Optimization of Recycled Glass Fibre-Reinforced Plastics Gear via Integration of the Taguchi Method and Grey Relational Analysis

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Abstract. The increase in demand for industrial gears has resulted in the increase in usage of plastic-matrix composites particularly glass fibre-reinforced plastics as the gear materials. The usage of these synthetic fibers is to enhance the mechanical strength and the thermal resistance of the plastic gears. Nevertheless, the production of large quantities of these synthetic fibre-reinforced composites poses a serious threat to the ecosystem. Comprehending to this fact, the present work aimed at investigating the effects of incorporating recycled glass fibre-reinforced plastics in various compositions particularly on dimensional stability and mechanical properties of gear produced with diverse injection moulding processing parameters setting. The integration of Grey relational analysis (GRA) and Taguchi method was adopted to evaluate the influence of recycled glass fibre-reinforced plastics and variation in processing parameters on gear quality. From the experimental results, the blending ratio was found as the most influential parameter of 56.0% contribution in both improving tensile properties as well as in minimizing shrinkage, followed by mould temperature of 24.1% contribution and cooling time of 10.6% contribution. The results obtained from the aforementioned work are expected to contribute to accessing the feasibility of using recycled glass fibre-reinforced plastics especially for gear application.

1. Introduction
To date, with advances in the development of plastic materials with wide spectrum of fiscal and practical properties available, plastics have become one of the most sought-after materials in the world particularly in the plastic gear industry. Plastic moulded gears offer some unique properties that are
not achievable with metal based gears. The advantages include light weight, lower noise, higher modulus, self-lubrication, chemical resistance and, the most appealing of all, low cost. Because of their ability to run without lubrication and resist corrosion, plastic gears have been widely used in the automotive, food and textile industries, office machinery and household utensils as well as a host of other applications [1-3].

As mentioned the increase in demand for industrial gears has resulted in the increase in usage of plastic-matrix composites particularly glass fibre-reinforced plastics as the gear materials. This is to enhance the mechanical strength and the thermal resistance of the plastic gears. Nevertheless, the production of large quantities of these synthetic fibre-reinforced composites poses a serious threat to the ecosystem. These materials have become a major treat due to their non-biodegradability in the waste stream. Glass fibre filled plastic wastes can take decades and probably centuries to decompose. In Malaysia specifically, no viable recycling process appears to exist for these materials except being discarded to landfill and incineration. However, the limitation of landfill capacity and non-biodegradable properties of plastic makes the landfill method inevitable since the plastic waste consumes a large space and a lot of time to decompose in landfill sites. On the other hand, incineration of plastic emits hazardous gasses during disposal of plastic waste which affects the environment and human health. Comprehending to these limitations of landfill and incineration, recycling or reusing plastic waste as a single resin or in combination with other plastics were being developed and considered as a necessity [4-6].

However, plastic recycling is hindered by a wide range of barriers including mistrust of the quality of the recycled plastics as well as restrictions imposed by standards and specifications. Most plastic manufacturers and consumers were reluctant to use recycled plastics because of the perception that recycled plastics are inferior to the virgin resin and more difficult to handle [7]. Apart from that, improvements of mechanical and material properties of the recycled plastic products are still possible. From manufacturing perspective, optimization of injection moulding parameters is well known in improving the quality of the final product. Optimization of injection moulding process is an appealing approach in improving the quality of the recycled plastic products. Injection moulding process is the most commonly used method in plastic processing industry [8-9]. Although injection moulding is one of the most widely used processes in plastic manufacturing, the quality of the products is easily affected by different injection moulding conditions. Material selection, part and mould design, and processing parameters play important roles in determining the quality of the final product [10-11]. In industrial practice, part and mould design are commonly assumed as fixed because any modification and alteration of part and mould design may lead to high production cost. Hence, processing parameters can be manipulated in order to improve the quality of the recycled product to a satisfactory level.

Comprehending to the facts stated, the proposed research is aimed at investigating the effects of incorporating recycled glass fibre-reinforced plastics in various compositions on dimensional stability and mechanical properties of gear produced with diverse injection moulding processing parameters setting. The integration of Grey relational analysis (GRA) and Taguchi method will be adopted to evaluate the influence of recycled glass fibre-reinforced plastics and variation in processing parameters on gear quality. The results obtained from the aforementioned work are expected to contribute to accessing the feasibility of using recycled glass fibre-reinforced plastics especially for gear application.

2. Methodology
In this study, polyamide 66 (PA66) filled with 33% glass fibre material was specified as the gear material to be studied, under the grade name of VITAMIDE AR17 supplied by Perrite. The general properties of the virgin PA66-GF were shown in Table 1. The recycled PA66-GF pellets were prepared with the same grade as the virgin material by crushing the existed products and post industrial wastes using a granulator. A spur gear design accordance with American Gears
Manufacturers Association (AGMA) was used. The details of geometry and specification of the gear were shown in Figure 1.

![Figure 1](image)

**Figure 1.** Geometry and specification of spur gear with module = 15; pressure angle = 20°; number of teeth = 20; face width = 10mm

### Table 1: General Properties of PA66-GF AR17

| Properties                  | Value  |
|-----------------------------|--------|
| Tensile strength (Mpa)      | 195    |
| Strain at break (%)         | 3.5    |
| Melting temperature (°C)    | 260    |
| Density (kg/m³)             | 1400   |
| Flexural modulus (Mpa)      | 10000  |

### 2.2 Implementation of Taguchi method / GRA optimization procedures

#### 2.2.1 Determination of quality characteristics

Regarding to the competitive and dynamics market of plastic gear in power and motion transmission application, simultaneous optimization of several quality characteristics is a major concern to quality engineer. There was numerous quality characteristics of injection moulded products such as warpage, shrinkage, sink index, weld line, shear stress, fibre orientation, etc. However, considering the functionality of the plastic gear, shrinkage and tensile properties were chosen as the quality characteristics to be studied in this research.

#### 2.2.2 Selection of control parameters

There were four processing parameters including mould temperature, melting temperature, cooling time and injection time were selected for optimization with the aim of minimizing the shrinkage behaviour in tooth thickness, addendum as well as dedendum circles and enhancing the tensile ultimate strength, Young’s modulus and elongation at break of the gears produced. In this study, the recycled blending compositions at various ratios was also considered as control parameters. The ratios were varied from 0, 5, 10, 15, 20, 25, 30, 35 to 40% by weight of recycled and virgin PA66-GF. Table 2 shows the control parameters that have been selected in this work.
Table 2. Controlled factors and their levels

| Factors                      | Levels |
|------------------------------|--------|
|                              | 1 2 3 4 5 6 7 8 9 |
| A-Blending ratio (%)         | 0 5 10 15 20 25 30 35 40 |
| B-mould temperature (°C)    | 50 60 70 |
| C-melting temperature (°C)  | 280 290 300 |
| D-cooling time (s)           | 10 20 30 |
| E-injection time (s)         | 0.6 0.8 1.0 |

2.2.3 Selection of Taguchi’s orthogonal array (OA)
Selection of an appropriate OA was based on the total degree of freedom (DOF) of the overall processing parameters. It was decided to study the interaction between the processing parameters because the processing parameters were dependent to each other in affecting the quality of a product. Hence, it was important to study the interaction among the processing parameters. In this study also, a mixed levels orthogonal array was decided to use since there was a nine levels parameter being considered in designing the experiment. Considering a nine levels parameter has eight DOF (DOF = number of levels – 1), four processing parameters each at three levels parameter has two DOF was equal to eight DOF and two interactions of three levels parameters contributes eight DOF (DOF interaction = DOF factor X DOF factor). Therefore, the total DOF required is 24 DOF. As discussed previously in screening experiment, the total DOF of selected OA must be greater than or equal to the total DOF required for the experiment. Hence, an L27 OA having 26 DOF was chosen for this study because it is the lowest order array that can accommodate all the parameters (Table 3)

Table 3. L27 array with interactions

| FACTORS | B | CXD | CXE | C | D | E | CXD | CXD |
|---------|---|-----|-----|---|---|---|-----|-----|
| TRIAL NO. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1       | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2       | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 |
| 3       | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 |
| 4       | 1 | 2 | 2 | 2 | 1 | 1 | 2 | 2 |
| 5       | 1 | 2 | 2 | 2 | 2 | 2 | 3 | 3 |
| 6       | 1 | 2 | 2 | 2 | 3 | 3 | 3 | 3 |
| 7       | 1 | 3 | 3 | 3 | 1 | 1 | 1 | 2 |
| 8       | 1 | 3 | 3 | 3 | 3 | 3 | 2 | 2 |
| 9       | 1 | 3 | 3 | 3 | 3 | 3 | 2 | 2 |
| 10      | 2 | 1 | 2 | 2 | 1 | 1 | 3 | 3 |
| 11      | 2 | 1 | 2 | 2 | 3 | 3 | 3 | 3 |
| 12      | 2 | 1 | 2 | 2 | 3 | 3 | 3 | 3 |
| 13      | 2 | 2 | 3 | 3 | 1 | 2 | 2 | 2 |
| 14      | 2 | 2 | 3 | 3 | 1 | 2 | 2 | 2 |
| 15      | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 |
| 16      | 2 | 3 | 1 | 1 | 2 | 3 | 3 | 3 |
| 17      | 2 | 3 | 1 | 1 | 3 | 3 | 3 | 3 |
| 18      | 2 | 3 | 1 | 1 | 4 | 4 | 4 | 4 |
| 19      | 3 | 1 | 3 | 2 | 1 | 2 | 3 | 3 |
| 20      | 3 | 1 | 3 | 2 | 2 | 2 | 2 | 2 |
| 21      | 3 | 1 | 3 | 2 | 3 | 3 | 3 | 3 |
| 22      | 3 | 2 | 1 | 1 | 3 | 2 | 1 | 2 |
| 23      | 3 | 2 | 1 | 1 | 3 | 2 | 1 | 2 |
| 24      | 3 | 2 | 1 | 1 | 3 | 2 | 1 | 2 |
| 25      | 3 | 3 | 2 | 1 | 1 | 3 | 2 | 1 |
| 26      | 3 | 3 | 2 | 1 | 1 | 3 | 2 | 1 |
| 27      | 3 | 3 | 2 | 1 | 1 | 3 | 2 | 1 |
3. Analysis and experimental results

After obtaining all the experimental results for shrinkage behaviour and tensile properties of all 27 trials as shown in Table 3, the analysis of the results was performed by computing the S/N ratio followed by data normalization of S/N results using GRA. Then, ANOVA was performed to determine the significance of each controlled parameters and interaction among the processing parameters. The procedures were described in details as follows:

3.1 Signal to noise (S/N) ratio

S/N ratio to measure the sensitivity of the quality characteristic being investigated in a controlled manner. Whenever an experiment involves with repeated specimens at each of the trial runs, the S/N ratio has been found to provide a practical way to measure and control the combined influence of deviation of the population mean from the target and the variation around the mean.

For shrinkage, the calculation of the smaller-the-better was selected meanwhile the higher-the-better was used to characterize the tensile properties. The results of shrinkage and tensile properties were converted into S/N ratio as shown in Table 4.

3.2 Data normalization using GRA

GRA is an effective way of analysing the relationship between data and can analyse many factors with complicated interrelationships among multiple performance characteristics which can overcome the disadvantages of statistical method. The computation of GRA was performed as follows:

| Trial No. | Shrinkage | Tensile |
|-----------|-----------|---------|
|           | Adherence | Dent depth | Teeth thickness | Maximum load | Young's modulus | Elongation at break |
| 1         | -2.419    | -7.9224 | 7.6147         | 70.1257 | 39.6288 | -1.6901 |
| 2         | -2.7674   | -9.5645 | 7.3802         | 68.7184 | 38.4801 | -2.1219 |
| 3         | -4.1644   | -6.1677 | 5.3718         | 70.0588 | 50.0047 | -1.8007 |
| 4         | -6.3910   | -8.4102 | 8.1417         | 69.0984 | 38.8287 | -2.1229 |
| 5         | -6.7312   | -8.9843 | 13.9848        | 68.1697 | 36.8226 | -1.9561 |
| 6         | -7.0381   | -9.5586 | 16.2875        | 67.5360 | 32.8095 | -2.5663 |
| 7         | -7.1334   | -6.7882 | 10.8136        | 68.5215 | 35.9218 | -2.3713 |
| 8         | -6.9165   | -9.0113 | 10.8156        | 69.4531 | 35.7428 | -1.5151 |
| 9         | -6.8158   | -8.5484 | 8.4620         | 68.4994 | 36.6669 | -1.8971 |
| 10        | -7.3199   | -9.6722 | 10.8437        | 68.1357 | 36.5493 | -2.8889 |
| 11        | -6.6862   | -9.0099 | 8.9883         | 69.5218 | 38.9524 | -2.2047 |
| 12        | -7.4114   | -9.9348 | 9.5783         | 68.1664 | 38.7415 | -1.9424 |
| 13        | -8.2067   | -8.3189 | 8.6764         | 67.5651 | 39.1274 | -3.2488 |
| 14        | -6.0399   | -8.5508 | 9.4606         | 69.2850 | 38.4389 | -4.1021 |
| 15        | -6.3800   | -8.1236 | 9.5200         | 67.0021 | 37.6109 | -1.9470 |
| 16        | -7.2318   | -8.8771 | 10.6718        | 68.3456 | 39.8158 | -2.2112 |
| 17        | -7.7039   | -9.7271 | 12.5900        | 68.6876 | 39.5734 | -2.7174 |
| 18        | -8.2942   | -8.2288 | 14.0472        | 67.7721 | 39.0182 | -2.7212 |
| 19        | -7.1774   | -9.0409 | 11.7388        | 68.4680 | 39.3888 | -2.7187 |
| 20        | -6.2099   | -8.4229 | 10.4117        | 67.7224 | 39.0779 | -2.1629 |
| 21        | -6.4530   | -8.0419 | 9.9997         | 68.4537 | 38.4576 | -2.1761 |
| 22        | -7.1872   | -8.7389 | 11.0820        | 68.8022 | 39.9728 | -2.9001 |
| 23        | -8.8302   | -8.5466 | 12.1836        | 68.4736 | 39.4133 | -2.6727 |
| 24        | -6.4851   | -8.2117 | 11.9438        | 68.5170 | 36.9667 | -2.2354 |
| 25        | -6.5045   | -8.1774 | 8.7673         | 67.0709 | 39.2703 | -2.8647 |
| 26        | -7.1896   | -8.6867 | 5.1474         | 68.5102 | 36.3647 | -2.5166 |
| 27        | -7.6210   | -8.5342 | 8.2098         | 67.9104 | 38.1629 | -2.2471 |

Step 1: Data pre-processing

Data pre-processing is a process of transforming the original data or also referred as an original sequence to a comparable sequence. This pre-process step also called as 'grey relational generation'. For this purpose, the shrinkage and tensile properties were normalized in the range between zero and one due to the different measurement units and scales of the raw data. The normalization can be done from three different approaches depending on desired quality characteristic.
Lower the better

\[ y^*_i(k) = \frac{\max y^0_i(k) - y^*_i(k)}{\max y^0_i(k) - \min y^*_i(k)} \]  

(1)

Higher the better

\[ y^*_i(k) = \frac{y^0_i(k) - \min y^*_i(k)}{\max y^0_i(k) - \min y^*_i(k)} \]  

(2)

Nominal the better

\[ y^*_i(k) = 1 - \frac{|y^0_i(k) - y^*_i(k)|}{\max y^0_i(k) - \min y^*_i(k)} \]  

(3)

where \( y^*_i(k) \) is the value after the grey relational generation (data pre-processing), \( \max y^0_i(k) \) is the largest value of the original sequence, \( \min y^0_i(k) \) is the smallest value of the original sequence \( y^0_i(k) \) and \( y^*_i(k) \) is the desired value. Similar to S/N ratio characterization, the data pre-processing of shrinkage was done based on the smaller the better meanwhile the higher the better was used to characterize the tensile properties.

The data pre-processing for the 27 trials were tabulated in Table 5.

**Table 5. Data pre-processing of 27 trials**

| Trial No. | Data pre-processing | Shrinkage | Tensile |
|-----------|---------------------|-----------|---------|
|           |                     | Adhesion  | Strength |
| 1         | 0.2801              | 0.4016    | 0.7895  |
| 2         | 0.3267              | 0.4234    | 0.7777  |
| 3         | 0.4500              | 0.5000    | 1.0000  |
| 4         | 0.6311              | 0.6311    | 0.6311  |
| 5         | 0.6895              | 0.7141    | 0.7141  |
| 6         | 0.7900              | 0.7890    | 0.7890  |
| 7         | 0.2109              | 0.4209    | 0.7209  |
| 8         | 0.2709              | 0.5090    | 0.6809  |
| 9         | 0.2503              | 0.2268    | 0.7268  |
| 10        | 0.9001              | 1.0000    | 0.6000  |
| 11        | 0.7601              | 0.1890    | 0.8600  |
| 12        | 0.6524              | 0.5594    | 0.8887  |
| 13        | 0.5794              | 0.5994    | 0.8502  |
| 14        | 0.6914              | 0.6914    | 0.8228  |
| 15        | 0.6716              | 0.7457    | 0.8547  |
| 16        | 0.6150              | 0.6240    | 0.7162  |
| 17        | 0.6504              | 0.5880    | 0.7580  |
| 18        | 0.6010              | 0.5335    | 0.7345  |
| 19        | 0.5507              | 0.5183    | 0.7183  |
| 20        | 0.5770              | 0.7300    | 0.7570  |
| 21        | 0.7200              | 0.7200    | 0.7200  |
| 22        | 0.7401              | 0.9094    | 0.7302  |
| 23        | 0.8014              | 0.8981    | 0.8000  |
| 24        | 0.8984              | 0.8894    | 0.8994  |
| 25        | 0.8984              | 0.8894    | 0.8994  |
| 26        | 0.8984              | 0.8894    | 0.8994  |
| 27        | 0.8984              | 0.8894    | 0.8994  |

Step 2: Grey relational coefficient (GRC)

Following data pre-processing, a grey relational coefficient was calculated from the normalized data to express the relationship between the desired and actual shrinkage and tensile properties. The grey relational coefficient can be expressed as follows:

\[ \xi_i(k) = \frac{\Delta_{\text{min}} + \xi \cdot \Delta_{\text{max}}}{\Delta_{0 i}(k) + \xi \cdot \Delta_{\text{max}}} \]  

(4)
where $\Delta_w(k)$ is the deviation sequence of the reference sequence $y_0^*(k)$ and comparability sequence $y_i^*(k)$, namely:

$$\Delta_w(k) = \| y_0^*(k) - y_i^*(k) \|$$  

(5)

$$\Delta_{max} = \max_{i \in I} \max_k \| y_i^*(k) - y_j^*(k) \|$$  

(6)

$$\Delta_{min} = \min_{i \in I} \min_k \| y_i^*(k) - y_j^*(k) \|$$  

(7)

$\xi$ is distinguishing or identification coefficient which is defined in the range $0 \leq \xi \leq 1$. $\xi=0.5$ is generally used.

Step 3: Grey relational grade (GRG)
After obtaining the GRC, the grey relational grade (GRG) was computed by averaging the grey relational coefficient. The grey relational grade can be defined as follows and tabulated in Table 6.

$$\gamma_i = \frac{1}{n} \sum_{k=1}^n \xi_i(k)$$  

(8)

The multiple quality characteristic performances of shrinkage and tensile properties were evaluated based on the grey relational grade. The complicated multiple performances have been converted into optimization of a single grey relational grade. The optimal level of the processing parameters was the level with the highest grey relational grade.

Table 6. Grey relational analysis results

| Trial No. | Additive | Damping | Thrust | Minimum load | Young's modulus | Elongation at break | Grey Relational Coefficient, GRC |
|-----------|----------|---------|--------|--------------|-----------------|---------------------|---------------------------------
| 1         | 0.5491   | 0.4203  | 0.7038 | 0.0000       | 0.7899          | 0.7298              | 0.1111                          |
| 2         | 0.1134   | 0.0530  | 0.7118 | 0.5412       | 0.4417          | 0.5314              | 0.6281                          |
| 3         | 0.2325   | 0.2323  | 3.0000 | 0.5407       | 0.5425          | 0.6372              | 0.7017                          |
| 4         | 0.2772   | 0.2984  | 0.5023 | 0.5284       | 0.5024          | 0.5284              | 0.7017                          |
| 5         | 0.1292   | 0.5420  | 0.5094 | 0.4577       | 0.4510          | 0.5200              | 0.1122                          |
| 6         | 0.5460   | 0.5425  | 0.5023 | 0.5478       | 0.4520          | 0.5478              | 0.5500                          |
| 7         | 0.1274   | 0.5033  | 0.4691 | 0.4930       | 0.5541          | 0.5766              | 0.7086                          |
| 8         | 0.8933   | 0.7085  | 0.4491 | 0.0155       | 0.4900          | 0.7979              | 0.8637                          |
| 9         | 0.4907   | 0.0400  | 0.5011 | 0.4549       | 0.4449          | 0.8167              | 0.9112                          |
| 10        | 0.1537   | 1.0000  | 0.4498 | 0.4523       | 0.6377          | 0.9335              | 0.8663                          |
| 11        | 0.6114   | 0.7284  | 0.5011 | 0.1525       | 0.5385          | 1.0000              | 0.8678                          |
| 12        | 0.1492   | 0.2802  | 0.7172 | 0.1427       | 0.4904          | 0.2721              | 0.8620                          |
| 13        | 0.1461   | 0.5553  | 0.6022 | 0.2333       | 0.5828          | 0.3535              | 0.8545                          |
| 14        | 0.5981   | 0.5578  | 0.7178 | 0.5412       | 0.4530          | 0.7960              | 0.8545                          |
| 15        | 0.8901   | 0.5877  | 0.5473 | 0.5277       | 0.5323          | 0.5121              | 0.8064                          |
| 16        | 0.7406   | 0.0002  | 0.9781 | 0.4220       | 0.0320          | 0.9429              | 0.8020                          |
| 17        | 0.3585   | 0.0530  | 0.4677 | 0.4082       | 0.8633          | 0.4419              | 0.6226                          |
| 18        | 0.1302   | 0.5259  | 0.3992 | 0.5864       | 0.5500          | 0.4994              | 0.6084                          |
| 19        | 0.7732   | 0.7314  | 0.6498 | 0.4252       | 0.8307          | 0.4957              | 0.7964                          |
| 20        | 0.2228   | 0.5729  | 0.2501 | 0.2678       | 0.2676          | 0.4257              | 0.9801                          |
| 21        | 0.1467   | 0.5500  | 0.7123 | 0.4440       | 0.4500          | 0.5808              | 0.6220                          |
| 22        | 0.1766   | 0.0477  | 0.4534 | 0.3692       | 0.5000          | 0.3512              | 0.5545                          |
| 23        | 0.8600   | 0.9719  | 0.4440 | 0.4542       | 0.7903          | 0.4239              | 0.5463                          |
| 24        | 0.9461   | 0.8527  | 0.4419 | 0.8230       | 0.7909          | 0.5639              | 0.6130                          |
| 25        | 0.9690   | 0.5320  | 0.6417 | 0.3338       | 0.6123          | 0.3754              | 0.1614                          |
| 26        | 0.7964   | 0.7488  | 0.5913 | 0.3644       | 0.3835          | 0.4620              | 0.5557                          |
| 27        | 0.8432   | 0.8580  | 0.3883 | 0.3529       | 0.5621          | 0.4615              | 0.8060                          |

4. Discussion on results analysis
4.1 Main effects analysis
A main effect is a statistical term associated with experimental designs. To develop a clear understanding of how the optimum condition was selected, the main effects were further performed in this study and plotted in Figure 2.
Since the GRG represents the level of correlation between the reference and the comparability sequences, the larger GRG means the comparability sequence exhibits a stronger correlation with the reference sequence. In addition, the higher GRG also indicates the best multiple quality characteristic performances. Ignoring the interaction effects, notice that Fig. 2 shows the largest value of GRG for factors A, B, C, D and E are at level A1, B1, C1, D1 and E3 respectively. Hence, the optimal combination parameters achieving maximum tensile properties as well as minimum shrinkage were predicted to be A1 B1 C1 D1 E3, namely virgin PA66-GF, mould temperature of 50 ℃, melting temperature of 280 ℃, cooling time of 10 s and injection time of 1 s.

In studying the feasibility study of recycled PA66-GF blending composition, Fig. 2 illustrates that A4 of 15% wt recycled PA66-GF presents the most comparable performance with the virgin PA66-GF. Hence, another optimum parameter conditions to indicate the best multiple quality characteristic performances relative to the recycled PA66-GF blending composition were predicted to be A4 B1 C1 D1 E3, namely 15% wt PA66-GF, mould temperature of 50 ℃, melting temperature of 280 ℃, cooling time of 10 s and injection time of 1 s. Thus, these two sets of optimum conditions were verified in the confirmation test at the end of this study to assess the usability of the recycled blending material compared to its virgin.

### 4.2 Interaction Effects Analysis

To determine whether the interaction is present in this study, a proper interpretation of the results is necessary. The average effect of interactions C X D and C X E with respective factor level were performed and the results illustrated in Fig. 3.

The intersecting lines represent the interaction among parameters C, D and E. When re-examining the optimum condition obtained from the previous section of factors A1 B1 C1 D1 E3, Fig. 3 depicts that $C_1D_1$ and $C_1E_3$ have the higher values. Coincidentally, the optimum condition for interaction effects was the same as the optimum conditions obtained from main effects analysis in Fig. 2, hence no optimum condition modification is needed. Further analyses of the significance influence of interactions were made possible by the ANOVA.

### 4.3 Analysis of Variance (ANOVA)

Taguchi method does not only facilitate the response plot to visualize the impact of varying parameters on the multiple quality characteristic performance, but it can also perform ANOVA to
estimate the relative contribution and significance of each parameter to the overall measured responses. The results of ANOVA were tabulated in Table 7.

**Table 7. ANOVA results of the experiment**

| Symbol | Parameters/Factors | DOF, f | Sum of squares, S | Variance, \( \sigma^2 \) | Variance Ratio, \( \frac{\sigma^2}{\text{error}} \) | Pure Sum of Squares | Percent Contribution P (%) |
|--------|-------------------|--------|-------------------|----------------------|-------------------------------|---------------------|--------------------------|
| A      | Blending Ratio    | 8      | 0.0629            | 0.0079               | 2.73                          | 0.0394              | 56.0%                    |
| B      | Mold Temperature  | 2      | 0.0270            | 0.0135               | 4.69                          | 0.0213              | 24.3%                    |
| C      | Melting Temperature | 2     | 0.0027            | 0.0013               | 0.47                          | -0.0031             | 2.6%                     |
| D      | Cooling Time      | 2      | 0.0119            | 0.0059               | 2.06                          | 0.0061              | 10.6%                    |
| E      | Injection Time    | 2      | 0.0020            | 0.0010               | 0.35                          | -0.0037             | 1.8%                     |
| E \times D | 4     | 0.0065           | 0.0016            | 0.97                | -0.0059                        | 5.8%                |
| E \times C | 4     | 0.0005           | 0.0024            | 0.82                | -0.0020                        | 8.5%                |
| All other/ Error | 2 | 0.0008 | 0.0029 | 0.97 | -0.0059 | 5.1% |

In view of the fact that the percentage contributions of all parameters and interactions on the multiple quality characteristic performance, the blending ratio was found as the most influential parameter in improving tensile properties as well as in minimizing shrinkage. The results match with the earlier findings of [12] where the fibre glass material exhibited a strong influence in reducing shrinkage compared to other parameters. This phenomenon was due to the glass fibres orientation effect along the direction of injection flow during the injection moulding process. Whereas, the injection time was found to have the least contribution in affecting the multiple quality characteristics performance with only 1.8% contribution.

**4.4 Confirmation results**

The final step of the design of experiment is the confirmation test, which verifies if the optimum conditions suggested by the matrix experiment do indeed give the improvement projected. The verification experiment was performed by conducting the test with predicted optimal parameter settings as highlighted in the previous section. In addition, the accuracy of Taguchi optimization approach with feasible recycled PA66-GF blending composition also can be proved via the confirmation test. In this study, the confirmation test was carried out by adopting the optimal processing parameter conditions of B1 C1 D1 E3 for virgin PA66-GF and 15% wt recycled PA66-GF to produce the plastic gear. The plastic gears undergo a tensile test and shrinkage test and the experimental performance of the plastic gears were tabulated in Table 8.

**Table 8. Confirmation results of optimization prediction**

|                | Shrinkage (%) | Tensile properties |
|----------------|--------------|--------------------|
|                | Addendum     | Diameter           | Thickness of wall | Maximum load (N) | Young’s Modulus (Mpa) | Elongation at Break (mm) |
| Virgin PA66-GF | 2.1990       | 2.6757             | 0.1803            | 2569.5436        | 85.9006               | 0.0520                    |
| 15% wt recycled PA66-GF | 2.2213 | 2.7587             | 0.1811            | 3147.4450        | 79.9019               | 0.0194                    |
| Difference (%) | 0.02        | 0.086              | 0.068             | 5877.9014        | 94.8019               | 0.1014                    |

The confirmation test indicates that the shrinkage of the plastic gear produced by 15% wt recycled PA66-GF blends has improved to a higher quality level which slightly better than the performance of the part produced by virgin PA66-GF. The reduction in molecular weight and fibre breakage during recycling process have indirectly minimized the shrinkage. Whereas for tensile properties, the plastic gear made of 15% wt recycled PA66-GF blend has also improved the strength of the plastic gear to withstand the maximum load and elongation at break at 22.49% and 19.65% respectively which better than virgin PA66-GF gear. The results match with the findings of Bernasconi et al. [13] where recycled products behaved in a stronger manner compared to its virgin because of fibre breakage during recycling led to a consequent decrement of fibres contribution in composite strength. However, the Young’s modulus and melt flow index of virgin PA66-GF gear were still better than the gear made...
of 15% wt recycled PA66-GF blends since the properties of the material have been altered during the reprocessing of the material [14].

5. Conclusion
• From this research, the blending ratio is found as the most influential parameter of 56.0% contribution in both improving tensile properties as well as in minimizing shrinkage, followed by mould temperature of 24.1% contribution and cooling time of 10.6% contribution. In view of Taguchi’s interaction effect, melting temperature and cooling time give 5.8% contribution and melting temperature and injection time give 8.5% contribution which is relatively a small contributions compared to parameter effect. Therefore, integration of both Taguchi method and grey relational analysis enhanced the efficiency of the optimization process in determining the influence of processing parameters and interaction among parameters subjected to desire multiple quality characteristics.
• The integrated methodology has proven its capabilities in determining the optimal conditions with multi responses quality characteristics. In this study, the optimal processing parameter conditions of B1 C1 D1 E3 (mould temperature of 50 °C, melting temperature of 280 °C, cooling time of 10 s and injection time of 1 s) were obtained for both virgin and 15% wt recycled PA66-GF to satisfy the multi performance quality characteristics of injection moulded plastic gear.
• The experimental results depicted that 15% of recycled PA66-GF blending composition behave almost similar to the virgin material in term of melt flow index. Comprehending to this fact, 15% recycled PA66-GF blend is considered reliable to satisfy quality requirements. This phenomenon is supported with improvement in shrinkage of 15% recycled PA66-GF blend gears compared to virgin PA66-GF gears. In addition, for tensile properties, the plastic gears made of 15% wt recycled PA66-GF blend have also improved the strength of the plastic gear to withstand the maximum load and elongation at break at 22.49% and 19.65% respectively better than virgin PA66-GF gears. However, the Young’s modulus of virgin PA66-GF gear is still better than the gear made of 15% wt recycled PA66-GF blends. This phenomenon is due to the degradation on the molecular weight of recycled PA66-GF during recycling process. Apart from that, overall performance of 15% recycled PA66-GF is considered as a good candidate in substituting the virgin PA66-GF in plastic production.

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