and propagates with tensile stress normal to the crack plane, leading to diminished performance of the part due to final cohesive separation of damaged material. On the other hand, the dimensional stability of the part could be determined directly from the shrinkage analysis. Therefore, shear stress and shrinkage were determined as the quality characteristics that represent the objective of conducting the simulation runs.

There are total 19683 simulation runs needed to be carried out based on a 3^9 full factorial design. It is very time consuming and expensive to carry out such a huge amount of simulation runs. Therefore, Taguchi's orthogonal array (OA) has been integrated in the simulation runs to reduce the effort and cost with a minimum number of test runs. An appropriate size of OA has to be rigorously selected to accommodate all the factors and their levels. The selection of OA will be further discussed in the following section.

2.3.5 CAE Selection of Orthogonal Array (OA)

The decision of selecting an appropriate OA depends on the total degree of freedom (DOF) of the processing parameters. To limit the study, it was decided not to study the interaction among the parameters. Considering there are total of nine processing parameters each at three levels where each three-level parameter has two DOF (DOF = number of levels-1), the total DOF required is 18. As per Taguchi's method, the total DOF of selected OA must be greater than or equal to the total DOF required for the experiment. Therefore, a L_{27} OA having 26 DOF was chosen for this study because it is the lowest order array that can accommodate all the nine processing parameters (melting temperature, mould temperature, injection pressure, packing pressure, packing time, cooling time, and packing switchover) each at three levels. It is impractical to carry out an experiment of 3^9 full factorial design which has total 19683 experimental trials. With the aid of Taguchi method, the OA is managed to reduce the number of experiment to only 27 simulation runs while giving an accurate result. All the nine processing parameters were assigned to column 1-9 and the remaining unassigned four columns (column 10-13) were neglected. Melting temperature was assigned as A, mould temperature was assigned as B, injection pressure was assigned as C, packing pressure at first and second stroke were designated as D and E respectively, packing time at first and second stroke were designated as F and G correspondingly. Column H and J were allocated by cooling time and packing switchover respectively. Table 2.5 tabulated the design of experiment for the simulation runs using the L_{27} OA. Further information on Taguchi method can be found in Roy (1990).

a. Signal to Noise Ratio

The signal to noise (S/N) ratio was used to measure the sensitivity of the quality characteristic being investigated in a controlled manner. The noise factors are the uncontrollable factor in which its influence on the product or process are unknown and inevitable such as humidity and weather. The S/N ratio is computed from the mean-square deviation by the equation:

$$S/N = -10 \log (MSD) \tag{2.4}$$

where MSD = mean-square deviation from the target value of the quality characteristic.

Depending on the objective, there are three different categories for the Taguchi method as define the signal–noise (S/N) ratios, which are the-lower-the-better, the-nominal-the-better and the-higher-the-better (Lin et al, 2008). Different calculation of mean square deviation is used for three different categories of quality characteristics in the analysis of S/N ratio:

The-lower-the-better:

$$MSD = \frac{1}{n}\sum y^2 \tag{2.5}$$

The-nominal-the-better:

$$MSD = \frac{1}{n}\sum (y-m)^2 \tag{2.6}$$

The-higher-the-better:

$$MSD = \frac{1}{n}\sum \frac{1}{y^2} \tag{2.7}$$

where y = the experimental result, m = target value of results, n = number of repetitions.

Despite of three categories of quality characteristic were involved in the analysis, larger S/N ratio is desired as it will result in smaller product variance around the target value. To optimize the shear stress and shrinkage, the equation describing the smaller-the-better characteristic can be used for the analysis as the minimum shear stress and shrinkage will yield better performance of the part. The simulation results of both shear stress and shrinkage were first converted into S/N ratio and then the S/N ratios were normalized and summed up as a respond value which represents both quality characteristics concurrently for further analysis in following section.

- A measure of the total deviation of the individual factor from the computed data.

$$S_A = A_1^2 / N_{A1} + A_2^2 / N_{A2} + A_3^2 / N_{A3} - C.F. \quad (2.12)$$

where A_1 = Sum of mean S/N ratio in which parameter A_1 is present.

N_{A1} = Number of experiments in which parameter A_1 is present.

$$S_e = S_T - \text{(Factor sum of squares involved in experiment)} \quad (2.13)$$

where e = error in experiment

Step 5: Degree of Freedom, (DOF)

- A measure of information that determined from a given set of data.

$$f_T = \text{(total number of trial x number of repetition)} - 1 = (\text{n x r}) - 1 \quad (2.14)$$

DOF for each factor, f_A = (number of level of factor A) – 1 (2.15)

DOF of the error, $f_e = f_T$ - (DOF of each factor involved in experiment) (2.16)

Step 6: Variance, V

- A measure of the distribution of the data from each other.

$$V_A = S_A / f_A \text{(mean variance A)} \quad (2.17)$$

$$V_e = S_e / f_e \text{(error variance)} \quad (2.18)$$

Step 7: Factor F-Ratio (Variance Ratio), F

- A measure of the significance of the factor with respect to the variance of all the factors included in the error term. The F value obtained in the analysis is compared to the standard F-tables at a specific confidence level.

$$F_A = V_A / V_e \quad (2.19)$$

Step 8: Pure Sum of Square, S'
- Mean sum of square due to error variance.

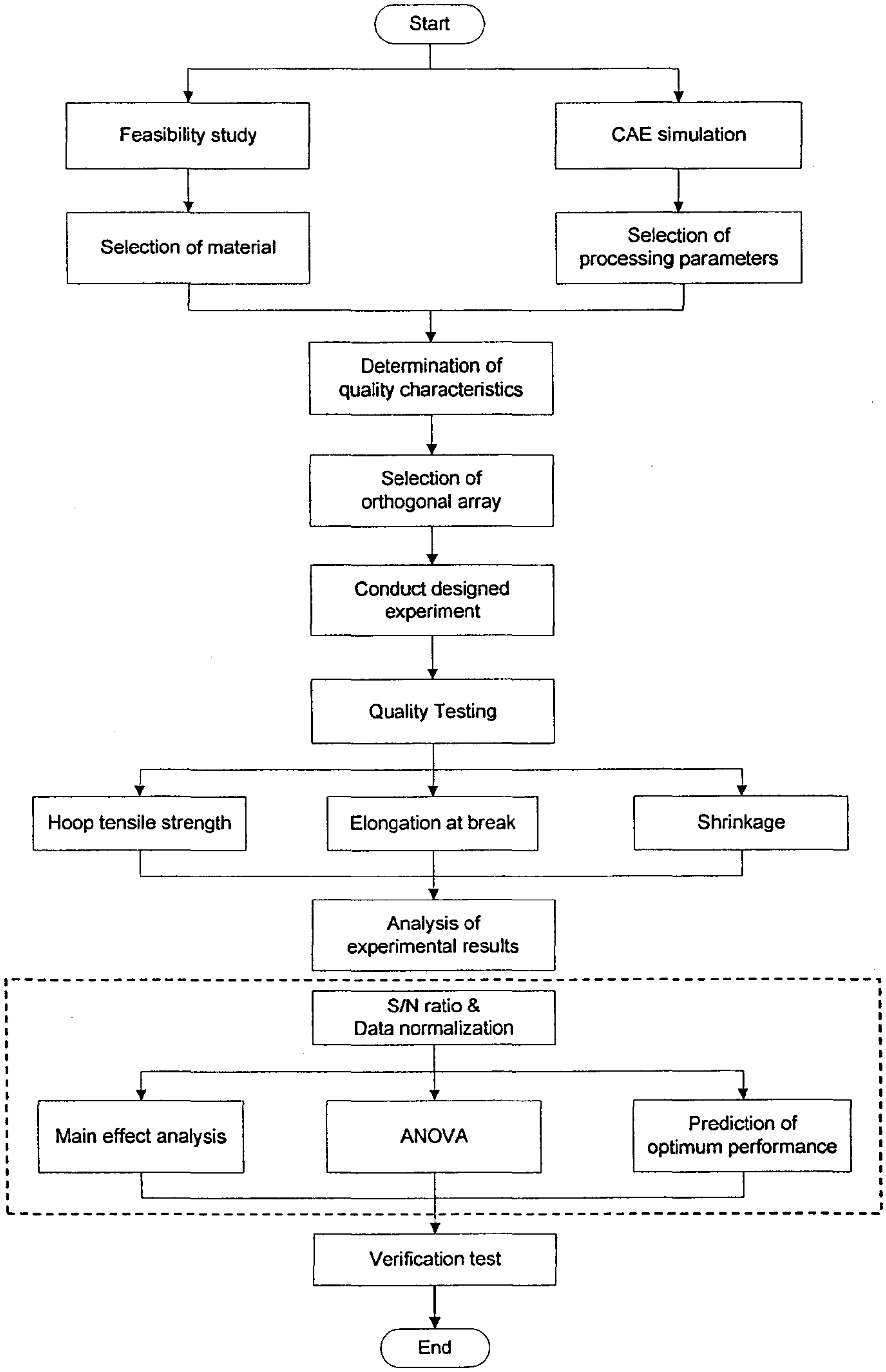

Figure 2.8: Flow chart of processing optimization experiment

2.4.3 Selection of Orthogonal Array (OA) Processing Optimisation

After determining the number of processing parameters and their levels, an appropriate orthogonal array has to be established for laying out the design of experiments that need to be carried out. For the optimization experiment of four processing parameters each at three levels, a L_9 OA was chosen to allocate the processing parameters including melting temperature, packing switchover, injection pressure, and packing pressure at second stroke. Table 2.7 shows the layout of L_9 OA in the design of experiment.

Table 2.7: Design of experiments using L_9 orthogonal array

Trial No.	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

As illustrated in Table 2.7, melting temperature was designated as factor A, packing switchover was assigned as factor B, injection pressure and packing pressure at second stroke were designated as factor C and D correspondingly. There are total nine experimental trials to be conducted under different combination of process conditions as shown in the L_9 OA, to obtain the optimal processing parameters for the improvement of hoop tensile strength, elongation at break, and shrinkage. The evaluation of hoop tensile properties and shrinkage of the part (Figure 2.2) will be carried out followed by the melt flow index test in the next section.

2.4.5 Quality Testing Processing Optimisation

a. Hoop Tensile Test

Similar to the quality testing in the feasibility study, the hoop tensile strength and elongation at break were measured in accordance with ASTM D2290-04 using an Instron 3367 series table-mounted universal testing machine.

b. Main Effect Analysis

Main effect is the effect of one independent variable within one level of other independent variables. To compute the main effect of a processing parameter, the mean response for one level was calculated as the average of all responses that were obtained with that level. The mean response of the respond value for each parameter at level 1, 2, and 3 were calculated and plotted into a graph to provide a better picture of the performance comparison for each processing parameter at different levels. The combination of the processing parameters at the optimal level is able to produce the best-performing reprocessed ABS part.

c. Analysis of Variance

Similar to the simulation experiment, the processing optimization also performed analysis of variance (ANOVA) to identify the process parameters that are statistically significant.

d. Prediction of Performance at Optimal Process Conditions

Taguchi method allows the prediction of performance of the part as a function of process conditions. However, the insignificant processing parameters were not included in the prediction of performance. Therefore, the optimum performance of the reprocessed ABS at the optimal parameters setting was calculated through the addition of the contribution of the significant factors and the average performance as defined:

$$y_{predicted} = y_{average} + (y_A - y_{average}) + (y_B - y_{average}) + (y_C - y_{average}) + (y_D - y_{average}) \quad (2.23)$$

where $y_{average}$ is the overall average response for the orthogonal array and y_A, y_B, y_C, and y_D are the response average for parameters A, B, C, and D respectively at optimal levels.

2.6 Confirmation Test

After identifying the most influential parameters, a confirmation test was carried out to verify the accuracy of the predicted performance obtained from Taguchi optimization process compared to the experimental performance. Therefore, the accuracy analysis of the results obtained can be evaluated by conducting the confirmation test at the optimum combination of factor level. Typically, the result from the confirmation test should be in good unanimity with the optimum performance estimated by the Taguchi optimization process. If the predicted outcome and the experimental results are in disagreement, possible interactions have to be considered and catered for in a new experiment.

3.2.1 Melt Flow Index (MFI)

Thermo-mechanical degradation has a great effect on the molecular weight of polymers during reprocessing. The effects of degradation on molecular weight of reprocessed ABS at different blending compositions of virgin resins and recyclates were tested by MFI measurement as it allows an indirect analysis of the effects of degradation on viscosity, and indirectly, on the molecular weight. Graphical displays on the relative MFI for different recycled ABS content subjected to 10 reprocessing cycles is shown in Figure 3.1.

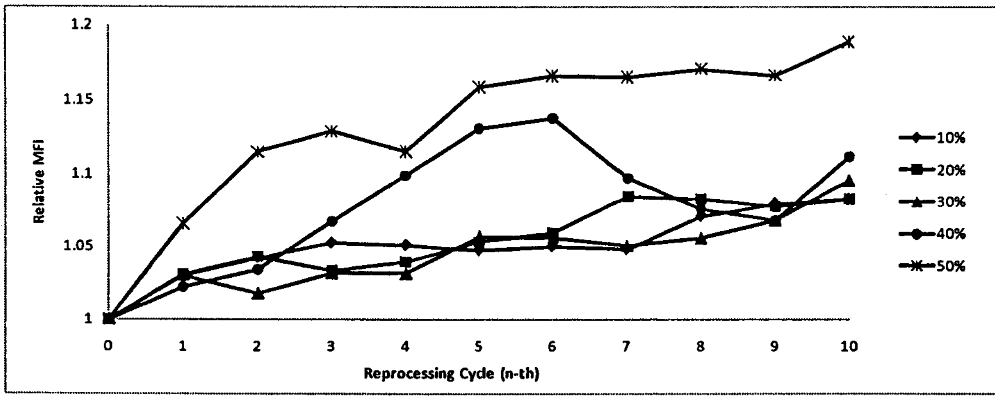

Figure 3.1: Relative MFI of recycled ABS as a function of the number of reprocessing cycles

The blending composition of 10%, 20% and 30% of recycled ABS content illustrates a steady increment for 10 successive reprocessing cycles. It is apparent that blending not more than 30% of recycled ABS with the virgin resin does not amplify the degradation as the increment of MFI is less than 10%. For the 60/40 virgin and recycled ABS blend, it is clearly seen that the MFI increases progressively up to 14% for the first successive six reprocessing cycles and then decreases slightly after the sixth reprocessing cycle. Further data points show that the continued reprocessing results in an increase of MFI by 11%. On the other hand, the relative MFI for the blend of ABS virgin materials mixing with 50% recycled ABS content appears to increase rapidly (about 19%) within 10 reprocessing cycles, indicating that the molecular weight of reprocessed ABS reduced with increasing reprocessing cycle.

the findings, it can be concluded that reprocessing has no significant effect on the variation of hoop tensile strength of ring stopper. The mechanical properties of ABS which are determined by the rigid SAN matrix, possesses a virtually complete retention of the tensile strength during reprocessing. Nevertheless, there is a minor influence of the volume percentage of recycled ABS materials on the hoop tensile strength.

3.2.3 Elongation at Break

The ductility of the ring stopper measured as the percent elongation at break starting from virgin ABS as a function of the number of recycling cycles is shown in Figure 3.3 for the ABS blends comprising up to 50% recycled resins. The ductility of the specimen produced of 100% virgin resin is measured to investigate the embrittlement of the ABS blend of varying proportions of recycled resins (0-50%) subjected to 10 reprocessing cycles and the elongation at break for virgin ABS resin is found to be 3.81%.

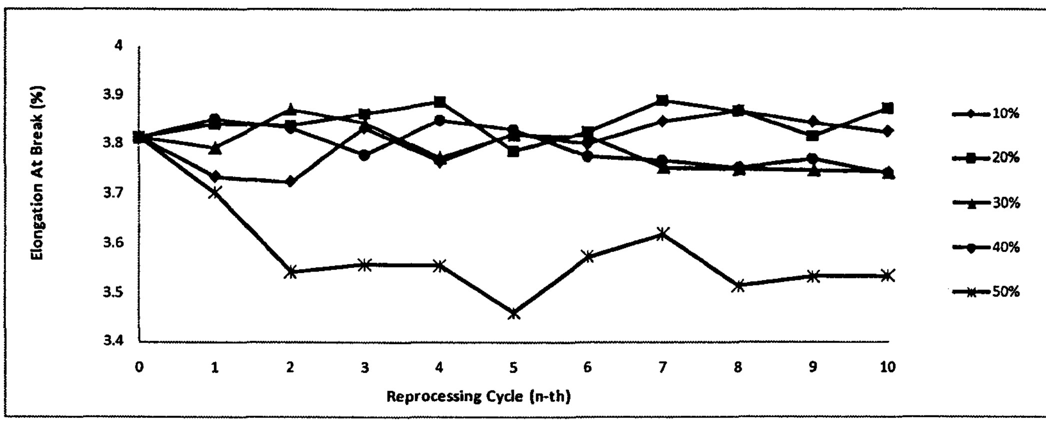

Figure 3.3: Effect of reprocessing cycle on elongation at break

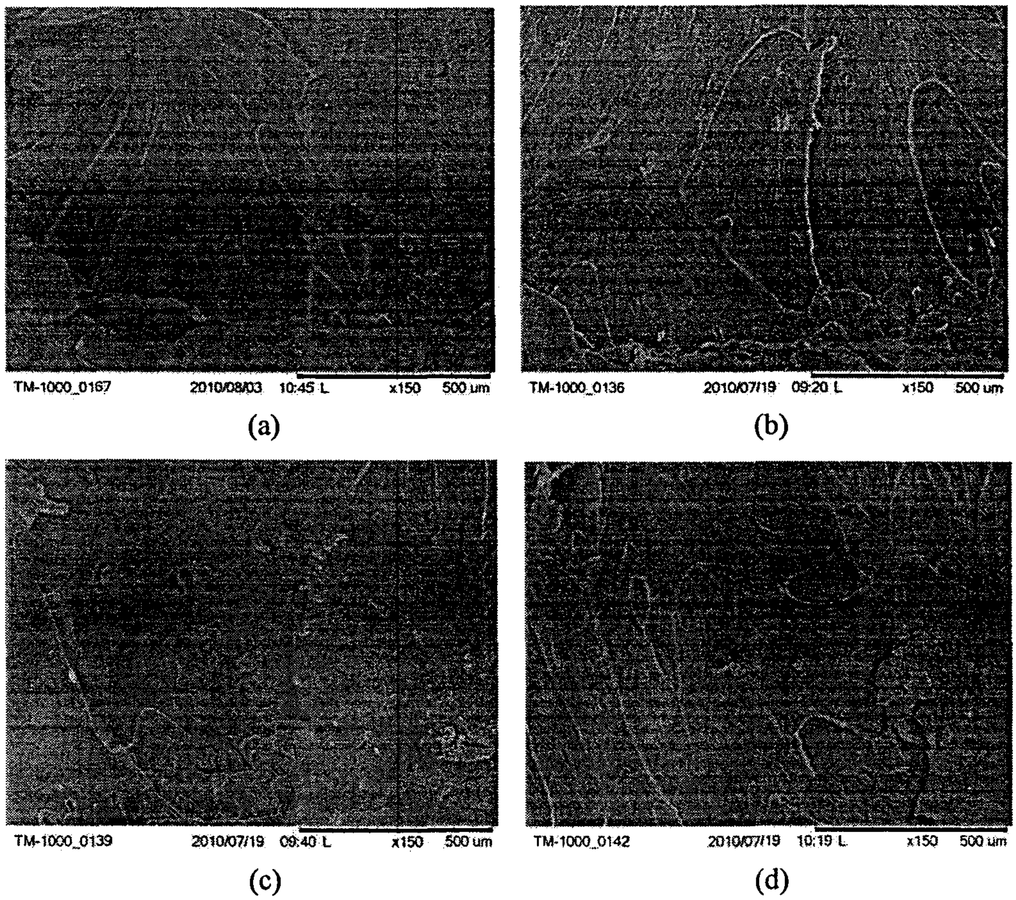

Figure 3.4: Micrograph of tensile fracture surface of: (a) virgin ABS; (b) 20% of recycled ABS subjected to 1 reprocessing cycle; (c); 20% of recycled ABS subjected to 5 reprocessing cycles; (d) 20% of recycled ABS subjected to 10 reprocessing cycles

On the other hand, the blending composition of recycled ABS appears to have important effect on the formation of stress whitening. From Figure 3.5(a), stress whitening is relatively scarce in the blend of 10% recycled ABS. However, when the ABS specimens were tensile-deformed to yielding, the number of stress whitening increases with the increasing percentage of recycled ABS from 20% to 50% as shown in Figure 3.5(b) to 3.5(e). As a result, it is found that numerous stress whitening areas are spotted on the tensile fracture surface of the ABS blend comprising 50% recyclates, inevitably leading to lower elongation at break. The microscopic observations are in reasonably good agreement with the results of hoop tensile test. The phenomenon of stress whitening gives lower elongation at break of the virgin and recycled ABS blend due to the presence of inhomogeneous shear deformation produces necking. Hence, this localizes the plastic deformation and the stress whitening to the vicinity of the necked region.

From the experimental findings in the feasibility study, the 10-times-reprocessed blends of 10%, 20% and 30% recycled ABS have shown comparable with or even better performance than the virgin ABS specification. Even though the hoop tensile strength of the blends of 40% recycled ABS is slightly lower, its elongation at break is almost identical to the virgin ABS. A negative impact is observed at a specified level of ABS recyclate content which leads to unsatisfactory performance where the elongation at break decreases dramatically at 50% of recycled ABS content. The experimental findings are supported by the microscopic observations where the number of stress whitening is relatively scarce even though the ABS blend is subjected to 10 reprocessing cycles whereas the number of stress whitening on the tensile fracture surface of the ABS ring stopper increases as the percentage of recycled ABS increases. On the other hand, the MFI for the virgin and recycled ABS blends ranging from 10-50% all increase with increasing reprocessing cycles, indicating the reduction of molecular weight caused by chain scissions mechanism during reprocessing. Therefore, all ABS blends fulfil the rule of thumb to be used as the raw material in the production as the MFI increment for all blends is strictly controlled within 20%.

In overall, significant influence was found on the blending composition of recycled ABS on the hoop tensile properties, rheological properties and morphology whereas reprocessing appears to have trivial effect on the performance of the ring stopper. As a result, the blending approach is a promising technique to utilize the recycled plastic as the raw material in a long-run production as the mixing of virgin resins with the recyclates is able to mask the batch-to-batch variation even though the blend is subjected to multiple reprocessing.

Generally speaking, the main purpose of blending different proportions of the recycled ABS (0–50%) with the virgin resin is to produce recycled ring stopper with maximum recycled content, but without affecting the functionality of the ring stopper in the application. The results of feasibility study indicated that larger amount up to 30% recycled ABS can be added without significantly altering processing and mechanical properties of the final product. No significant decrease of mechanical and rheological properties was observed for 20% high purity level of recyclates. The 15% blending rule is not completely valid as some valuable information was missed out where no experimental data in between 20% to 50% of recyclates blending. In this research, the threshold value of recycled ABS blending composition should be set at maximum 40% to balance maximum recycling with minimum property loss. The experimental results obtained from the feasibility study are adequate to ensure the product performance produced of the blending of 40% ABS recyclates associated with technical product specifications. Hence, the blending of 40% ABS recyclates is proposed in the optimization experiment to improve the performance of the ring stopper produced of reprocessed ABS for reaching quality same as that from virgin resin.

Table 3.1: Simulation results for the 3D model

Trial No.	Factor									Result	
	A	B	C	D	E	F	G	H	J	X (kPa)	Y (%)
1	240	50	1400	500	600	1	2	8	75	1218	0.625
2	240	50	1400	500	700	2	3	10	80	627	0.611
3	240	50	1400	500	800	3	4	12	85	598	0.605
4	240	60	1500	600	600	1	2	10	80	634	0.616
5	240	60	1500	600	700	2	3	12	85	595	0.564
6	240	60	1500	600	800	3	4	8	75	965	0.618
7	240	70	1600	700	600	1	2	12	85	594	0.624
8	240	70	1600	700	700	2	3	8	75	703	0.565
9	240	70	1600	700	800	3	4	10	80	584	0.542
10	250	50	1500	700	600	2	4	8	80	589	0.557
11	250	50	1500	700	700	3	2	10	85	551	0.513
12	250	50	1500	700	800	1	3	12	75	938	0.382
13	250	60	1600	500	600	2	4	10	85	545	0.621
14	250	60	1600	500	700	3	2	12	75	746	0.612
15	250	60	1600	500	800	1	3	8	80	539	0.446
16	250	70	1400	600	600	2	4	12	75	697	0.599
17	250	70	1400	600	700	3	2	8	80	535	0.591
18	250	70	1400	600	800	1	3	10	85	532	0.436
19	260	50	1600	600	600	3	3	8	85	506	0.569
20	260	50	1600	600	700	1	4	10	75	683	0.471
21	260	50	1600	600	800	2	2	12	80	478	0.432
22	260	60	1400	700	600	3	3	10	75	624	0.513
23	260	60	1400	700	700	1	4	12	80	497	0.495
24	260	60	1400	700	800	2	2	8	85	491	0.356
25	260	70	1500	500	600	3	3	12	80	494	0.609
26	260	70	1500	500	700	1	4	8	85	454	0.475
27	260	70	1500	500	800	2	2	10	75	540	0.473

From Table 3.1, the parameters setting for trial number 1 yields a combination of melting temperature (A) of 240 °C, mould temperature (B) of 50 °C, injection pressure (C) of 1400 bar, packing pressure (D) of 500 bar and packing time (F) of 1 s for the first progressive stroke, packing pressure (E) of 600 bar and packing time (G) of 2 s for the second progressive stroke, cooling time (H) of 8 s and packing switchover (J) of 75%. There are total 27 simulation runs accomplished as the parameters setting shown in OA. The results of X and Y represent the values of shear stress and shrinkage for the ring stopper in the simulation experiment.

Table 3.2 shows the S/N ratio for shear stress and shrinkage was transformed to a commensurable value between 0 and 1 to represent the aspiration level of satisfaction for the quality characteristic with the ratio. The normalized values X and Y which represent the shear stress and shrinkage respectively are summed up given the same importance to result in a combined value (C). The purpose of combining these quality characteristics is to study the effect of processing parameters on multiple quality characteristics simultaneously instead of focusing on single quality characteristic individually. Considering the combined value as the response for multiple quality characteristics, higher combined value indicates that the simulation model possesses minimum shear stress and shrinkage concurrently.

3.3.2 Analysis of Variance (ANOVA)

The main objective of conducting the simulation experiment in this study is to identify the significant processing parameters affecting the tensile properties and dimensional stability of the ring stopper. The significant processing parameters will be further applied in the optimization experiment. To investigate the effect of different processing parameters on the predetermined quality characteristics, the ANOVA is performed to determine the relative contribution of each processing parameter. The ANOVA computes quantities known as degrees of freedom (DOF), sums of squares, variance, F-ratio, and percentage contribution as shown in Table 3.3.

Table 3.3: ANOVA table for the simulation results before pooling

Column	Parameter	DOF	Sum of Squares	Variance	F	Percent
A	Melt temperature	2	1.993	0.996	55.57	44.11
B	Mould temperature	2	0.036	0.018	1.02	0.01
C	Injection pressure	2	0.002	0.001	0.06	-0.76
D	Packing pressure 1	2	0.215	0.108	6.01	4.05
E	Packing pressure 2	2	0.911	0.455	25.40	19.72
F	Packing time 1	2	0.240	0.120	6.68	4.59
G	Packing time 2	2	0.068	0.034	1.90	0.73
H	Cooling time	2	0.028	0.014	0.79	-0.17
J	Packing switchover	2	0.800	0.400	22.31	17.22
	All others / error	8	0.143	0.018		10.51
	Total	26	4.437			100.00

In ANOVA, the F-ratio which is also known as variance ratio, denoted as F in the Table 3.3, is used to identify the significance of the processing parameters by performing a test of significance against the error term at a desired confidence level. A large value of F will result in high percentage contribution, indicating the relative importance ranking of the processing parameters in influencing the quality characteristics. However, the processing parameter with highest percentage contribution need not necessarily be significant because only the computed F-ratios significant processing parameters on the quality characteristics of the final product out of numerous processing variables with minimal simulation trials required. In addition, the data collected via Taguchi-based numerical simulation incurs no extra manufacturing cost as no raw material, injection moulding machine and mould personnel is required in the simulation experiment. As a result, the traditional method of selecting the significant processing parameters for processing optimization based on the experience or handbooks can be eliminated due to its ineffectiveness.

As mentioned earlier, the main objective of conducting the simulation experiment is to identify the processing parameters rated most influential in affecting the shear stress and shrinkage of the injection-moulded ring stopper. In this study, the effect of nine processing parameters on the quality characteristics is investigated via ANOVA to determine their relative significance. The results show that three processing parameters, namely melting temperature, packing pressure at second progressive stroke and packing switchover, are statistically significant in influencing the performance of the ring stopper. Therefore, the optimization experiment will be carried out by taking into deliberation of these results.

3.4 Results of the Optimization Experiment

From the findings of the feasibility study, the 60/40 blending composition of virgin and recycled ABS at 10^{th} reprocessing cycle is selected as the raw material in the processing optimization phase due to its overachieving performance at high recyclates percentage and reprocessing cycles. On the other hand, the outcome of the simulation experiment showed that three significant processing parameters, including melt temperature, packing switchover and packing pressure at second progressive stroke, were found to have significant influence on the shear stress and shrinkage of the ring stopper, these processing parameters are chosen to be further optimized in this study. Nevertheless, the reviewed literature concluded that the melt temperature and injection pressure are the decisive factors in improving the tensile properties of plastic product wherein these two factors should be taken into account in the optimization. Considering the main goal is to enhance the hoop tensile strength and elongation at break as well as to reduce the shrinkage of the ring stopper produced of recycled ABS, the melt temperature, packing switchover, injection pressure, and packing pressure at second progressive stroke, are selected for optimization and the Taguchi's L_9 orthogonal array is used as design of experiment to allocate the four processing parameters in the optimization experiment as tabulated in Table 3.5.

Table 3.6: S/N ratios and data normalization of optimization results

Trial No.	S/N ratio (dB)			Normalized			
	X	Y	Z	X	Y	Z	C
1	33.927	11.662	14.715	0.733	0.981	0.000	1.714
2	34.037	11.530	25.666	1.000	0.586	0.350	1.936
3	33.858	11.668	36.723	0.565	1.000	0.703	2.268
4	33.890	11.665	22.499	0.641	0.991	0.249	1.881
5	33.916	11.502	46.021	0.705	0.502	1.000	2.207
6	33.716	11.436	16.673	0.218	0.303	0.063	0.584
7	33.695	11.523	18.692	0.168	0.562	0.127	0.858
8	33.698	11.498	15.918	0.174	0.489	0.038	0.701
9	33.626	11.335	17.501	0.000	0.000	0.089	0.089

From Table 3.6, the S/N ratio for hoop tensile strength, elongation at break and shrinkage was transformed to a commensurable value between 0 and 1 to represent the aspiration level of satisfaction for the quality characteristic with the ratio. The summation of the normalized values X, Y and Z representing hoop tensile strength, elongation at break and shrinkage respectively, is computed given the same importance to result in a combined value (C). The purpose of combining these quality characteristics is to study the effect of processing parameters on multiple quality characteristics simultaneously instead of focusing on single quality characteristic individually. Considering the combined value as the response for multiple quality characteristics, higher combined value indicates that the ring stopper possesses maximum hoop tensile strength, elongation at break and minimum shrinkage concurrently.

3.4.2 Main Effects Analysis

A main effect is the effect of an independent variable on a dependent variable averaging across the levels of any other independent variables. To figure out the mean response at each level of the processing parameters, the average performance based on the sum of combined value for each parameter at different levels were computed.

Considering three quality characteristics including hoop tensile strength, elongation at break and shrinkage involved in this study, the main effects analysis is performed in two stages: single quality characteristic and multiple quality characteristics. Different processing parameters have different effects on the quality responses and changing a parameter can lead to an improvement or deterioration in product quality. Therefore, the main effects of processing parameter on hoop tensile strength, elongation at break and shrinkage is computed individually as shown in Table 3.7 to 3.9. For better interpretation of the main effects analysis, the results in the main effects table can be converted into a graphical display as shown in Figure

Considering single quality characteristic in terms of elongation at break, two opposite trends are observed in Figure 3.7 where the elongation at break of the ring stopper is higher when the melt temperature and packing switchover decrease. On the contrary, the increment of injection pressure and packing pressure at second progressive stroke will enhance the elongation at break of the part. As a result, the combination of melt temperature at 240 °C, packing switchover at 75%, injection pressure of 1600 bar and packing pressure at second progressive stroke of 800 bar results in the greatest performance for elongation at break.

Table 3.8: Main effects analysis for elongation at break

Column	Parameter	Level 1	Level 2	Level 3
A	Melt temperature	11.620	11.535	11.452
B	Packing switchover	11.617	11.510	11.480
C	Injection pressure	11.532	11.510	11.564
D	Packing pressure 2	11.500	11.496	11.611

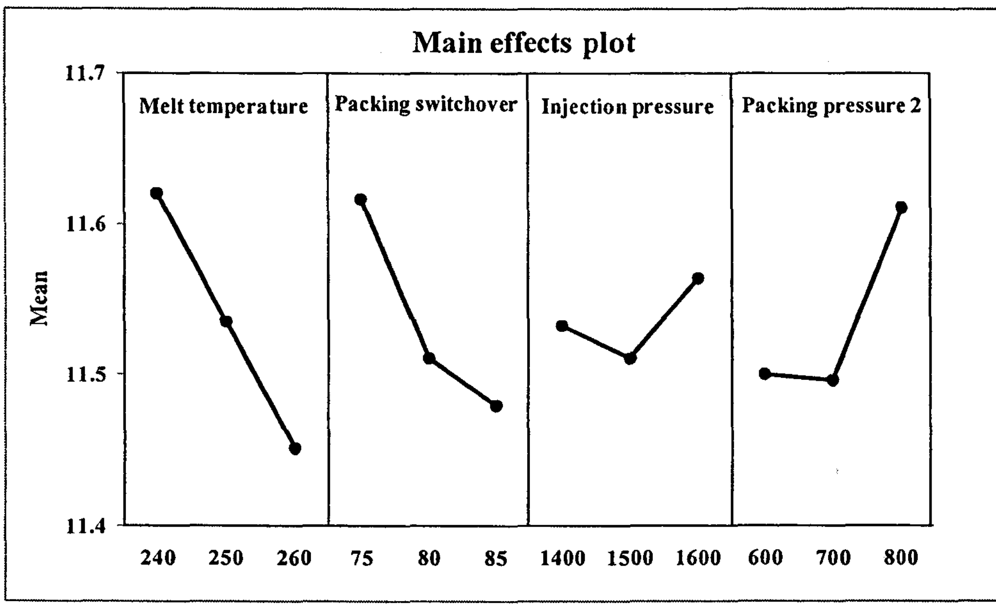

Figure 3.7: Main effects plot for elongation at break

From the main effects analysis of hoop tensile strength, elongation at break and shrinkage of the ring stopper (Figure 3.6, 3.7 and 3.8), it is found that each scenario results in a set of processing parameters which is used to optimize single quality characteristic. For instance, the optimal process conditions which achieve the highest performance of hoop tensile strength, elongation at break and shrinkage are $A_1B_2C_2D_1$, $A_1B_1C_3D_3$ and $A_2B_2C_3D_1$ correspondingly. Each quality characteristic has different set of optimal process conditions and it is impractical to use one of them to simultaneously improve multiple quality characteristics. Therefore, it is of crucial to enhances hoop tensile strength, elongation at break and shrinkage of the ring stopper simultaneously with only one combination of optimal parameters setting. The S/N ratios of hoop tensile strength, elongation at break and shrinkage are normalized and added into a combined value which represents multiple quality characteristics. Hence, the main effects for the multiple quality characteristics are computed based on the analysis of the combined values as shown in Table 3.10.

From Figure 3.9, it is clearly shown that the multiple quality characteristics of the ring stopper are greatly influenced by the adjustments of the processing parameters. The best combination of parameters and levels could easily be obtained from the main effects analysis by selecting the level of each parameter with the highest mean value. As a result, the optimal parameters setting which statistically result in the maximum hoop tensile strength and elongation at break, as well as minimum shrinkage for the ring stopper, are predicted to be $A_1/B_2/C_3/D_3$. As seen in the main effect plot, the optimal parameters setting represent a melt temperature of 240 °C, 80% packing switchover, 1600 bar injection pressure and 800 bar packing pressure at second progressive stroke.

process conditions. The quantities such as degrees of freedom, sum of squares, variance, F-ratio and percentage contribution are computed.

As discussed thoroughly in simulation experiment, F-ratio test is used to determine the significance of the processing parameters. The larger the value of F, the more important that parameter is in influencing the process response. However, the F-ratio and pure sum of squares cannot be computed in the optimization experiment due to the degree of freedom for the error term is equal to zero. As a result, the percentage contribution of each processing parameter is directly calculated from the sums of squares and the significance of each processing parameter on the hoop tensile strength, elongation at break and shrinkage of the ring stopper can be determined by the percentage contribution. An alternative by using the 10% rule, which is to consider a parameter insignificant when its influence is less than 10% of the highest parameter influence. The insignificant parameters should be pooled and their contributions will not be considered in the projection of the optimum performance. On the other hand, the percentage contribution of the significant parameters is recalculated after pooling the insignificant parameters to the error term.

For hoop tensile strength, the percentage contributions of injection pressure and packing pressure at second progressive stroke result in only 4.97% and 0.07% respectively, which are much less than 10% of the highest parameter influence (7.18%), in this case, it is melt temperature with the percentage contribution of 71.75% before pooling. Therefore, the two insignificant parameters are pooled. From Table 3.11, melt temperature is found to be the most significant parameter with the highest percentage contribution of 69.24%, followed by packing switchover at 20.69%. On the other hand, the percentage contribution of the error term shows 10.07%. In ANOVA, small percentage contribution of the error term represents that there is less influence from parameters which are not included in the study or that from other noise factors. Therefore, the low percentage contribution of the error term implies that the control parameters are suitably chosen for the experiments.

Table 3.11: ANOVA table for hoop tensile strength in optimization experiment

Column	Parameter	DOF	Sum of Squares	Variance	F	Percent
A	Melt temperature	2	0.110	0.055	28.51	69.24
B	Packing switchover	2	0.036	0.018	9.22	20.69
C	Injection pressure	(2)	(0.008)		Pooled	
D	Packing pressure 2	(2)	(0.000)		Pooled	
	All others / error	4	0.008	0.002		10.07
	Total	8	0.153			100.00

second progressive stroke (7.03%). No result is shown for the error term as the degree of freedom of the error term is zero. Given that all processing parameters are significant, the contribution of each parameter will be considered to compute the predicted performance of the ring stopper at optimal process conditions.

Table 3.14: ANOVA table for multiple quality characteristics in optimization experiment

Column	Parameter	DOF	Sum of Squares	Variance	F	Percent
A	Melt temperature	2	3.214	1.607		62.13
B	Packing switchover	2	0.673	0.337		13.01
C	Injection pressure	2	0.922	0.461		17.83
D	Packing pressure 2	2	0.364	0.182		7.03
	All others / error	0				
	Total	8	5.173			100.00

3.4.4 Prediction of Performance at Optimal Process Conditions

Recall that the study of the main effects revealed that the optimum conditions for the ring stopper to possess maximum hoop tensile strength and elongation at break, as well as minimum shrinkage simultaneously are predicted to be $A_1/B_2/C_3/D_3$. From the calculations, the hoop tensile strength, elongation at break and shrinkage of ring stopper at optimal parameters setting $A_1B_2C_3D_3$ is estimated to be 50.17MPa, 3.845% and 0.0077% correspondingly. As the optimal process conditions $A_1B_2C_3D_3$ is not one of the experimental trials as layout in L_9 orthogonal array, thus a confirmation test needs to be conducted by comparing the unanimity of experimental performance and the predicted performances at the optimal process conditions.

analyzed individually. Nevertheless, it is more practical to improve three quality characteristics at an optimal combination of processing parameters concurrently.

The hoop tensile properties of the ring stopper produced of the ABS blend consisting of 40% recyclates have been improved to higher quality level which is equivalent or slightly better than the performance of the part produced of virgin resins. It is evident that the hoop tensile strength and elongation at break of the ring stopper made of virgin resins are 50.22 MPa and 3.81% correspondingly, whereas the optimized hoop tensile strength and elongation at break of the recycled ring stopper achieves 50.74 MPa and 3.95% respectively. Consequently, it is implied that the performance of the ring stopper made of ABS recyclates can be effectively enhanced to achieve satisfactory product quality via the Taguchi optimization approach. The use of recycled ABS in the plastic industry not only significantly lowers the raw material cost but it is a good solution for managing the industrial plastic wastes effectively, indirectly reducing the adverse effect on the environment. Considering the significant performance improvement on the recycled materials by using a fast and systematic optimization approach, it can be concluded that the use of recycled ABS in place of virgin ABS in the plastic production is practically and economically viable.

3. The integration of Taguchi method and numerical simulation offers a fast, reliable and systematic solution in determining the significant processing parameters.
   Injection moulding has been a challenging process for many manufacturers and researchers to produce products meeting requirements at the lowest cost. However, the enormous amount of process parameter manipulation during plastic production creates a very intense effort to obtain optimal process conditions. Numerical simulation aids the designers and engineers as it is capable to simulate the scenarios without carrying out in the real practises whereas the Taguchi method offers the advantages in reducing the simulation experiments and analyzing the results to determine the significant processing parameters. The Taguchi method coupled with numerical simulation is commonly used as the preliminary experiment to screen out the significant parameters from numerous processing parameters prior subjected to the optimization. Therefore, many researchers present the integrated approach of Taguchi method and numerical simulation to replace the traditional selection of processing parameters based on the past experience or handbooks.

4. The implementation of Taguchi method as an effective approach in optimizing the processing parameters has improved the performance of final product.
   Optimizing processing parameter is routinely performed in the plastic industry, particularly whenever there is a quality issue with the final product. The optimal processing parameters setting are recognized as one of the most important procedures in injection moulding for improving the product quality. A distinction of Taguchi method in providing much-reduced variance for the experiment with optimal processing parameters allows it to be an efficient tool for the design of high quality manufacturing system. Each element of Taguchi method, including orthogonal array, S/N ratio, main effects analysis, ANOVA and prediction of performance at optimal process conditions, is designed to have its specific function in design, analysis and optimization process. From this research, the optimal processing parameters for simultaneously improving the multiple quality characteristics are melt temperature of 240°C, 80% packing switchover, 1600 bar injection pressure and 800 bar packing pressure at second progressive stroke. In addition, the performance of ring stopper at optimal process conditions can be estimated via Taguchi method. The predicted performance yields less than 3% error compared to the experimental results of confirmation test, indicating that Taguchi method is an accurate optimization tool.

injection molding. International Communications in Heat and Mass Transfer, 37, p.1359-1365.

14. Roy, R.K. (1990) A primer on the Taguchi method. New York: Van Nostrand Reinhold.
15. Roy, R.K. (2001) Design of Experiment Using the Taguchi Approach: 16 Steps to Product and Process Improvement. New York: John Wiley and Sons.
16. Sankaran, S., Mallick, P.K. (2009) Fatigue properties of injection molded 33% e-glass fiber reinforced polyamide- 6,6. 9th Annual Automotive Composites Conference and Exhibition, ACCE 2009, p.807-818.
17. Santos, P., Pezzin, S.H. (2003) Mechanical properties of polypropylene reinforced with recycled-pet fibres. Journal of Material Processing Technology, 143-144, p.517-520.
18. Sauer, J.A., Chen, C.C. (1983) Crazing and fatigue behavior in one- and two-phase glassy polymers. Advances in Polymer Science, 52-53, p.169-224.
19. Shi, F., Lou, Z.L., Lu, J.G., Zhang, Y.Q. (2003) Optimization of Plastic Injection Moulding Process with Soft Computing. International Journal of Advanced Manufacturing Technology, 21(9), p.656-661.
20. Shie, J. (2008) Optimization of injection-molding process for mechanical properties of polypropylene components via a generalized regression neural network. Polymers for Advanced Technologies, 19, p.73-83.
21. Tanniru, M., Misra, R.D.K. (2006) Reduced susceptibility to stress whitening during tensile deformation of calcium carbonate-reinforced high density polyethylene composites. Materials Science and Engineering A, 424, p.53-70.
22. Vilaplana, F., Karlsson, S. (2008) Quality Concepts for the Improved Use of Recycled Polymeric Materials: A Review. Macromolecular Materials and Engineering, 293, p.274-297.
23. Żenkiewicz, M., Rytlewski, P., Moraczewski, K., Stepczyńska, M., Karasiewicz, T., Malinowski, R., Ostrowicki, W. (2009) Some effects of multiple injection moulding on selected properties of ABS. Journal of Achievements in Materials and Manufacturing Engineering, 37(2), p.361-368.

DOI: 10.1080/10426914.2010.529587

Investigating the Effects of Injection Molding Parameters on the Mechanical Properties of Recycled Plastic Parts Using the Taguchi Method

Nik Mizamzul Mehat[1] and Shahrul Kamaruddin[2]

[1]*Department of Mould Technology, Kolej Kemahiran Tinggi MARA, Balik Pulau, Malaysia*
[2]*School of Mechanical Engineering, University Sains Malaysia, Pulau Pinang, Malaysia*

The growing amount of plastic parts produced nowadays makes the search for alternatives in recycling and the further use of these nonbiodegradable materials imperative. The degradation of the mechanical properties of recycled plastic products poses the primary limitation for the usage of recycled plastic. One of the foremost causes of mechanical property degradation is variation in processing parameters. An appropriate optimization method that effectively controls all influential processing parameters during manufacturing is therefore critical. This study investigates the effects of injection molding parameters on the mechanical properties of recycled plastic parts. The preliminary experiment is conducted by using Moldflow Plastic Insight (MPI) integrated with the L_{18} Taguchi orthogonal array (OA). The significant processing parameters obtained from the preliminary experiment were used to conduct the principal experiment. By adopting L_9 Taguchi OA, the parts made from recycled plastic were produced by injection molding. ANOVA confirms that the most significant factor for flexural modulus of a recycled toolbox tray is injection time (~ 40.49% percentage contribution). For stress at yield, the most significant factor is melt temperature with percentage contribution of about 43.34%.

Keywords Flexural modulus; Injection molding; Recycled plastic; Simulation; Stress at yield; Taguchi method.

Introduction

Processing parameters critically influence the quality of injection-molded parts. The plastic injection moulding (PIM) process is complex, involving many processing parameters such as pressure, temperature, and time. These parameters are dependent on each other and, by changing any one of these parameters, one or all will be affected. These processing parameters need to be optimized to improve part quality and maximize production capacity. The advanced development of injection molding flow analysis simulations has assisted designers/engineers to predict and overcome problems in selecting the optimum processing parameters. Thus, relying on experience, intuition, or trial and error in obtaining information regarding the processing parameters can be avoided [1, 2]. However, single-handedly implementing these simulation package enhancements requires the optimization of processing parameters to adopt a trial-and-error procedure. In fact, to determine the optimal processing parameters for producing a good quality injection-molded plastic part, the simulation model must be carried out in a number of replications if the experiment is single-handedly performed. As a result, the experimental procedures are cumbersome and chaotic [3]. Therefore, to reduce this acrimonious condition, optimization methodologies are normally coupled with simulation to assist engineers in identifying the optimal processing parameters for the setup and start-up of the injection molding process. One of these efficient and simple optimization methods is the Taguchi method [4–6].

The Taguchi method, also known as Robust Design, was developed by Dr. Genichi Taguchi [7] and is extensively used to optimize the performance characteristics of a plastic part produced through the setting of the design parameters. This method is also essential for designing high-quality systems and determining the optimum settings for the controllable parameters to make the product or process insensitive to noise factors [8, 9]. The Taguchi method introduces an integrated approach that is simple and efficient for finding the best range of designs for quality, performance, and computational cost [10, 11]. There are three stages applied in this method: (1) system design, (2) parameter design, and (3) tolerance design [12]. Of all the three, parameter design is often identified as the most crucial and dominant stage for process optimization [13, 14]. In general, parameter design of the Taguchi method utilizes Orthogonal Array (OA), signal-to-noise (S/N) ratios, and ANOVA. Taguchi OA is a highly fractional orthogonal design used to estimate the main effects by only a few experimental runs. Thus, adopting OA can reduce research and development costs by simultaneously studying a large number of parameters instead of studying one parameter at a time as done in traditional methods [15, 16]. Roy [17] further discussed the Taguchi concept.

In recent years, the Taguchi Method has become a widely accepted technique for improving productivity and optimizing processes. There is a number of published studies discussing the effect of processing parameters on the quality of injection-molded parts. Most studies focus on

Received July 22, 2010; Accepted September 28, 2010
Address correspondence to Shahrul Kamaruddin, University Sains Malaysia, School of Mechanical Engineering, Nibong Tebal, Pulau Pinang, Malaysia; E-mail: meshah@eng.usm.my

Int J Plast Technol
DOI 10.1007/s12588-012-9037-1

COVER ARTICLE

Quality control and design optimisation of plastic product using Taguchi method: a comprehensive review

Nik Mizamzul Mehat · Shahrul Kamaruddin

Received: 15 March 2011 / Accepted: 21 September 2012

Abstract The Taguchi method is a powerful approach for solving quality problems in various aspects of the engineering field. Due to the increase of plastic parts consumption in each day, continuing customer satisfaction and economic viability in a competitive plastic industry environment are gaining tremendous attention. Thus, Taguchi method offers a simple yet systematic approach to optimize design for performance, enhancing the product quality and reduce the cost as well. A lot of studies have been conducted on the efficiency of this method. However a total comprehensive review of the implementation of the Taguchi method particularly in the plastic industry is limited. This paper presents an extensive review of past literature on the application of the Taguchi method in plastic industries focusing on product quality enhancing and obtaining the desired properties for new materials. From the review, it can be concluded that the Taguchi method has made extensive contribution to the plastic industry by bringing focused and awareness to robustness to improving quality.

Keywords Taguchi method · Plastic · Quality · Design · Optimization

Introduction

Plastics have become one of the most sought after materials in the world today. Due to its intrinsic advantages of properties such as lightness, resistance to corrosion and ease to shape, plastic has provided an affordable yet robust material for many of the

N. M. Mehat
Department of Mould Technology, Kolej Kemahiran Tinggi MARA Balik Pulau, Genting, 11000, Balik Pulau, Penang, Malaysia
e-mail: nik_miza78@yahoo.com

N. M. Mehat · S. Kamaruddin (✉)
School of Mechanical Engineering, Universiti Sains of Malaysia, Engineering Campus, 14300 Nibong Tebal, Pulau Pinang, Malaysia
e-mail: meshah@eng.usm.my

Published online: 06 November 2012

ATTACHMENT 3

SCHOOL OF MECHANICAL ENGINEERING
UNIVERSITI SAINS MALAYSIA

Tarikh: 28 Ogos 2013

Prof Madya Lee Keat Teong
Pengarah
Pejabat Pengurusan Dan Kreativiti Penyelidikan
Canselori
11800 Usm
Pulau Pinang

Tuan,

Laporan Projek Penyelidikan Geran Jangka Pendek

Berhubung dengan perkara di atas, di sini saya sertakan laporan akhir projek penyelidikan Geran Jangka Pendek USM berikut:

Tajuk Projek : Improvement Of Quality Characteristic Of An Injection Moulding Product Made Form Recycle Plastic By Optimising The Injection Moulding Parameters Using Taguchi Method

No Akaun : 304/PMEKANIK/6039020

Saya ingin memohon maaf di atas kelewatan menghantar laporan. Segala kerjasama yang pihak tuan berikan amat saya hargai, dan saya dahului dengan ucapan ribuan terima kasih.

Terima Kasih.

Yang benar,

(Prof Madya Dr Shahrul Kamaruddin)
Ketua Penyelidik