Hindawi Publishing Corporation
ISRN Industrial Engineering
Volume 2013, Article ID 869736, 10 pages
http://dx.doi.org/10.1155/2013/869736

Research Article

Modeling and Analysis of Injection Moulding Process Parameters for Plastic Gear Industry Application

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Received 18 April 2013; Accepted 8 May 2013

Academic Editors: A. Gomez and J. Wei

The performance of plastic gears in wide variety of power and motion transmission applications is rather limited due to weak mechanical properties and divergent mechanism of failures. A methodical simulation is carried out to analyze the gear performance with various gating system types, gate locations, and processing parameters via grey-based Taguchi optimization method. With the obtained optimum results in simulation stage, the flow patterns of polymer melt inside the mould during filling, packing, and cooling processes are studied and the plastic gear failures mechanism related to processing parameters are predicted. The output results in the future can be used as guidance in selecting the appropriate materials, improving part and mould design, and predicting the performance of the plastic gear before the real process of the part manufacturing takes place.

1. Introduction

Gears have been in use for more than three thousand years and commonly utilized in power and motion transmission under different loads and speeds. Due to the fiscal and practical advantages, the demand of using plastics in gearing industry is significantly increased and indubitably continues in the future. In comparing with metal gears, plastic gears have several advantages such as light weight, noiseless running, resistance to corrosion, lower coefficients of friction, and ability to run under none lubricated conditions [1, 2]. Plastic gears can be produced by hobbing or shaping, likewise to metal gears or alternatively by injection moulding. With the continuous expansion of technology, plastic injection moulding bears itself to considerably more economical means of mass production to meet the rapidly rising market demand of plastic gearing in various applications. Injection moulded plastic gears have been used with success in the automotive industry, office machines, and household utensils, in food and textile machinery, as well as a host of other applications' areas [3]. Unlike metal gears, the potential uses of plastic gear, however, are rather limited due to weak mechanical properties, poor heat conductors, and tendency to undergo creep [4]. Apart from that, the plastic gear tooth experiences complex stresses during service and can fail by divergent mechanism. Investigations on plastic gear failures were extensively conducted. Senthilvelan and Gnanamoorthy [5] observed different types of failures on the Nylon 66 spur gears such as gear tooth wear, cracking at the tooth surface, tooth root cracking, and severe shape deformation. In the review work of Breeds et al. [6] and Hooke et al. [7], a sharp increase in wear loss over the addendum and dedendum of acetal gears is also observed to be strikingly different resulting from the differences in friction forces and increasing torque on each gear face during the running operation. Despite wear failure, plastic base gears, in addition, are sensitive to temperature due to heat generation during service which resulted in surface fatigue and fatigue cracking at tooth root acceleration [8]. On the other report of Osman and Velex [9], plastic gears can also fail due to contact fatigue or surface pitting as a result of dynamic tooth loads during the running operation.

Referring to the modes of failures, there are many factors contributing to the occurrence of plastic gear deficiencies. Material selection for the gears in instance is a critical decision in manufacturing the plastic gear by using injection moulding process as some plastic gear failures are caused by poor material selection. There are several different types of nylon (e.g., Nylon 6, Nylon 6/6, and Nylon 12) widely used in gear production that offer great toughness and wear well against other plastics and metals. Terashima et al. [10] reported that nylon materials lose their tensile strength within the range of 5–10% when exposed to a temperature increase of 10°C each. Furthermore, Nylon 6/6 has poor thermal properties with low heat conductivity and large thermal expansion. Under high load and high speed, these characteristics can lead to local accumulations of heat, tooth wear, and decreased performance. In contrast, acetal is strong, has good resistance to creep and fatigue, has a low coefficient of friction, and is resistant to abrasion and chemicals [11]. However, acetal is so brittle that it has a low level of resistance to shock load compared to nylon and also known to be noisy under greaseless condition [12].

Apart from material selection, a proper part or mould design also plays a major role in getting the most out of plastic gears. A high quality moulded plastic gear starts with the design and construction of a high quality plastic gear mould. The mould shall always have proper cooling channels, venting, properly sized gates and runners, ample coring and ejection capabilities, quality mould surface finish, precision fits and tolerances, concentricity between mould components, and proper mould material selection. Any misjudgment in the part and mould design can lead to disastrous consequences on the plastic gear produced and cause subsequent modifications in the production line, indirectly incurring high production cost [13]. In the research conducted by Luscher et al. [14], the number of gates, if kept small, was shown to have a strong influence on the periodicity of both run-out and long-term transmission error on moulded polyketone gears. However, the gating scheme had minimal influence on the total magnitude of the errors for the same gears.

As plastic materials exhibit extremely convoluted properties, the complexity of the moulding process makes it very challenging to attain the desired gear part properties. The intricacy of injection moulding process in producing a wide range of parts with complex shape including those with tight tolerances [15, 16] has created a very intense effort to keep the quality characteristic of moulded plastic gear under control. Even if it is possible to select an optimal material for a specific gear task based on the properties such as strength, wear, stiffness, damping, and noise production, due to the complexity of injection moulding process which involving many processing parameters, such as pressure, temperature, and time, improper setting of processing parameters could negatively affect the final quality of the moulded plastic gear. In fact, the optimum properties of the plastic material with the most innovative part and mould design cannot be achieved and become meaningless without optimum processing parameters during the gear manufacturing. In addition, poor processing practices relying on experience, intuition, or trial and error in obtaining information regarding the processing parameters will also create the conditions for gear failure modes that could not be predicted or accounted for by even the most prudent of designers.

Table 1: Mesh statistic of gear model.

Mesh statistic	
Number of elements	537216
Minimum aspect ratio	1.156
Maximum aspect ratio	19.709
Average aspect ratio	1.547
Match percentage	83.3%
Reciprocal percentage	68.1%

Be acquainted with the importance of the factors mentioned above on the final quality of moulded plastic gears; therefore, by intriguing the evolution of injection moulding flow analysis simulation packages available in the market nowadays, this research is conducted to study the effect of the types of gating system and gate locations on the quality of a moulded plastic gear as well as on the processing parameters. An attempt has also been made to identify the crucial processing parameters affecting the quality characteristics of plastic gear with the optimized gating system and determine the optimum level of injection moulding parameters for multiresponse characteristics of plastic gear using grey relational analysis coupled with Taguchi optimization method. With the obtained optimum results in simulation stage, the flow patterns of polymer melt inside the mould during filling, packing, and cooling processes can be studied and the plastic gear failures mechanism related to processing parameters can be predicted. The output results in the future can be used as a guidance to facilitate the engineers/designers in selecting the appropriate materials, improving part and mould design as well as predicting the performance of the plastic gear part before the real process of the part manufacturing takes place.

2. Experimental Procedures

2.1. Simulation Model and Material. Preliminary study of injection moulding flow analysis is undertaken by using moldflow plastic insight (MPI) version 6.1 software. For the gear three dimension (3D) geometrical drawing, it was initially done in SolidWorks (Figure 1) and further imported to MPI for injection moulding analysis simulation. The spur gear design which is compliant to American Gears Manufacturers Association (AGMA) standards was used. The details geometry and specification for the gear are shown in the Figure 2. In order to run the MPI analysis, the gear model must have an appropriate finite element mesh created. In this study, the gear model is meshed using 3D mesh technology [17]. Table 1 shows the meshing information of the gear simulation model. The crystalline thermoplastic polypropylene (PP) is specified for the meshed gear model. The PP manufacturer is Idemitsu Petrochemical Co. Ltd.; the trade name is Polypro J2000G.

2.2. Preliminary Filling Analysis of Gear Model. After creating the initial 3D mesh for the gear model, a preliminary filling analysis is conducted to forecast and visualize the filling pattern or the transient progression of the polymer flow

Figure 1: 3D model of spur gear.

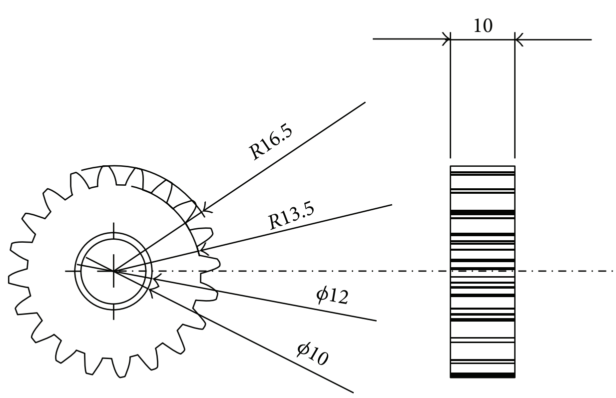

Figure 2: Geometry and specification of spur gear: module = 1.5; pressure angle = 20°; number of teeth = 20; face width = 10 mm.

front within the feed system and mould cavity before the optimization of processing parameters takes place. Filling pattern plays an important role in determining and identifying any potential aesthetic issues such as short shot, hesitation, air traps, and weld line due to wrongly gear types and locations selected. Selecting on location of gating system not only affects flow pattern but also significantly influences on anisotropic or directional shrinkage result from flow-induced orientation and eventually contributes to warpage and residual stresses in moulded gear.

Three different types and locations of gate for the model gear as shown in Figure 3 are studied in order to optimize the filling of plastic material into the cavity of the gear part. The best gate type and location for the polymer fill inside the cavity will be selected. The selected gating system should produce a balanced flow front within the part, with no underflow or over packing effects as well as unidirectional.

Referring to the Figure 4, inside gating system, the material is injected in one spot and from there the melt material flows to fill out the cavity. This creates a weld line opposite to the gate. The area where the weld is located will be of limited strength as the plastic material is less fluid at that point in time. An unbalanced filling around a core which results in deflection in the core can be seen. Due to the fact that, shrinkage of the material in the direction of the flow will be different from that perpendicular to the flow, a side gated gear will be somewhat elliptical rather than round. On the other hand, in gear model with diaphragm gate (Figure 5), the injection of material is in all directions at the same time which is important for the concentricity of the gear. There is no presence of a weld line. Since the diaphragm is fed from a concentric sprue, uniform flow to all parts of the gate is easy to maintain. This will result in radial flow pattern developing from the gate. Though this radial flow pattern will result in residual conflicting strains, the symmetry of these strains, the resulting stresses, and the structural rigidity provided by the gear shape will generally result in the most acceptable moulding conditions. For the gear with multiple pin gating (Figure 6), the plastic is injected at several places symmetrically located. By using this type of gating, system results in a more uniform filling pattern with reasonable viscosity of plastic when the material welds, as well as creates uniform shrinkage in all direction.

From the results of filling pattern in preliminary filling analysis conducted, it is clarified that diaphragm and multiple pin gating gear strongly influence the uniformity of the transient progression of the polymer flow front in the cavity. However, the multiple-pin gating system is not economical to be used for single cavity mould due to the complexity of three plate mould machining processes which require high cost of tools production. Therefore, in this case the model gear with diaphragm gate is selected as best location gate and will be further studied in the next processing parameters optimization in CFW analysis.

2.3. Cool + Flow + Warp (CFW) Analysis. CFW analysis is conducted after the optimized gating system for the studied model gear is completely determined in the preliminary filling analysis. A systematic approach based on Taguchi method is adopted in designing the experiment. The Taguchi method is an efficient tools and widely applied in designing high-quality manufacturing system [18], mechanical component [19], and process optimization [20, 21]. The popularity of Taguchi method is due to its robustness in designing high-quality system based on orthogonal array experiments, which provides much reduced variance for the experiment with optimum setting of process control parameters.

In this study, volumetric shrinkage and deflection were selected as response variables to characterize and evaluate the gear simulation model related to injection moulding process parameters. These two quality characteristics are carefully chosen as controlling features to be studied due to its impact on the quality of final moulded gear to be produced in future. Shrinkage and deflection negatively influence the dimensional stability and accuracy of the involute profile, concentricity, roundness, tooth spacing uniformity, and the size of the gear, hence, impacting the quality of the end moulded gear, noise, vibration, and product life. In this study, the-lower-the-better quality characteristic or, in other words, the minimum volumetric shrinkage and deflection are

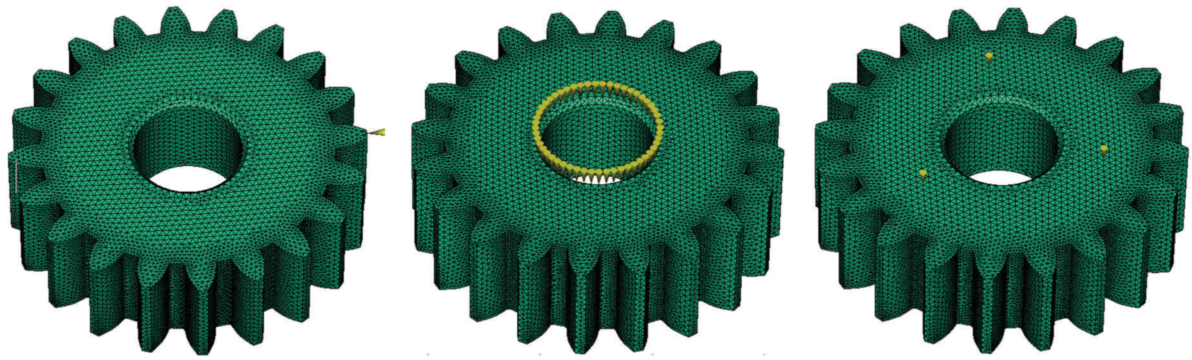

FIGURE 3: Three different types and locations of gates for the model gear.

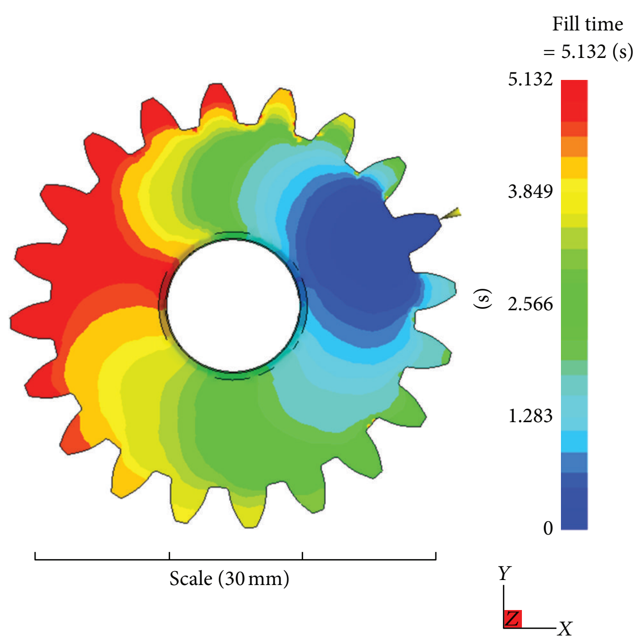

FIGURE 4: Filling pattern for side gating gear.

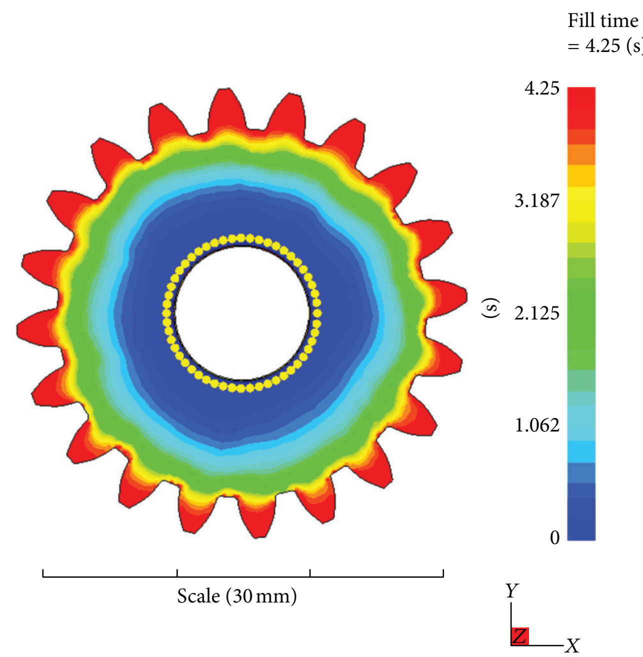

FIGURE 5: Filling pattern for diaphragm gating gear.

preferable in studying the effects of processing parameters on the moulded gear. After careful examination of all possible parameters that can affect the quality characteristics, six processing parameters (melt temperature, mould temperature, packing pressure, packing time, injection time and cooling time) were selected and were varied to obtain optimum levels of parameters for acceptable quality. The injection moulding process parameters, and their levels used in conducting the MPI simulation are shown in Table 2.

After determining the number of processing parameters and their levels, an appropriate orthogonal array (OA) has to be established for laying out the design of the experiment that needs to be conducted. The Taguchi's OA is an attempt to uncover subtle interactions among process variables with a small fraction of all possible combinations. Ilzarbe et al. [22] reported that Taguchi's OA achieved the highest usage in engineering application with 31%, outweighing other types of experimental design due to its practicality. The selection of the OA is concerned with the total degree of freedom (DOF) of the injection moulding process parameters. The DOF is defined as the number of comparisons among the process parameters required to optimize the parameters. In this study, there are six injection moulding process parameters each with

TABLE 2: Injection moulding parameters and their levels.

Column	Factors	Level 1	Level 2	Level 3
A	Melt temperature (°C)	200	230	260
B	Mold temperature (°C)	20	30	50
C	Packing pressure (%)	60%	80%	120%
D	Packing time (s)	5	10	30
E	Injection time (s)	1	2	3
F	Cooling time (s)	10	30	50

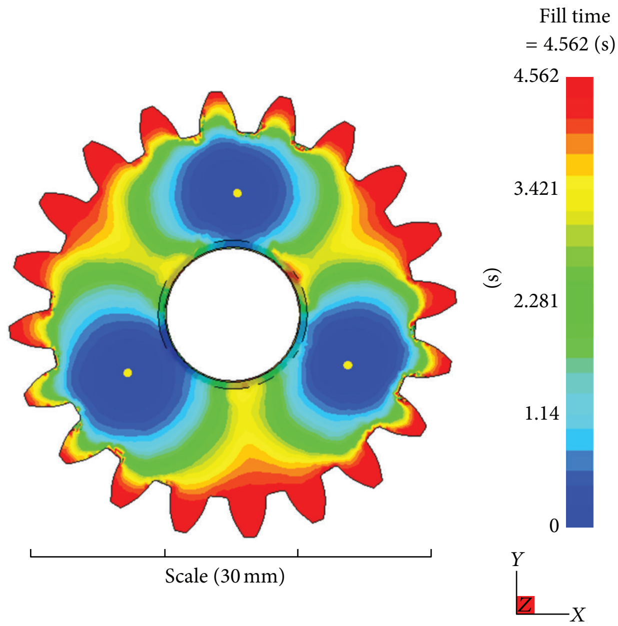

Figure 6: Filling pattern for multiple pin gating gear.

Table 3: Design of experiment using L_{18} $(2^1, 3^7)$.

Factors no/trials no	1	2	3	4	5	6	7	8
		A	*B*	*C*	*D*	*E*	*F*	
1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3
4	1	2	1	1	2	2	3	3
5	1	2	2	2	3	3	1	1
6	1	2	3	3	1	1	2	2
7	1	3	1	2	1	3	2	3
8	1	3	2	3	2	1	3	1
9	1	3	3	1	3	2	1	2
10	2	1	1	3	3	2	2	1
11	2	1	2	1	1	3	3	2
12	2	1	3	2	2	1	1	3
13	2	2	1	2	3	1	3	2
14	2	2	2	3	1	2	1	3
15	2	2	3	1	2	3	2	1
16	2	3	1	3	2	3	1	2
17	2	3	2	1	3	1	2	3
18	2	3	3	2	1	2	3	1

three levels. By neglecting the interaction among the injection moulding parameters, the total DOF is twelve. The DOF for the OA should be greater than or at least equal to that of the process parameters. Thereby, an L_{18} $(2^1, 3^7)$ OA is considered. The experimental layout as illustrated in Table 3 is used for conducting the simulation on gear model.

In Table 3, the trial numbers indicate the number of conducted simulations. In this study, 18 simulations are conducted and assigned as Trials 1–18. Factors *A*–*F* represent the processing parameters: *A* for melt temperature, *B* for mold temperature, *C* for packing pressure, *D* for packing time, *E* for injection time, and *F* for cooling time. All these factors are assigned to Columns 2–7. The two remaining columns (i.e., Columns 1 and 8) are eliminated and will not be used when running the experiment.

3. Analysis Method

The Grey relational analysis (GRA) associated with the Taguchi method is applied to analyze the data obtained in CFW analysis as well as to determine the optimal processing parameters for the desired multiple quality characteristics of the moulded plastic gear. The grey theory is based on the random uncertainty of small samples which developed into an evaluation technique to solve certain problems of system that are complex and have incomplete information. The method is a normalization evaluation technique which is extended to solve the complicated multiperformance characteristics optimization effectively.

3.1. Data Preprocessing. A data preprocessing is required in view of the fact that the range and unit in one data may differ from the others. Moreover, it is necessary when the sequence scatter range is too large or the target sequence directions are different. The data pre-processing involves the transfer of the original sequence to a comparable sequence. Let the original reference sequence and comparability sequences be represented as $x_0^{(O)}(k)$ and $x_i^{(O)}(k)$, $i = 1, 2, \ldots, m$; $k = 1, 2, \ldots, n$, respectively. There are four methodologies of data pre-processing available for the GRA based on the characteristics of the data sequence as follows.

The-larger-the better characteristic is as follows:

$$x_i^*(k) = \frac{x_i^{(O)}(k) - \min x_i^{(O)}(k)}{\max x_i^{(O)}(k) - \min x_i^{(O)}(k)}. \quad (1)$$

The-smaller-the-better characteristic is as follows:

$$x_i^*(k) = \frac{\max x_i^{(O)}(k) - x_i^{(O)}(k)}{\max x_i^{(O)}(k) - \min x_i^{(O)}(k)}. \quad (2)$$

The-nominal-the-better characteristic is as follows:

$$x_i^*(k) = 1 - \frac{\left|x_i^{(O)}(k) - OB\right|}{\max\left\{\max x_i^{(O)}(k) - OB, OB - \min x_i^{(O)}(k)\right\}}. \quad (3)$$

Alternatively, the original sequence can be normalized using the simplest methodology in which the values of the original sequence can be divided by the first value of the sequence:

$$x_i^*(k) = \frac{x_i^{(O)}(k)}{x_i^{(O)}(1)}, \quad (4)$$

where $x_i^{(O)}(k)$ = the original sequence, $x_i^*(k)$ = the sequence after the data preprocessing, $\max x_i^{(O)}(k)$ = the largest value of $x_i^{(O)}(k)$, and $\min x_i^{(O)}(k)$ = the smallest value of $x_i^{(O)}(k)$.

Table 4: Experimental results of multiple quality characteristic for gear model.

Experimental run	Factors						Volumetric shrinkage (%)	Deflection (mm)
	A	*B*	*C*	*D*	*E*	*F*		
1	200	20	60	5	1	10	18.37	0.4375
2	200	30	80	10	2	30	19.06	0.3740
3	200	50	120	30	3	50	19.47	0.3576
4	230	20	60	10	2	50	20.25	0.3966
5	230	30	80	30	3	10	20.13	0.3510
6	230	50	120	5	1	30	21.02	0.5374
7	260	20	80	5	3	30	22.26	0.5851
8	260	30	120	10	1	50	23.27	0.4294
9	260	50	60	30	2	10	22.41	0.3835
10	200	20	120	30	2	30	18.70	0.3444
11	200	30	60	5	3	50	19.27	0.4254
12	200	50	80	10	1	10	18.31	0.3921
13	230	20	80	30	1	50	21.03	0.3606
14	230	30	120	5	2	10	20.28	0.5127
15	230	50	60	10	3	30	20.04	0.3857
16	260	20	120	10	3	10	22.33	0.4080
17	260	30	60	30	1	30	23.27	0.3828
18	260	50	80	5	2	50	22.46	0.6049

3.2. Grey Relational Coefficient and Grey Relational Grade. Following data preprocessing, a grey relational coefficient can be calculated with the preprocessed sequences. The grey relational coefficient is defined as follows:

$$\gamma\left[x_0^*(k), x_i^*(k)\right] = \frac{\Delta_{\min} + \zeta\Delta_{\max}}{\Delta_{0i}(k) + \zeta\Delta_{\max}}, \qquad 0 < \gamma\left[x_0^*(k), x_i^*(k)\right] \le 1, \tag{5}$$

where $\Delta_{0i}(k)$ is the deviation sequence of the reference sequence, $x_0^*(k)$ is the comparability sequence, $x_i^*(k)$; namely,

$$\Delta_{0i}(k) = |x_0^*(k) - x_i^*(k)|,$$
$$\Delta_{\max} = \min_{\forall j \in i} \max_{\forall k} |x_0^*(k) - x_j^*(k)|,$$
$$\Delta_{\min} = \min_{\forall j \in i} \min_{\forall k} |x_0^*(k) - x_j^*(k)|$$
$$\zeta = \text{distinguishing coefficient } \zeta \in |0, 1|.$$

On the other hand, the grey relational grade is a weighting sum of the grey relational coefficient and is defined as follows:

$$\gamma\left(x_0^*, x_i^*\right) = \sum_{k=1}^{n} \beta_k \gamma\left[x_0^*(k), x_i^*(k)\right], \qquad \sum_{k=1}^{n} \beta_k = 1. \tag{6}$$

Here, the grey relational grade $\gamma(x_0^*, x_i^*)$ represents the level of correlation between the reference sequence and the comparability sequence. If the two sequences are identically coincidence, then the value of grey relational grade is equal to one. The grey relational grade also indicates the degree of influence that the comparability sequence could exert on the reference sequence. Therefore, if a particular comparability sequence is more important to the reference sequence than the other comparability sequences, the grey relational grade for that comparability sequence and reference sequence will exceed that for other grey relational grades. Grey relational analysis is actually a measurement of absolute value of data difference between sequences and could be used to measure approximation correlation between sequences.

4. Analysis and Discussion of Experimental Results

4.1. The Optimum Injection Moulding Process Parameters. The results of volumetric shrinkage and deflection of the gear model with the optimized diaphragm gating system for different combination of injection moulding parameters of eighteen experimental runs (Table 3) are listed in Table 4. In order to find the optimum levels of melt temperature (factor A), mould temperature (factor B), packing pressure (factor C), packing time (factor D), injection time (factor E), and cooling time (factor F) for the desired multiple quality characteristics of the PP moulded gear, the results in Table 4 are needed to be normalized as the range and unit in one data are different from the others. By adopting the GRA, typically, lower values of volumetric shrinkage and deflection in the moulded gear as the target values are desirable. Thus, the data sequence have the-smaller-the-better characteristic. The values of volumetric shrinkage and deflection are set to be the reference sequence $x_0^{(O)}(k)$, $k = 1, 2$. Moreover, the results of eighteen experiments were the comparability sequences $x_i^{(O)}(k)$, $i = 1, 2, 3, \ldots, 18$, $k = 1, 2$. Table 5 lists all of the

Table 5: The sequences of each quality characteristics after data preprocessing.

	Volumetric Shrinkage (%)	Deflection (mm)
Reference sequence	1.0000	1.0000
Comparability sequences		
Experiment no. 1	0.9879	0.6426
Experiment no. 2	0.8488	0.8864
Experiment no. 3	0.7661	0.9493
Experiment no. 4	0.6089	0.7996
Experiment no. 5	0.6331	0.9747
Experiment no. 6	0.4536	0.2591
Experiment no. 7	0.2036	0.0760
Experiment no. 8	0.0000	0.6737
Experiment no. 9	0.1734	0.8499
Experiment no. 10	0.9214	1.0000
Experiment no. 11	0.8065	0.6891
Experiment no. 12	1.0000	0.8169
Experiment no. 13	0.4516	0.9378
Experiment no. 14	0.6028	0.3539
Experiment no. 15	0.6512	0.8415
Experiment no. 16	0.1895	0.7559
Experiment no. 17	0.0000	0.8526
Experiment no. 18	0.1633	0.0000

sequences following data preprocessing using (2), where the reference and comparability sequences are denoted as $x_0^*(k)$ and $x_i^*(k)$, respectively.

As for the deviation sequences, Δ_{01} can be calculated as follows:

$$\Delta_{01}(1) = \left|x_0^*(1) - x_1^*(1)\right| = |1 - 0.9879| = 0.0121,$$
$$\Delta_{01}(2) = \left|x_0^*(2) - x_1^*(2)\right| = |1 - 0.6426| = 0.3574. \quad (7)$$

So, $\Delta_{01} = (0.0121, 0.3574)$.

The same calculating method was performed for $i = 1$–18 and the results of all Δ_{0i} for $i = 1$–18 are listed in Table 6.

Investigating the data presented in Table 6, we can find that $\Delta_{\max}(k)$ and $\Delta_{\min}(k)$ are as follows:

$$\Delta_{\max} = \Delta_8(1) = \Delta_{18}(2) = 1.0000$$
$$\Delta_{\min} = \Delta_{12}(1) = \Delta_{10}(2) = 0.0000. \quad (8)$$

The distinguishing coefficient ζ can be substituted for the grey relational coefficient in (5). Given that all the process parameters have equal weighting, the value of ζ is defined as 0.5. Table 7 lists the grey relational coefficient and grade for all eighteen comparability sequences.

In order to calculate the average grey relational grade for each injection moulding parameters level, the main effects' analysis of the Taguchi method was employed. It was done by sorting the grey relational grades corresponding to levels of the injection moulding parameters in each column of the orthogonal array, and taking an average on those with

Table 6: The deviation sequences.

Deviation sequences	$\Delta_{0i}(1)$	$\Delta_{0i}(2)$
Experiment no. 1	0.0121	0.3574
Experiment no. 2	0.1512	0.1136
Experiment no. 3	0.2339	0.0507
Experiment no. 4	0.3911	0.2004
Experiment no. 5	0.3669	0.0253
Experiment no. 6	0.5464	0.7409
Experiment no. 7	0.7964	0.9240
Experiment no. 8	1.0000	0.3263
Experiment no. 9	0.8266	0.1501
Experiment no. 10	0.0786	0.0000
Experiment no. 11	0.1935	0.3109
Experiment no. 12	0.0000	0.1831
Experiment no. 13	0.5484	0.0622
Experiment no. 14	0.3972	0.6461
Experiment no. 15	0.3488	0.1585
Experiment no. 16	0.8105	0.2441
Experiment no. 17	1.0000	0.1474
Experiment no. 18	0.8367	1.0000

the same level. For instance, for the factor A (as shown in Table 3), experiments Nos. 1, 2, 3, 10, 11, and 12 were set at level 1. Therefore, the average grey relational grade for A_1 can calculated as follows:

$$\overline{A}_1 = \frac{(0.7798 + 0.7913 + 0.7947 + 0.9321 + 0.6687 + 0.8660)}{6} = 0.8054. \quad (9)$$

Similarly, the average grey relational grades for A_2 and A_3 are calculated as follows:

$$\overline{A}_2 = \frac{(0.6375 + 0.7643 + 0.4404 + 0.6832 + 0.4968 + 0.6742)}{6} = 0.6160,$$
$$\overline{A}_3 = \frac{(0.3684 + 0.4692 + 0.5730 + 0.5267 + 0.5528 + 0.3537)}{6} = 0.4740. \quad (10)$$

Using the similar method, calculations were performed for each injection moulding parameter level and the main effects' analysis was constructed as shown in Table 8 and plotted in Figure 7.

In view of the fact that the grey relational grade represents the level of correlation between the reference and

Table 7: The grey relational coefficient and grey relational grade for eighteen comparability sequences.

Experimental run (comparability sequences)	Volumetric shrinkage (%)	Deflection (mm)	Grey relational grade
	Grey relational coefficient		
1	0.9764	0.5832	0.7798
2	0.7678	0.8148	0.7913
3	0.6813	0.9080	0.7947
4	0.5611	0.7139	0.6375
5	0.5767	0.9518	0.7643
6	0.4778	0.4029	0.4404
7	0.3857	0.3511	0.3684
8	0.3333	0.6051	0.4692
9	0.3769	0.7691	0.5730
10	0.8641	1.0000	0.9321
11	0.7209	0.6166	0.6687
12	1.0000	0.7319	0.8660
13	0.4769	0.8894	0.6832
14	0.5573	0.4363	0.4968
15	0.5891	0.7593	0.6742
16	0.3815	0.6719	0.5267
17	0.3333	0.7723	0.5528
18	0.3741	0.3333	0.3537

Table 8: The main effect analysis for grey relational grade.

Column	Parameters	Level 1	Level 2	Level 3
A	Melt temperature (°C)	0.8054	0.6160	0.4740
B	Mould temperature (°C)	0.6546	0.6239	0.6170
C	Packing pressure (%)	0.6477	0.6378	0.6100
D	Packing time (s)	0.5180	0.6608	0.7167
E	Injection time (s)	0.6319	0.6307	0.6328
F	Cooling time (s)	0.6678	0.6265	0.6012

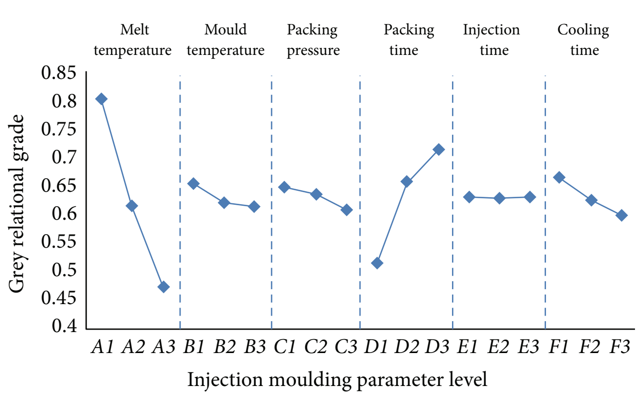

Figure 7: Main effects plot for grey relational grade.

the comparability sequences, the larger grey relational grade means that the comparability sequence exhibits a stronger correlation with the reference sequence. Basically, the larger the grey relational grade, the better the multiple quality characteristics are. From Figure 7, it is clearly shown that the multiple quality characteristics of the PP moulded gear with optimized diaphragm gating system are greatly influenced by the adjustments of the processing parameters. Considering multiple quality characteristic in terms of volumetric shrinkage and deflection, two opposite trends are observed where the increment of melt temperature, mould temperature, packing pressure, and cooling time result in greater volumetric shrinkage and deflection of the moulded gear. On the contrary, the increment of packing time and injection time reduces the volumetric shrinkage and deflection.

As in this case, the best combination of processing parameters and levels could easily be obtained from the main effect analysis by selecting the level of each parameter with the highest grey relational grade. Referring to Figure 4, A_1, B_1, C_1, D_3, E_3, and F_1 show the largest value of grey relational grade for factors A, B, C, D, E, and F, respectively. As a result, the optimal parameter setting which statistically results in the minimum volumetric shrinkage, as well as deflection for the PP moulded gear, is predicted to be $A_1B_1C_1D_3E_3F_1$. Restated, the melt temperature is 200°C, mould temperature is 20°C, packing pressure is 60%, packing time is 30 s, injection time is 3 s, and cooling time is 10 s.

From the result of optimum combination of processing parameters and levels, the increasing of melt temperature of PP seems to not greatly improve the ability of the molten material to flow through a thin section of the diaphragm gate to the cavity of the mould. However, since the diaphragm is fed from a concentric sprue, uniform flow to all parts of the gate is easy to maintain, which has enhanced the filling rate or the injection time of the molten material to be filled in the cavity. Therefore, greater time for the molten material to be filled in the cavity is expected to result in minimum volumetric shrinkage and deflection of the moulded gear. The way of the diaphragm gate has been attached to the gear cavity

Table 9: ANOVA table for the grey relational grade for eighteen comparability sequences.

Column	Parameters	DOF	S	V	F	%
A	Melt temperature (°C)	2	0.3318	0.1659	81.264	67.579
B	Mold temperature (°C)	2	0.0048	0.0024	1.180	0.981
C	Packing pressure (%)	2	0.0046	0.0023	1.123	0.934
D	Packing time (s)	2	0.1260	0.0630	30.861	25.664
E	Injection time (s)	2	0.0000	0.0000	0.003	0.003
F	Cooling time (s)	2	0.0136	0.0068	3.320	2.761
All others/error		5	0.0102	0.0020		2.079
Total		17	0.4910			100.000

is greatly influencing the determination of optimum packing and cooling process in the mould. The packing pressure of 60% and packing time of 30 s as well as cooling time of 10 s are recognized to be the optimum packing and cooling for the minimum volumetric shrinkage and deflection in the studied moulded gear.

4.2. The Significance of Injection Moulding Parameters. In order to examine the extent to which injection moulding parameters significantly influence the performance of moulded gear, analysis of variance (ANOVA) of the Taguchi method is performed on the grey relational grade for eighteen comparability sequences (Table 7). The computed quantity of degrees of freedom (DOF), sum of square (S), variance (V), F-ratio (F), and percentage contribution (%) are presented in Table 9.

In ANOVA, the F-ratio which is also known as variance ratio, denoted as F in the Table 9, 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 parameters with highest percentage contribution need not necessarily be significant because only the computed F-ratios of the processing parameters which are greater than the F-Table of specific confidence level are statistically considered as significant [23]

In the present study, the degrees of freedom for the numerator is 2 and that for the denominator is 5, from the F-Table at 0.01 level of significance (99% confidence), the obtained result $F0.01\ (2{,}5) = 13.274$. Referring to Table 9, out of six processing parameters, only two parameters, including melt temperature and packing time, are considered as significant as their F-ratios and are greater than the threshold values obtained from the F-Table of 99% confidence level.

As shown in Table 9, it can be observed that the melt temperature is the most influential processing parameter which demonstrates the strongest comparability sequence among the injection moulding processing parameters, with the percentage contribution of 67.579%. The analysis revealed that the melt temperature had the strongest correlation with the volumetric shrinkage and deflection in the moulded gear for the specific material selected. Nevertheless, injection time was found to have the least importance on volumetric shrinkage and deflection concurrently with the lower percentage contribution of only 0.003%.

5. Conclusions

The findings of simulation experiment reveal that the advancement of the simulation packages is capable of simulating the scenarios of the polymer melt without conducting the real experiment. As in this study, MPI software is a useful tool to predict volumetric shrinkage and deflection of the moulded gear under different process conditions. The integration of the grey-based Taguchi optimization method and numerical simulation provides designers and engineers with a systematic and efficient approach to identify the most significant processing parameters on the quality characteristics of the final moulded gear out of numerous processing variables with minimal simulation trials required. Through a series of analysis and optimization, it was found out that gate types and locations have a great influence on the filling pattern or the transient progression of the polymer flow front within the feed system and mould cavity. Predicting and visualizing the filling pattern in mould cavity using simulation packages before the real manufacturing process takes place reduces the incurring high production cost due to subsequent mould modification in production line as well as minimizing the potential aesthetic issues in the moulded gear. From the main effect analysis of the average grey relational grade, it was also found that the largest value of grey relational grade for melt temperature, mould temperature, packing pressure, packing time, injection time, and cooling time were 220°C, 20°C, 60%, 30 s, 3 s, and 10 s, respectively. Therefore, the optimal combination of processing parameters for producing a moulded gear with the minimum volumetric shrinkage and deflection was determined as A_1, B_1, C_1, D_3, E_3, and F_1 when multiple quality characteristics are simultaneously considered. Out of six important injection moulding process parameters investigated in this study, only two parameters, including melt temperature and packing time, are considered as significant on the examined quality characteristics of the moulded gear. The melt temperature showed the strongest comparability sequence with the percentage contribution of 67.579% followed by packing time of 25.664%. Injection time was found to have least importance on volumetric shrinkage and deflection concurrently with the lower percentage contribution of only 0.003%.

Acknowledgment

The authors acknowledge the Research Grant provided by University Sains Malaysia, Pulau Pinang, for funding the study that resulted in this paper.

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