Effect of processing parameters on the shrinkage behaviour of injection moulded polypropylene gear

A A Jamaluddin¹, N M Mehat² and S Kamaruddin¹
¹Mechanical Engineering Department, Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak Darul Ridzuan, Malaysia
²Department of Mechanical Engineering Technology, Faculty of Engineering Technology, Uniciti Alam Campus, Universiti Malaysia Perlis, Sungai Chuchuh, Padang Besar, 02100, Perlis, Malaysia.

Abstract. The polymer gears are widely used as basic motion transfer elements in many industries. Continuous improvement on the quality performance of polymer gears is very important for their ability to meet present demand. So that, controlling the parameters setting in polymers gears are very importance in order to get the best gears quality. In this study, the influences of injection moulding processing parameters on shrinkage of polypropylene gears was investigated by using Taguchi approach. It was found that the optimal processing parameters for addendum circle shrinkage, dedendum circle shrinkage and tooth thickness shrinkage are A₁B₁C₃D₃E₁F₂G₃, A₃B₁C₃D₃E₃F₁G₃, and A₁B₃C₃D₂E₃F₂G₁ respectively. This results showed that pattern of fluctuation showed either an improvement or reduction in quality characteristics upon the change of process parameters setting.

1. Introduction

An increasing demand of polymer gears used as a basic and motion transfer components make it is widely used in many industries starting from lightweight industries such as copy machine, printers and facsimiles until to heavyweight industries such as automotive, robotics and starter motors manufacturing [1]. The light weight, noise reduction, anti-corrosion, oil free condition as well as low materials and manufacturing cost advantages that owned by polymers gear have contribute to their increasing of application compare to metal gears [2]. Nowadays, an injection moulding process offer the shorts product cycle, excellent aesthetics appearance and high flexibility of part geometry for polymer gears production with low cost and high productivity rate. Although injection moulding is the most widely used process in polymers gear manufacturing, there are still needs tremendous efforts to solve the problems especially regarding to shrinkage in polymer gears. Over the past few decades, a lot of studies are conducted with purpose to enhance the performance and durability of polymer gears by means of internal structure enhancement [3], [4] and design modification [5], [6]. Apart of material enhancement, another consideration for the possibility of optimizing the injection moulding process from the manufacturing point of view should not grossly underestimated. It could be an appealing approach to enhance the polymer gear’s quality especially when it relates to shrinkage problem, considering no extra processing cost is required. Generally, there are numerous processing parameters that need to be controlled during injection moulding which can be classified into four namely, temperature, pressure, time, and distance [7]. With plastic materials exhibiting extremely convoluted properties, and the intricacy of the moulding process, attaining the desired final moulded gear quality particularly when it comes into shrinkage, is a very challenging task. Thus, the aim of this study is to investigate the impact...
of variation in processing parameters on shrinkage behaviour in moulded polymer gears as well as to determine the optimal processing parameters that can minimize the shrinkage problem in polymer gear. Seven processing parameters including melting temperature, mould temperature, injection pressure, injection time, packing pressure, packing time and cooling time with three levels of each was systematically analysed and investigated in this study via the Taguchi method.

2. Methodology

Polypropylene (PP) was used as gear material in this study, denoted as Titanpro Polypropylene 6331 by Titan Chemicals. Prior to injection moulding processs, the PP was dried at 80 °C for 2 hours to remove moisture for better moulding quality. The spur gear with module 1.5, pressure angle 20°, 20 teeth and 10mm thickness compliance with American Gears Manufacturers Association (AGMA) was the part studied (Figure 1).

2.1. Design of experiment

The experiment was conducted by using Taguchi method approach in order to study the influences of processing parameters on polymer gears shrinkage. Seven parameters of melting temperature, mould temperature, injection pressure, injection time, packing pressure, packing time and cooling time with three levels of each factor was selected, as shown in Table 1. Shrinkage in addendum circle, dedendum circle and tooth thickness of the gear were studied. The orthogonal array (OA) L₁₈, as tabulated in Table 2 are used in designing the experiments. All the trials in L₁₈ OA was conducted by using Battenfeld TM750/210 injection moulding machine with five repetitions of each trial.

| Column | Parameters                  | Level 1 | Level 2 | Level 3 |
|--------|-----------------------------|---------|---------|---------|
| A      | Melting temperature (ºC)    | 220     | 230     | 240     |
| B      | Mould temperature (ºC)      | 40      | 50      | 60      |
| C      | Injection pressure (bar)    | 80      | 90      | 100     |
| D      | Injection time (s)          | 1       | 2       | 3       |
| E      | Packing pressure (%)        | 70      | 80      | 90      |
| F      | Packing time (s)            | 5       | 10      | 15      |
| G      | Cooling time (s)            | 50      | 60      | 70      |

2.2. Shrinkage Measurement.

Rax Vision DC 3000 Mitutoyo profile projector was used to measure the shrinkage rate of moulded gear addendum and dedendum circle as well as tooth thickness by measuring their two dimensional contours. To reduce the variance in measurement, five samples of each injected gear are measured and their relative shrinkage rate are calculated based on following equation:
S = (D - Dm)/Dm x 100%  
Where S = shrinkage, D = injected gear dimension and Dm = mould dimension

\[ S = \frac{D - Dm}{Dm} \times 100\% \]  
(1)

### Table 2. L\(_{18}\) OA of experimental study

| Trials | A | B | C | D | E | F | G |
|--------|---|---|---|---|---|---|---|
| 1      | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2      | 1 | 2 | 2 | 2 | 2 | 2 | 2 |
| 3      | 1 | 3 | 3 | 3 | 3 | 3 | 3 |
| 4      | 2 | 1 | 2 | 2 | 2 | 2 | 1 |
| 5      | 2 | 2 | 2 | 3 | 3 | 1 | 1 |
| 6      | 2 | 3 | 3 | 1 | 1 | 2 | 2 |
| 7      | 3 | 1 | 2 | 1 | 3 | 2 | 3 |
| 8      | 2 | 3 | 2 | 2 | 1 | 3 | 1 |
| 9      | 3 | 3 | 1 | 3 | 2 | 1 | 2 |
| 10     | 1 | 1 | 1 | 1 | 2 | 2 | 1 |
| 11     | 1 | 2 | 1 | 1 | 3 | 3 | 2 |
| 12     | 1 | 3 | 2 | 1 | 3 | 1 | 3 |
| 13     | 2 | 1 | 2 | 1 | 3 | 1 | 3 |
| 14     | 2 | 3 | 1 | 3 | 2 | 1 | 3 |
| 15     | 2 | 3 | 2 | 2 | 3 | 1 | 2 |
| 16     | 3 | 1 | 3 | 3 | 3 | 1 | 2 |
| 17     | 3 | 2 | 1 | 3 | 1 | 2 | 3 |
| 18     | 3 | 3 | 2 | 1 | 1 | 2 | 3 |

### 3. Results and Discussion

#### 3.1 Signal-to-Noise Ratio (S/N)

Taguchi method introduced the S/N ratio approach in order to measure the deviation of quality characteristics from their target value. The higher value of S/N ratio indicate the minimization of noise sensitivity of any process. The S/N ratio can be divided into three stages: the-lower-the-better, the-nominal-the-better and the-bigger-the-better. The objective of this study is to minimize the value of shrinkage in addendum and dedendum circle, as well as in tooth thickness of the PP injected moulded gears. The S/N ratio for all 18 trials are reported in Table 3.

### Table 3. The S/N ratio of quality characteristics

| Trials | Addendum circle (dB) | Dedendum circle (dB) | Tooth thickness (dB) |
|--------|-----------------------|----------------------|----------------------|
| 1      | 33.800                | 32.821               | 25.347               |
| 2      | 34.258                | 33.043               | 25.783               |
| 3      | 34.659                | 33.900               | 26.577               |
| 4      | 33.741                | 32.753               | 22.275               |
| 5      | 34.511                | 33.176               | 25.398               |
| 6      | 34.740                | 33.559               | 25.955               |
| 7      | 34.398                | 33.287               | 22.150               |
| 8      | 34.882                | 33.506               | 22.286               |
| 9      | 34.227                | 33.038               | 22.298               |
| 10     | 34.327                | 33.659               | 25.530               |
| 11     | 33.825                | 32.649               | 25.906               |
| 12     | 34.166                | 33.059               | 26.595               |
| 13     | 34.636                | 33.463               | 22.529               |
| 14     | 35.217                | 33.983               | 22.258               |
| 15     | 34.020                | 32.831               | 25.636               |
| 16     | 31.803                | 34.140               | 22.639               |
| 17     | 34.626                | 33.491               | 22.142               |
| 18     | 33.627                | 32.845               | 21.837               |
3.2 The effects of processing parameter on PP gears shrinkage

For better interpretation of the S/N results tabulated in Table 3 in determining the optimal levels of each processing parameters studied in this research, the results in Table 3 can be presented graphically. Figure 3 demonstrates the impact of variation in melting temperature (A), mould temperature (B), injection pressure (C), injection time (D), packing pressure (E), packing time (F) and cooling time (G) on the shrinkage behaviour in addendum and dedendum circle as well as in tooth thickness of the PP gears.

![Figure 2. Shrinkage S/N Ratio Response Plot](image)

From Figure 2, it is clearly shown that shrinkage behaviour in addendum and dedendum circle as well as in tooth thickness of the injected PP gears, which in this case, are presented by the S/N ratio, are affected significantly by variations in processing parameters. It can be observed that for the shrinkage in addendum circle of the moulded PP gear, the increment of melting temperature, mould temperature, injection pressure and packing time levels, the shrinkage rate has been minimized. However, the shrinkage rate seen to be increased upon the increment of injection time, packing pressure and cooling time levels. For shrinkage in dedendum circle of the moulded PP gear, the increasing of melting temperature, injection pressure, injection time and cooling time is observed in minimizing the shrinkage rate. Otherwise, the increasing of mould temperature, packing pressure and packing time levels have increased the shrinkage rate. Meanwhile, for the case of tooth thickness, the increment of mould temperature, injection pressure, injection time and packing time levels has reduced the shrinkage rate of tooth thickness. In contrary, the increment of melting temperature, packing pressure and cooling time is observed to increase the tooth thickness shrinkage.

The best combination of processing parameters and levels can be easily obtained from Figure 2 by selecting the level of each parameters with the highest value of S/N response. For addendum circle shrinkage minimization, A1B1C3D3E1F2G3 is identified as an optimal parameters combination, represent 220ºC melting temperature, 40ºC mould temperature, 100bar injection pressure, 3s injection time, 70% packing pressure, 10s packing time and 70s cooling. Meanwhile, A3B1C3D3E3F1G3 is identified as an optimal parameters combination in minimizing the shrinkage in dedendum circle represent 240 ºC melting temperature, 40 ºC mould temperature, 100 bar injection pressure, 3 s injection time, 90 % packing pressure, 5 s packing time and 70 s cooling time. On the other hand, A1B3C3D2E3F2G1 is identified as optimal processing parameters in minimizing the tooth thickness shrinkage of the moulded PP gear. The parameters setting are melting temperature of 220 ºC, mould temperature of 60 ºC, injection pressure of 100 bar, injection time of 2s, packing pressure of 90 %, packing time of 10s and cooling time of 50s.

3.3 Analysis of Variance (ANOVA)

To examine the extent to which processing parameters affects the shrinkage in addendum and dedendum circle as well as in tooth thickness of the moulded PP gear, ANOVA of the Taguchi method for the S/N ratios (Table 3) is performed. ANOVA enables engineers to quantitatively estimate the relative contribution of each processing parameter to the overall measured quality characteristics. Table 4
presents a summary of percentage contribution, denoted as “P” of all seven parameters on shrinkage in addendum and dedendum circle as well as in tooth thickness of the moulded PP gear. Roy [8] suggested of using the 10% rule, where, a parameter is considered insignificant when its influence is less than 10% of the highest parameter influence.

![Table 4: ANOVA of percentage contribution](image)

| Parameters          | Addendum circle | Dedendum circle | Tooth thickness |
|---------------------|-----------------|-----------------|-----------------|
| Melting temperature °C | 9.960           | 3.440           | 69.549          |
| Mould temperature °C  | 19.612          | 1.985           | 9.941           |
| Injection pressure (bar) | 2.293          | 70.533          | 0.385           |
| Injection time (s)    | 16.002          | 7.238           | 0.434           |
| Packing pressure (%)   | 12.202          | 1.230           | 9.639           |
| Packing time (s)       | 6.503           | 3.050           | 4.675           |
| Cooling time (s)       | 10.029          | 6.628           | 2.495           |

From the results of percentage contribution (P) in Table 4, the mould temperature appears to be the most decisive processing parameter in reducing the shrinkage in addendum circle of the moulded PP gear. The percentage contribution of the mould temperature is 19.612%, outweighing the other processing parameters followed by injection time, packing pressure, cooling time, melting temperature, packing time and injection pressure for the case of addendum circle. For dedendum circle, only two out of seven processing parameters, namely injection pressure and injection time, are considered to be significant, following the 10% rule. Meanwhile for tooth thickness, the most decisive processing parameter in reducing the shrinkage is found to be melting temperature with the percentage of contribution (P) of 69.549%. By using 10% rule, the second significant parameter is mould temperature followed by packing pressure.

4. Conclusion
In this study, the influence of processing parameters on shrinkage in addendum and dedendum circle as well as in tooth thickness of PP injection moulded gears was investigated by using Taguchi approach. The findings from the analysis of the results, obviously showed that the variation in parameters setting have significant impact in minimizing the shrinkage in addendum and dedendum circle as well as in tooth thickness of the moulded PP gear. The set of optimal processing parameters that predicted in minimizing the shrinkage in addendum circle is identified as melting temperature of 220 °C, mould temperature of 40 °C, injection pressure 100 bar, injection time 3 s, packing pressure of 70%, packing time of 10s and cooling time of 70s. For the shrinkage in dedendum circle, the set of optimal processing parameters is predicted to be melting temperature of 240 °C, mould temperature of 40 °C, injection pressure 100 bar, injection time 3 s, packing pressure of 90%, packing time of 5s and cooling time of 70s. As for tooth thickness, the set of optimal processing parameters that predicted in minimizing the shrinkage is identified as melting temperature of 220 °C, mould temperature of 60 °C, injection pressure 100 bar, injection time 2 s, packing pressure of 90%, packing time of 10s and cooling time of 50s.

References
[1] Singh PK, Akant Kumar Singh S 2018 Trib. Int. 118 264.
[2] Senthilvelan S, Gnanamoorthy R 2007 Mat. and Desig. 28 765–772
[3] Hirogaki T, Aoyama E, Katayama T, Iwasaki S, Yagura Y, Sugimura K 2004 Comp. Struct. 66 47.
[4] Kurokawa M, Uchiyama Y, Iwai, T, Nagai S 2003 Wear 254 468.
[5] Düzciikoğlu H 2009 Mat. and Desig 30 1060.
[6] İmrek H 2009 Trib. Int. 42 503.
[7] Fei NG, Mehat NM, Kamaruddin S 2013 ISRN Ind. Eng. 2013 462174
[8] Roy RK 2001 Design of experiment using the Taguchi approach: 16 steps to product and process improvement, John Wiley and Sons, New York.