Reducing the Shrinkage in Plastic Injection Moulded Gear via Grey-Based-Taguchi Optimization Method

Nik Mizamzul Mehat, Shahrul Kamaruddin and Abdul Rahim Othman, *Member, IAENG*

Abstract— **The application of plastic moulded gears in contrast of metal base gears are limited to functionally less important component due to its weak mechanical properties and divergent mechanism of failures. Shrinkage behaviour is one of the crucial problem in plastic moulded gear which negatively impacting the dimensional stability and accuracy of the involute profile, concentricity, roundness, tooth spacing uniformity and the size of the gear. Integrating the grey relational analysis and Taguchi method, the shrinkage behavior in tooth thickness, addendum and dedendum circles of moulded gear is investigated via optimization of processing parameters. From the results of analysis and optimization, the optimal combination of processing parameters for the moulded gear to achieve minimum shrinkage was predicted as A_2, B_2, C_3, and D_1. The melt temperature showed the strongest comparability sequence among the four important injection moulding process parameters investigated in this study followed by packing pressure, cooling time and packing time.**

Index Terms— **Plastic moulded gear, shrinkage behavior, grey relational analysis, Taguchi method optimization**

I. Introduction

To date, plastic base gears have drawn significant attention in power and motion transmission applications. With the ability to run without lubrication and corrosion, plastic gears have been widely used in automotive industry, office machines and household utensils, in food and textile machinery, as well as a host of other applications areas [1]. Compared to metallic gears which suffer from chemical corrosion, lubrication related failures, expensive operating and maintenance cost, plastic gears are lighter, less noisy, low friction and cheaper to be produced in large quantities with complex shapes using injection moulding process [2,3]. However, the practicability of injection moulding in producing low cost plastic moulded gears is still restricted by the occurrence of shrinkage in the final parts. Severe shrinkage lead to deflection or warpage in moulded part as well as 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 shorten the service life of the gear result from different damage mechanism such as tooth fatigue, creep, excessive wear and plastic deformation. Many factors, including materials selection, part and mould design, as well as injection moulding processing parameters can affect shrinkage behavior in an injection moulded part. Semicrytalline plastics commonly shrink more than amorphous plastic due to the closer packing of the crystalline structure [4]. The study carried out by Chang and Faison [5] reported that shrinkage in high-density polyethylene (HDPE) rectangular bar is more than general-purpose polystyrene (GPS) and acrylonitrile-bitadiene-sytrene (ABS). More shrinkage occurs in the across-the-flow direction of HDPE than in its along-the-flow-direction. On the other hand, the effect of mould design on the part quality should not be underestimated in view of the fact that it is a complicated process. As the part and mould designs are closely interconnected, even though the part design might be perfect, any error in the design and fabrication of the mould would still reflect the defects on the injection moulded part. For instance, poor cooling system will give rise to non-uniform mould surface temperature and irrational gate location, would lead to differential shrinkage in moulded part [6,7]. For the effects of processing parameters on shrinkage in POM injection moulded part, Postawa and Koszkul [8] reported that the clamp pressure and the injection temperature were the key parameter. Other processing parameters such as packing pressure and melt temperature for rectangular moulded shape made from PP and PS respectively also affect the shrinkage behavior [9]. Increasing holding pressure and melt temperature were found to reduce the shrinkage in the part.

In this paper, the focus is concerned on the optimization of processing parameters via the integration of the Taguchi method and grey relational analysis (GRA) in minimizing the shrinkage behavior of the plastic injection moulded gear. The processing parameters are only considered after the gear and mould design have been established in simulation stage using Moldflow Plastic Insight (MPI) software. Since many processing parameters affect the shrinkage, a preliminary experiment has been conducted first using the MPI to screen out the only significant processing parameters to be investigated in the present study. Four parameters of melt

Manuscript received March 13, 2012; revised April 06, 2012. This work was supported in part by the Short-term Research Grant provided by University Sains Malaysia, Pulau Pinang.

Nik Mizamzul Mehat is with Department of Mould Technology, Kolej Kemahiran Tinggi MARA, Balik Pulau, Malaysia and currently is a postgraduate student in School of Mechanical Engineering, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal,14300, Pulau Pinang, Malaysia (6013-435-2004; email: nik_miza78@yahoo.com).

Shahrul Kamaruddin is an associated professor in School of Mechanical Engineering, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal,14300, Pulau Pinang, Malaysia (email: meshah@eng.usm.my.

Abdul Rahim Othman is also with School of Mechanical Engineering, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal,14300, Pulau Pinang, Malaysia as a deputy dean (email: merahim@eng.usm.my).

temperature, packing pressure, packing time and cooling time each at three levels were finally selected as the control conditions. In order to inspect the shrinkage behavior on the dimensional stability of the moulded gear, three quality characteristics are selected including tooth thickness, addendum and dedendum circles. The optimal combination of processing parameters and the most influential factor for the injection moulding process can be determined in this study using the Taguchi method and grey relational analysis (GRA) integration.

II. Experimental Procedures

In this study, the crystalline thermoplastic polypropylene (PP) is specified for the gear. The PP was manufactured by Propelinas Propylene Malaysia. The general properties of the PP are shown in Table 1. 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 1.

TABLE I
General Properties Of Pp

Properties	
Density (g/cm3)	0.90-0.91
Raw density (g/cm^3)	0.805
Melt flow index (g per 10 min)	10.78
Modulus of elasticity (MPa)	4100
Charpy impact toughness (kJ/m^2)	1.4–1.8

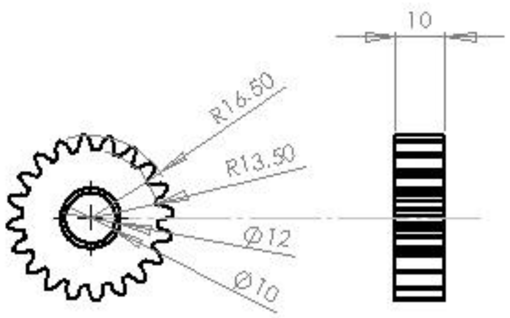

Fig. 1. Geometry and specification of spur gear with module = 1.5; pressure angle = 20°; number of teeth = 20; face width = 10mm.

The PP gears were injected by a Battenfeld TM750/210 injection moulding machine. The experiment was conducted with four controllable three-level processing parameters: melt temperature, packing pressure, packing time, and cooling time. Other processing parameters, such as mould temperature (25 ◦C), injection pressure (80bar), and stroke distance (60 mm), were kept constant during the experimentation. The selected processing parameters and their levels are shown in Table 2. The L_9 (3^4) orthogonal array OA, as shown in Table 3, was conducted to study the four processing parameter. Nine trials of PP gears with five repetitions were produced using the OA.

TABLE 2
Processing parameters and levels studied

Column	**Factors**	**Level 1**	**Level 2**	**Level 3**
A	Melt temperature (°C)	200	220	240
B	Packing pressure (%)	60	80	100
C	Packing time (s)	5	10	15
D	Cooling time (s)	30	40	50

TABLE 3
Orthogonal Arrray $L_9(3^4)$ of the Experimental Runs

Factors/ Trial No.	A	B	C	D
	Melt Temperature (°C)	Packing pressure (%)	Packing time (s)	Packing time (s)
1	200	60	5	30
2	200	80	10	40
3	200	100	15	50
4	220	60	10	50
5	220	80	15	30
6	220	100	5	40
7	240	60	15	40
8	240	80	5	50
9	240	100	10	30

III. Shrinkage Measurement

Rax Vision DC 3000 Mitutoyo profile projector was used to inspect the accuracy of specific profile of involute gear teeth after being moulded. In this study, the profile projector is used for measuring two-dimensional (2D) tooth thickness as well as addendum and dedendum circles by the coordinates of selected points along the gear profile. With large magnifications and micrometer readouts, this profile projector could ensure fairly accurate measurements compared to vernier caliper and micrometer. In the process of addendum and dedendum circles measurement, twenty edge points of each tooth gear were selected to be set in the profile projector. In order to ensure the integrity of the comparison procedure, five injection moulded gears which come from the same batch were measured to determine the repeatability of the part geometry. The relative shrinkage of the selected quality characteristics were calculated with the following equation:

$$S= (D-D_m)/D_m \text{ X } 100\% \quad (1)$$

Where S is shrinkage, D is the reading of diameter measurement using profile projector and D_m is the mould dimension.

IV. Analysis Method

A. Signal-to-noise ratio of Taguchi method

In analyzing the results, Taguchi introduced the use of the signal to- noise (S/N) ratio to determine the quality of the characteristics applied. As discussed by Oktem et al. [10], the S/N ratio is a measure of performance aimed at developing products and processes insensitive to noise factors. The part or process operation consistent with the highest S/N ratios always yields optimal quality characteristics with minimum variance. In the Taguchi method, quality characteristics can be categorized into the-lower-the- better, the-nominal-the-better and the-bigger-the-better. In this study the lower value of the shrinkage behavior in moulded gear is expected. Thus, S/N ratio characteristic the-lower-the-better is applied in the analysis, which can be calculated using Eq. (2):

$$S/N = -10 \text{ Log}_{10} \left(\frac{1}{n} \sum \frac{1}{y_i^2} \right) \quad (2)$$

where y_i is the value of the quality characteristics for the ith trials, n is number of repetitions

ISBN: 978-988-19252-2-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

B. Grey relational analysis

Let the original reference sequence and comparability sequences are represented as $x_0^{(O)}(k)$ and $x_i^{(O)}(k)$, i = 1, 2,…, m; k = 1, 2,…, n, respectively. A data preprocessing is required in view of the fact that the range and unit in one data may differ from the others. The data preprocessing involves the transfer of the original sequence to a comparable sequence. For this present study, the-smaller-the-better characteristics of the data sequence are selected to investigate the shrinkage behaviour in moulded gear and calculated as follows:

$$x_i^*(k) = \frac{\max x_i^{(O)}(k) - x_i^{(O)}(k)}{\max x_i^{(O)}(k) - \min x_i^{(O)}(k)} \quad (3)$$

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

Following data preprocessing, a grey relational coefficient can be calculated with the preprocessed sequences. The grey relational coefficient is defined as follows:

$$\gamma[x_0^*(k), x_i^*(k)] = \frac{\Delta_{min} + \zeta\Delta_{max}}{\Delta_{0i}(k) + \zeta\Delta_{max}} \quad (4)$$

Where $0 < \gamma[x_0^*(k), x_i^*(k)] \leq 1$, $\Delta_{0i}(k)$ is the deviation sequence of the reference sequence, $x_0^*(k)$ and the comparability sequence, $x_i^*(k)$, and ζ is the distinguishing coefficient $\zeta \in |0,1|$.

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

$$\gamma(x_0^*, x_i^*) = \sum_{k=1}^{n} \beta_k \gamma\,[x_0^*(k), x_i^*(k)]$$

$$\sum_{k=1}^{n} \beta_k = 1 \quad (5)$$

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.

V. Results And Discussion

The following sequential steps were adopted to determine the optimal combinations of the injection moulding process parameters using the Taguchi method integrated with grey relational analysis; (1) S/N ratios for the experimental data were calculated, (2) The S/N ratios were normalized using reference and comparability sequences then (3) The corresponding grey relational coefficients and grey relational grades were calculated. In this study, the experimental results of the shrinkage behavior on addendum circle (AC), dedendum circle (DC) and tooth thickness (TT) for each nine trials are statistically analyzed using S/N ratios based on the-lower-the-better quality characteristic (Eq. 2). The S/N ratios for each nine trials are summarized in Table 4.

TABLE 4
S/N Responses for L_9 OA

Trials No	AC (dB)	DC (dB)	TT (dB)
1	36.0686	36.6328	31.7095
2	35.9811	36.5991	27.5659
3	36.4239	37.0418	24.7762
4	36.5179	36.7071	21.8063
5	35.9042	36.3034	21.7231
6	36.0796	36.8566	21.0398
7	36.4248	37.1554	22.9662
8	37.2119	37.7488	20.2403
9	36.6474	37.9853	22.4707

The results in Table 4 are normalized for the next data preprocessing by using the-smaller-the-better characteristic as in Eq. 3. The values of AC, DC and TT are set to be the reference sequence $x_0^{(O)}(k)$, k = 1-3 and the comparability sequences $x_i^{(O)}(k)$, i = 1, 2, 3,…, 9, k = 1-3. The distinguishing coefficient ζ can be substituted for the grey relational coefficient in Eq. (4). Given that all the process parameters have equal weigthing, the value of ζ is defined as 0.5. Table 5 lists all of the sequences following data preprocessing, the grey relational coefficient (GRC) and grey relational grade (GRD) for all nine comparability sequences.

TABLE 5
Grey relational analysis results

	Data after pre-processing			GRC			GRD
	AC	DC	TT	AC	DC	TT	
Reference sequence	1.0000	1.0000	1.000				
Comparability sequences							
Trial 1	0.8743	0.8041	0.0000	0.7991	0.7185	0.3333	0.6170
Trial 2	0.9412	0.8242	0.3613	0.8948	0.7398	0.4391	0.6912
Trial 3	0.6026	0.5609	0.6045	0.5572	0.5324	0.5584	0.5493
Trial 4	0.5308	0.7600	0.8635	0.5159	0.6757	0.7855	0.6590
Trial 5	1.0000	1.0000	0.8707	1.0000	1.0000	0.7946	0.9315
Trial 6	0.8659	0.6711	0.9303	0.7885	0.6032	0.8777	0.7565
Trial 7	0.6020	0.4934	0.7623	0.5568	0.4967	0.6778	0.5771
Trial 8	0.0000	0.1406	1.0000	0.3333	0.3678	1.0000	0.5670
Trial 9	0.4317	0.0000	0.8055	0.4680	0.3333	0.7200	0.5071

(5)

The average GRD in Table 5 for each injection moulding parameters level are calculated using main effects analysis of the Taguchi method and plotted in Figure 2.

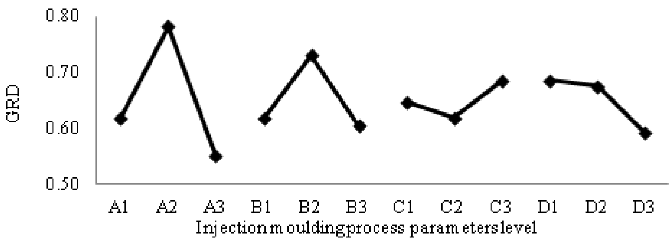

Fig. 2. Main effects plot for grey relational grade

Basically, the larger the grey relational grade, the better are the multiple quality characteristics. In this case, the comparability sequence with a larger value of grey relational grade will result in minimum of shrinkage of AC, DC and TT in the moulded gear. Referring to Figure 2, A_2, B_2, C_3, and D_1 show the largest value of GRD for factors A, B, C, and D respectively. As a result, the optimal parameters setting which statistically result in the minimum shrinkage in the three quality characteristics are predicted to be the melt

ISBN: 978-988-19252-2-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

temperature of 220°C, packing pressure of 80%, packing time of 15s, and cooling time of 30s. 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 GRD for nine comparability sequences (Table 5). The computed quantity of degrees of freedom (DOF), sum of square (S), variance (V), and percentage contribution (P) is presented in Table 6.

Referring to Table 6, as a level of confidence of 95% is used in this study, the sequential order of significance of the processing parameters to the shrinkage behavior in AD, DC and TT of PP moulded gear was melt temperature, packing pressure, cooling time and packing time accordingly. The most decisive factor will be given the maximum value of percentage of contribution for each processing parameters. As shown in Table 6, it can be observed that the melt temperature is the most influential processing parameter which demonstrates the highest P of 62.501%. The analysis revealed that the melt temperature had the strongest correlation to the shrinkage behavior in the moulded gear and in this case the predicted optimum melt temperature for the part is 220°C.

TABLE 6
ANOVA TABLE FOR THE GRD OF NINE COMPARABILITY SEQUENCES

Column	Parameters	DOF	S	V	P
A	Melt temperature (°C)	2	0.0851	0.0426	62.501
B	Packing pressure (%)	2	0.0286	0.0143	20.968
C	Packing time (s)	2	0.0068	0.0034	4.972
D	Cooling time (s)	2	0.0157	0.0079	11.560
All others/error		0	0.0000		0.0000
Total		8	0.1362		100

VI. CONCLUSION

The grey relational analysis based on the Taguchi method's OA and main effects analysis was recommended as a way of efficiently optimizing the injection moulding processing parameters in reducing the shrinkage problem in plastic moulded gear. Through a series of analysis and optimization of selected multiple quality characteristics, the results exhibited that the optimal combination of processing parameters for the moulded gear to achieve minimum shrinkage was determined as A_2, B_2, C_3, and D_1. The melt temperature showed the strongest comparability sequence among the four important injection moulding process parameters investigated in this study followed by packing pressure, cooling time and packing time

REFERENCES

[1] K. Mao, W. Li, C.J. Hooke and D. Walton, "Friction and wear behaviour of acetal and nylon gears", *Wear*", vol.267, pp.639–645, 2009.

[2] S.Senthilvelan and R.Gnanamoorthy, "Effect of gear tooth fillet radius on the performance of injection molded nylon 6/6 gears", *Materials and Design*,vol. 2, pp. 632–639, 2006.

[3] D. Jae Yoon, W.Cha, Sung, H. Tae Chong and W. Young Ha, "Study on the Accuracy ofInjection Molded Plastic Gear with the Assistance of Supercritical Fluid and a Pressurized Mold", *Polymer-Plastics Technology and Engineering*, vol.46,no. 9, pp.815-820, 2007.

[4] R.A. Malloy, *Plastic Part Design for Iyection Molding- An Introduction*, New York: Hanser Publishers, 1994, pp. 80.

[5] T.C. Chang, and E. Faison, "Shrinkage behavior and optimization of injection molded parts studied by the Taguchi method", *Polymer Engineering Science*, vol. 41, pp.703-710, 2001.

[6] H. Xiao Yan, L. De-Qun and X. Qiang, "Gate location optimization in injection molding based on empirical search method", *Materials Science Forum*, vol. 575–578, pp.55–62, 2008

[7] H. Zhou, Y. Zhang, J. Wen, D. Li, "An acceleration method for the BEM-based cooling simulation of injection moulding", *Engineering Analysis with Boundary Elements*, vol. 33, pp.1022-1030, 2009.

[8] P. Postawa and J.K. Koszkul, "Change in injection moulded parts shrinkage and weight as a function of processing conditions", *Journal of Materials Processing Technology*, vol. 162–163, pp.109–115, 2005.

[9] M. Altan, "Reducing shrinkage in injection moldings via the Taguchi, ANOVA and neural network methods", *Materials and Design*, vol. 31, pp.599–604, 2010.

[10] H. Oktem , T. Erzurumlu and I. Uzman, "Application of Taguchi optimization technique in determining plastic injection molding process parameters for a thin-shell part", *Materials and Design*, vol.28, pp.1271–1278, 2007.

ISBN: 978-988-19252-2-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)