Investigation on the effects of processing parameters on shrinkage behaviour and tensile properties of injection moulded plastic gear via the Taguchi method

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Abstract. Controlling numerous processing parameters and sustaining the optimal performance of multiple quality characteristics give a great challenge to manufacturer to produce a high-quality product with low operating cost. It was quite tricky to find the optimal combination parameters if used unsystematic techniques such as trial and error method. In this study, the Taguchi method was adopted to identify the significant processing parameters affected the shrinkage and tensile properties of plastic gears. The effectiveness of Taguchi’s OA in reducing the number of experiment was studied and the results were analysed by ANOVA. Through the analysis, six parameters; melting temperature, mould temperature, packing pressure, packing time, cooling time and injection pressure, were carried out as significant parameters that influence dimensional stability and mechanical properties of plastic moulded gear. The findings showed that the Taguchi method is a systematic and straightforward approach that can be used in obtaining the significant processing parameters particularly in plastic gear manufacturing.

1. Introduction
Plastic gears can be manufactured by either machining or injection moulding. The machining of plastic gears involves most of the same processes used in the machining of metal gears, such as milling or hobbing. Injection moulding, on the other hand, is the most common, yet important process used to manufacture plastic gear. More than one third of all thermoplastic materials are injection moulded. With the advancement of plastic injection moulding, it is becoming increasingly more challenging for today’s plastic production industry to manufacture precision gearing components within tight tolerance limits. Injection moulding can be used to mass produce an ample range of plastic parts with multifarious and intricate geometries [1-2]. In addition, final products that exhibit good dimensional accuracy, excellent surface finish at a high rate of production, with reduced cost and within a shorter time period, has further proven the value of the injection moulding process [3-4].

Despite the numerous advantages, there are some drawbacks associated with plastic injection moulding. Due to the intricacy of the injection moulding process, keeping the final product quality...
under control requires an intense effort. The quality characteristics of the injection moulded products can be characterized in terms of dimensional stability, aesthetical features, such as weld lines and sink marks, and mechanical properties [5]. As with plastic gears, the practicability of injection moulding in producing low cost plastic moulded gears still restricted by the occurrence of shrinkage in the final steps of the process. Severe shrinkage can lead to deflection or warpage in the moulded part, as well as negatively influence the dimensional stability and accuracy of the involute profile, the concentricity, the roundness, the tooth spacing uniformity, and the size of the gear. Thus, it can have a great impact on the quality of the final moulded gear, due to noise and vibration. It also shortens the gear’s service life due to different damage mechanism, such as tooth fatigue, creep, excessive wear, and plastic deformation [6].

Manufacturing an accurate plastic gear via the injection moulding process is more complicated than machining a similar gear, due to the interaction of many factors including material consideration, part and mould design, as well as variation in injection moulding processing parameters. With plastic materials exhibiting extremely convoluted properties, an intricacy of the moulding process, attaining the desired quality and accurate dimension of final moulded plastic gear is a very challenging task. Improper setting of processing parameters during the manufacturing process may lead to the degradation of dimensional accuracy, the shape of the final parts, the surface finish, and mechanical properties [7-8]. Therefore, in this work, the Taguchi method was adopted to evaluate the effects of injection moulding processing parameters on the quality of plastic gear produced in related with shrinkage behaviour and tensile properties. The findings will be contributed to an attempt in improving the quality of plastic injection moulded gear in particular from the manufacturing point of view, therefore the conventional trial and error method which would incurred high production cost and long set up times can be avoided.

2. Methodology

2.1. Material

In this study, High Density Polyethylene (HDPE) was used as raw material for injection moulding process. The HDPE HD5218AA grade was supplied by Etilinas Polyethylene Malaysia Sdn. Bhd. The general properties of virgin HDPE are listed in Table 1. Before running the experiment, all materials were dried in furnace at 80°C for 3 hours to remove moisture.

| Properties                      | Values |
|---------------------------------|--------|
| Density (g/cm³)                 | 0.95   |
| Melt Flow Rate (190°C / 2.16kg) (g/10min) | 4.0   |
| Tensile Strength at break (N/mm²) | 26     |
| Ultimate Elongation (%)         | 10     |
| Izod Impact Strength at 23°C (kJ/m²) | 20     |

2.2. Gear description

The spur gear based on American Gears Manufacturers Association (AGMA) standard was used as a main product in this study. The detail specifications and geometry of spur gear are illustrated in Figure 1. The spur gear was designed with outer addendum diameter of 33mm, dedendum diameter of 27 mm, core diameter and thickness of gear are 10mm respectively. Additionally, the moulded gear has 20 teeth with 20° pressure angle for each.
2.3. Design of experiment by Taguchi method
The objective of this study to identify the most significant processing parameter of injection moulding that influences the quality characteristic of moulded gear. Numerous processing parameters could affect the quality of moulded gear and the experiment runs will involve a large number of trials. Therefore, it is very difficult and requires a huge effort to obtain the optimal processing parameters setting. The procedures of designing the experiments by the Taguchi method are illustrated in Figure 2 and each stage is elaborated in the following section.

2.3.1. Determining the Quality of Characteristics
The dimensional stability and mechanical properties are the most important features need to be focused for good quality of plastic gear. The shrinkage of plastic material will lead some defect on the dimensional accuracy of gear especially on tooth spacing uniformity and concentricity of roundness shape (Mehat et al., 2013). Senthivelan and Gnamoorthy (2008) have claimed in their study that shrinkage defect on injection moulded gear significantly influences the imperfection of geometric. Regarding to mechanical properties, the optimum performance of plastic material is required as characteristics of plastic gear for better power transmission to sustain high load capacity. Comprehending this fact, the quality measurement in this study is done in term of shrinkage and mechanical properties of the plastic gear.

2.3.2. Selection of Processing Parameters
In this study, seven processing parameters are selected to be analyzed as the influencing factor toward dimensional stability and mechanical properties for optimization study. The parameters involved are melting temperature, mould temperature, packing pressure, packing time, cooling time, injection pressure and injection time. Three levels of parameter were considered for better interpretation of nonlinear effect and the details was tabulated in Table 2.

| Table 2. Processing Parameter and Levels |
|-------------------------------|--------------|-------|-------|-------|
| Label | Parameters       | Unit | Level 1 | Level 2 | Level 3 |
| A     | Melt Temperature | °C   | 170    | 190    | 210    |
| B     | Mould Temperature| °C   | 40     | 50     | 60     |
| C     | Packing Pressure | %    | 60     | 80     | 100    |
| D     | Packing Time     | second | 5     | 10     | 15     |
| E     | Cooling Time     | second | 30    | 40     | 50     |
| F     | Injection Pressure| Bar | 80    | 90     | 100    |
| G     | Injection Time   | second | 1     | 2      | 3      |
2.3.3. **Selection of Orthogonal Array (OA)**
According to Taguchi rules, the selection of suitable OA is depending on total number degree of freedom (DOF) of processing parameters and levels. In this study, seven processing parameters with three levels indicates 14 DOF where 2 DOF for each parameter. DOF is obtained by number of levels minus with one (DOF = number of levels -1). As requirement in Taguchi, the selection of OA should be equal or greater than the total number of DOF for ideal parameter setting. Hence $L_{18}$ OA is selected as a layout experiment since it has lowest array with 17 DOF that can placed all the seven processing parameters. The all seven parameters are assigned according to specific columns; melt temperature (A), mould temperature (B), packing pressure (C), packing time (D), cooling time (E), injection pressure (F) and injection time (G) as tabulated in Table 2.

2.4 **Quality Testing**
The experiment was conducted by following the combination of parameter setting that is provided in OA. All 18 trials needed to be run to accomplish the experiment in producing moulded gear by using Battenfeld TM750/210 injection moulding machine. The quality measurements of moulded gear are evaluated according to the following:

**2.4.1 Shrinkage Test**
The shrinkage test of moulded plastic gear has been measured by following a standard procedure of ASTM D955-08. Before the measurement process, all sample of plastic gear is kept at ambient temperature for 24 hours. In this study, the dimension of plastic gear was measured by projector.
profile RAX Vision DC 3000 Mitutoyo. The specimen was magnified by projector profile into 2D axis and the coordinates was pointed on 20 edge of tooth gear along addendum and dedendum circles. Otherwise, the tooth thickness gear was measured by micrometer. A larger magnification display and micrometer provided a high accuracy measurement. Probability error during measuring the geometry of specimen can be reduced. However, as precaution of human error, five samples for each trial were measured. The relative shrinkage of spur gear was calculated based on following equation:

\[ S = \frac{D - D_m}{D_m} \times 100\% \]  

(1)

Where: \( S \) = shrinkage, \( D \) = measurement using profile projector, \( D_m \) = mould dimension,

2.4.2 Tensile Test

The tensile test for circular object has some limitations in term of hold specimen method in symmetry condition. Due to this limitation, split disc fixture was designed and utilized for plastic gear specimen as shown in Figure 3. Based on ASTM D638-10, tensile test was performed by using Instron 3367 series table-mounted universal testing machine with 3mm/min of cross head speed under 50kN tensile load. To ensure the consistency of result, five specimens were tested for each trial.

Table 3. Taguchi's Orthogonal Array L_{18}

| Experiment | Factor |
|------------|--------|
|            | A      | B      | C      | D      | E      | F      | G      | -      |
| 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      | 2      | 2      | 3      | 3      | 3      |
| 5          | 1      | 2      | 2      | 2      | 3      | 3      | 3      | 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      | 2      |
| 9          | 1      | 3      | 3      | 1      | 3      | 2      | 2      | 1      |
| 10         | 2      | 1      | 1      | 3      | 3      | 2      | 2      | 2      |
| 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      | 3      | 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      |
3. Results and Discussion

3.1. S/N Ratio
In examining the results of shrinkage behaviour and tensile properties for the plastic gears produced, the Taguchi method proposed the utilization of the S/N ratio to decide the nature of the attributes employed. As discussed by Ozcelik et al. [8], the signal to noise (S/N) ratio is a measure of achievement targeted at developing products and processes insensitive to noise factors. A high signal to noise (S/N) ratio suggests that the signal is much higher than the arbitrary impact of the commotion factors. The process or part operation persistent with the higher signal to noise (S/N) ratio at all times yields optimal quality attributes with least variance. In the Taguchi method, the quality attributes can be assigned into the smaller the better, the nominal the better and the bigger the better. In this study, the smaller value of the shrinkage behaviour and the larger value for tensile properties are expected. The S/N ratio is computed from the mean square deviation equation as in Equation 2. The results of S/N ratios for both shrinkage behaviour and tensile properties are listed in Table 3.

\[
S/N = -10 \log(MSD)
\]

MSD = mean-square deviation from the target values of response.

3.2. Analysis of variance (ANOVA)
The aim of ANOVA application for this study is to identify the most influential parameters on dimensional stability and mechanical properties of HDPE plastic moulded gear. The ANOVA was performed individually on S/N ratios for each quality characteristic response in order to obtain the relative contribution of each processing parameter. The results of each quality characteristics of the HDPE gear produced are presented in Table 4. For shrinkage in addendum of the HDPE gear produced, injection pressure and cooling time was found as significance factor with percentage contribution 31.89% and 30.69% respectively. Subsequently packing time contributes 13.41%, followed by mould temperature 6.42% and melting temperature 5.62%. The other factors, packing pressure and injection time have small relative percentage of contribution in the shrinkage defect at addendum area.
Table 4. S/N Ratios of Experiment Results

| Trial | Addendum (dB) | Dedendum (dB) | Tooth Thickness (dB) | Modulus Young (dB) | Elongation at Max Load (dB) | Ultimate Strength (dB) |
|-------|---------------|---------------|----------------------|-------------------|-----------------------------|------------------------|
| 1     | 38.2944       | 36.7860       | 29.3726              | 26.8451           | 13.0695                     | 11.9234                |
| 2     | 43.7864       | 40.1624       | 30.6331              | 27.9088           | 9.4182                      | 10.7399                |
| 3     | 44.2118       | 42.1088       | 28.9331              | 27.4025           | 11.2166                     | 11.5466                |
| 4     | 52.8113       | 45.5206       | 29.8294              | 26.9618           | 12.9056                     | 11.9979                |
| 5     | 39.1721       | 37.0065       | 29.6370              | 27.5420           | 10.2981                     | 11.3933                |
| 6     | 47.6995       | 43.7616       | 30.3536              | 27.0902           | 10.9291                     | 11.4868                |
| 7     | 46.9182       | 41.9745       | 29.7179              | 26.7289           | 12.9262                     | 11.6653                |
| 8     | 40.9239       | 44.7115       | 31.5078              | 26.6409           | 13.3553                     | 11.7398                |
| 9     | 39.9659       | 37.8332       | 29.5171              | 26.5851           | 13.2602                     | 11.6972                |

Table 5. Percent contribution of shrinkage and tensile properties

| Parameters           | Percent Contribution | Percent Contribution |
|----------------------|----------------------|----------------------|
|                      | Addendum             | Dedendum             | Tooth Thickness | Modulus Young | Elongation at Max Load | Ultimate Strength |
| Melt Temperature     | 5.62                 | 1.71                 | 36.84           | 32.31         | 37.69                     | 22.95             |
| Mould Temperature    | 6.42                 | 13.42                | 9.40            | 6.02          | 33.69                     | 37.38             |
| Packing Pressure     | 2.87                 | 44.57                | 8.23            | 9.15          | 3.27                      | 2.19              |
| Packing Time         | 13.41                | 10.20                | 5.14            | 5.82          | 3.84                      | 3.17              |
| Cooling Time         | 30.69                | 3.54                 | 13.98           | 37.44         | 15.99                     | 13.52             |
| Injection Pressure   | 31.89                | 14.21                | 14.66           | 6.91          | 4.22                      | 12.82             |
| Injection Time       | 3.08                 | 6.52                 | 7.12            | 0.58          | 0.68                      | 6.07              |
| Error                | 6.02                 | 5.82                 | 4.63            | 1.77          | 0.62                      | 1.91              |

For the case of dedendum area, packing pressure is found as the most significant factor with percentage contribution of 44.57%. The remaining factors that insignificant to the dedendum shrinkage are identified as injection pressure, mould temperature, packing time by contributes 14.21%, 13.42% and 10.20% respectively. The result tabulated in Table 4 also indicated that the melting temperature is the most influencing factor for tooth thickness shrinkage with 36.84% of percentage contribution. Additionally, injection pressure and cooling time tend to be significance factors by contributing 14.66% and 13.98% correspondingly. Other factors contribute less than 10% was obtained; i.e. mould temperature with 9.40%, packing pressure with 8.23%, injection time 7.12% and lastly packing time contribute 5.14%.

On the other hand, for the case of tensile properties, the results showed that the mould temperature is the most influence factor by contribute 37.38% for ultimate strength, followed by melting temperature, cooling time and injection pressure with percentage of contribution of 22.95%, 13.52% and 12.82% respectively. The other factors; injection time, packing time and packing pressure are considered insignificant factors and they were less influence on ultimate strength of HDPE.
moulded gear. For Young's Modulus, the ANOVA analysis revealed that four parameters significantly affected the performance of modulus elasticity HDPE moulded gear. Cooling time is the most influential factor by a contribution of 37.44%, subsequently melting temperature with 32.31% followed by packing pressure with 9.15% and injection pressure 6.91%. The parameters; injection time, packing time and packing pressure are indicated as insignificant factors with percentage contribution 6.07%, 3.17% and 2.19%, correspondingly. For the case of elongation at maximum load, melting temperature shows the highest percentage contribution of 37.69%, followed by mould temperature, cooling time, injection pressure, packing time and lastly packing pressure with percentage contribution of 33.69%, 15.99%, 4.22%, 3.84% and 3.27% respectively. Parameter injection time has displayed less influence on elongation properties by contributing only 0.68%.

The results of significant parameters obtained from the ANOVA is summarized in Table 5. The injection time is found to be an insignificant factor and do not have strong influence toward any of six responses quality characteristics of HDPE moulded gear. Moreover, six parameters were considered as significant parameters which are melting temperature, mould temperature, packing pressure, packing time, cooling time and injection pressure.

### Table 6: Result of Significant Parameters

| Factor            | Addendum Shrinkage | Dedendum Shrinkage | Tooth Thickness Shrinkage | Ultimate Strength | Modulus Young | Elongation At Max Load |
|-------------------|--------------------|--------------------|---------------------------|-------------------|---------------|-----------------------|
| A. Melt Temperature | -                  | -                  | Yes                       | Yes               | Yes           | Yes                   |
| B. Mould Temperature | -                  | -                  | -                         | -                 | -             | Yes                   |
| C. Packing Pressure | -                  | Yes                | -                         | -                 | Yes           | Yes                   |
| D. Packing Time    | -                  | -                  | -                         | -                 | -             | Yes                   |
| E. Cooling Time    | Yes                | -                  | -                         | Yes               | Yes           | Yes                   |
| F. Injection Pressure | Yes               | -                  | -                         | Yes               | Yes           | Yes                   |
| G. Injection Time  | -                  | -                  | -                         | -                 | -             | -                     |

### 4. Conclusion

According to the analysis in the experiment, the Taguchi method has been utilized effectively in identifying the significant parameters for each single response of quality characteristic of HDPE moulded gear. Additionally, Taguchi method has provided a fast and credible method in designing of experiment set up. The credibility of Taguchi method was hindered in solving multi-response issues. Nevertheless, the limitation of Taguchi was overcome by the integration with other methods.

### 5. References

[1] Shen C, Wang L, Cao W and Qian L 2007 Polymer-Plastics Technology and Engineering 46 219.

[2] López A, Aisa J, Martinez A and Mercado D 2016 Measurement 90 349

[3] Dawoud M, Taha I and Ebeid, S J 2016 Journal of Manufacturing Processes 21 39.

[4] Guo W, Mao H, Li B and Guo X 2014 Procedia Engineering 81 670.

[5] Yang Y, Yang B, Zhu S and Chen X Journal of Materials Processing Technology 226 85.

[6] Mao K, Li W, Hooke C J and Walton D 2010 Tribology International 43 433.

[7] Mathurosemontri S, Uawongsuwan P, Nagai S and Hamada H 2016 Energy Procedia 89 255.

[8] Huszar M, Belblidia F, Davies H M, Arnold C, Bould D and Sienz J 2015 Sustainable Materials and Technologies 5 1.