Evaluation on the feasibility of using bamboo fillers in plastic gear manufacturing via the Taguchi optimization method

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Abstract. An increase in demand for industrial gears has instigated the escalating uses of plastic-matrix composites, particularly carbon or glass fibre reinforced plastics as gear material to enhance the properties and limitation in plastic gears. However, the production of large quantity of these synthetic fibres reinforced composites has posed serious threat to ecosystem. Therefore, this work is conducted to study the applicability and practical ability of using bamboo fillers particularly in plastic gear manufacturing as opposed to synthetic fibres via the Taguchi optimization method. The results showed that no failure mechanism such as gear tooth root cracking and severe tooth wear were observed in gear tested made of 5-30 wt% of bamboo fillers in comparing with the unfilled PP gear. These results indicated that bamboo can be practically and economically used as an alternative filler in plastic material reinforcement as well as in minimizing the cost of raw material in general.

1. Introduction
Gears have been in used for more than three thousand years and are commonly utilized in power and motion transmission under different loads and speeds. A variety of cast irons, powder metallurgy materials, and nonferrous alloys are used in gears. To date, with advance in the development of plastic materials, and with a wide spectrum of fiscal and practical properties available, plastics have become one of the most sought-after materials in the world today. Plastics have quickly become common throughout the modern world due to their intrinsic properties such as lightweight, versatility, and durability [1-2]. By possessing these tremendous range properties, plastics have become a good candidate for replacing the primary materials used for gear manufacturing and the demand for plastic gears has significantly increased and indubitably continues in the future [3].

An increase in demand for industrial plastic gears has resulted in increased use of plastic-matrix composites, particularly carbon or glass fibre-reinforced plastics as gear materials, to enhance the mechanical strength and the thermal resistance of plastic gears. Nevertheless, the production of large quantities of these synthetics fibre-reinforced composites poses a serious threat to the ecosystem. These fibres or fillers, especially glass, have become a waste management issue due to their non-biodegradability. Glass fibre filled plastic waste can take decades, and probably centuries, to decompose and constitute an environmental hazard. The disposition or the recycling of glass fibre reinforced composites is not easy and safe for environment, since even after recycling these thermoplastic composites, very small amounts of them can be incinerated.
As a consequence, researchers have been looking into the possibility of using natural fillers as reinforcement in plastic gear manufacturing. The use of natural fibres, as opposed to synthetic fibres such as carbon and glass fibres, has been widely recognized due to the positive effect on the environment with respect to ultimate disposability, not to mention the rising prices of raw materials used for manufacturing standard plastics. In addition, natural fibres have properties including low cost, lightweight, easy availability, high strength-to-weight ratio and also, less wear and tear in processing machinery [4-6].

Therefore, in this study, an attempt is given on the possibility of using natural filler especially the bamboo filler of the Bambusa Bluemeana species, which grows abundantly in Malaysia for reinforcement in plastic gear manufacturing. The Taguchi method is adopted in designing the experiments for gear performance testing. The wear behaviour of the gear produced by various loading rates of bamboo fillers are investigated in this study.

2. Gear performance testing procedures

The flowchart of the gear performance testing procedures is illustrated in Figure 1 and each stage of the experimental procedures is elaborated in the following section.

![Figure 1. Gear performance testing procedures.](image)

2.1. Selection of testing parameters

Five parameters control including percentage of bamboo loading, gear meshing gap, speed, load and running time were selected for conducting the gear performance test. Each parameter of gear meshing gap, speed, load and running time was set at four levels. As in this research, the percentage of bamboo filler incorporated to the PP gears varied from 0 wt%, 5 wt%, 10 wt%, 15 wt%, 20 wt%, 25 wt%, 30 wt% (refer Table 3.3), hence seven levels were set for bamboo loading (parameter A). Table 1 shows the parameters control and their levels.
Table 1. Parameters control and their levels in the gear performance test.

| Column | Factors                      | Level |
|--------|------------------------------|-------|
|        |                              | 1     | 2   | 3   | 4   | 5   | 6   | 7   |
| A      | Bamboo loading (%)           | 0     | 5   | 10  | 15  | 20  | 25  | 30  |
| B      | Gear meshing gap (mm)        | 3.0   | 3.1 | 3.2 | 3.3 |
| C      | Speed (Hz)                   | 12    | 13  | 14  | 15  |
| D      | Load (%)                     | 0     | 5   | 10  | 15  |
| E      | Running time (min)           | 30    | 40  | 50  | 60  |

2.2. Selection of Taguchi orthogonal arrays

After determining the number of control parameters and their levels, an appropriate OA was established for laying out the design of experiment in testing the performances of unfilled PP gears and bamboo-based PP composite gears at various bamboo loading percentage related to wear failure. The selection of an appropriate OA depends on the total DOF of the control parameters. In this study, there were four control parameters (meshing gap, speed, load, and running time) with four levels of each, and one control parameter (bamboo loading) with seven levels. As DOF was calculated by subtracting the number of levels with one (DOF = number of levels - 1), therefore for four control parameters with four levels each, the total DOF is equal to twelve and for control parameters with seven levels, the DOF is six. Hence, the total DOF required for all control parameters is 18 DOF. According to Roy (1990) [7], the total DOF of selected OA must be greater than or equal to the total DOF required for the experiment. There are some standard OAs which treats four levels factors such as L16, L32, and L64. However, in selecting an OA for mixed levels, an L32 OA was chosen to lay out the design of experiment in conducting the gear performance test in this study. Referring to Table 2, percentage of bamboo loading (A) was assigned to column 2 varied from 0 to 30 wt %, and all the four testing parameters with four levels were assigned to columns 3, 4, 5, and 6. The remaining five columns (Column 1, 7, 8, 9, and 10) were not used when running the experiments. The details of assigning the columns for the parameters studied can be found in Roy (1990) [7] and Roy (2001) [8]. There were total 32 trials need to be conducted under different combination of test parameters as shown in Table 3.9; however in this study, gear tests were conducted only up to 28 trials to be adjusted with percentage of bamboo loading varied from 0 to 30 wt %. All the gear tests were conducted under un lubricated dry conditions via gear test rig.

2.3. Test rig details

Figure 2 shows the gear test rig used for conducting gear performance test. In this test rig, the test gear was driven using a DC motor and was run at selected speed up to 1500 rpm. Test gear mates with an identical gear, was connected to the DC generator. The required test torque was introduced by loading the rheostat connected to the generator. Speed and digital counter were suitably placed to monitor the speed and number of cycles run, respectively. A pair of similar gears was allocated and continuously run following the designed L32 OA (refer to Table 3.9) for each trial. All the gear tests were conducted at the laboratory conditions (room temperature: 25 °C and humidity: 64 %). The wear performance of gear made from unfilled PP and bamboo-based PP composite gears were then systematically studied.
Table 2. The $L_{32}$ OA used in the gear performance test.

| Trial No. | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|-----------|----|----|----|----|----|----|----|----|----|----|
| 1         | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  |
| 2         | 1  | 2  | 1  | 1  | 1  | 1  | 1  | 2  | 2  | 2  |
| 3         | 1  | 3  | 1  | 2  | 3  | 3  | 3  | 3  | 3  | 3  |
| 4         | 1  | 4  | 1  | 3  | 4  | 4  | 4  | 4  | 4  | 4  |
| 5         | 1  | 5  | 1  | 2  | 3  | 3  | 3  | 3  | 3  | 3  |
| 6         | 1  | 6  | 1  | 1  | 2  | 1  | 2  | 1  | 2  | 2  |
| 7         | 1  | 7  | 2  | 1  | 2  | 2  | 3  | 2  | 1  | 2  |
| 8         | 1  | 8  | 3  | 2  | 2  | 3  | 3  | 4  | 2  | 1  |
| 9         | 1  | 9  | 4  | 3  | 2  | 3  | 3  | 4  | 3  | 1  |
| 10        | 1  | 10 | 4  | 4  | 3  | 3  | 4  | 3  | 4  | 3  |
| 11        | 1  | 11 | 5  | 4  | 4  | 4  | 4  | 3  | 4  | 3  |
| 12        | 1  | 12 | 6  | 5  | 5  | 5  | 5  | 5  | 5  | 5  |
| 13        | 1  | 13 | 7  | 6  | 6  | 6  | 6  | 6  | 6  | 6  |
| 14        | 1  | 14 | 8  | 7  | 7  | 7  | 7  | 7  | 7  | 7  |
| 15        | 1  | 15 | 9  | 8  | 8  | 8  | 8  | 8  | 8  | 8  |
| 16        | 1  | 16 | 10| 9  | 9  | 9  | 9  | 9  | 9  | 9  |
| 17        | 1  | 17 | 11| 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| 18        | 1  | 18 | 12| 11 | 11 | 11 | 11 | 11 | 11 | 11 |
| 19        | 1  | 19 | 13| 12 | 12 | 12 | 12 | 12 | 12 | 12 |
| 20        | 1  | 20 | 14| 13 | 13 | 13 | 13 | 13 | 13 | 13 |
| 21        | 1  | 21 | 15| 14 | 14 | 14 | 14 | 14 | 14 | 14 |
| 22        | 1  | 22 | 16| 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| 23        | 1  | 23 | 17| 16 | 16 | 16 | 16 | 16 | 16 | 16 |
| 24        | 1  | 24 | 18| 17 | 17 | 17 | 17 | 17 | 17 | 17 |
| 25        | 1  | 25 | 19| 18 | 18 | 18 | 18 | 18 | 18 | 18 |
| 26        | 1  | 26 | 20| 19 | 19 | 19 | 19 | 19 | 19 | 19 |
| 27        | 1  | 27 | 21| 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| 28        | 1  | 28 | 22| 21 | 21 | 21 | 21 | 21 | 21 | 21 |
| 29        | 1  | 29 | 23| 22 | 22 | 22 | 22 | 22 | 22 | 22 |
| 30        | 1  | 30 | 24| 23 | 23 | 23 | 23 | 23 | 23 | 23 |
| 31        | 1  | 31 | 25| 24 | 24 | 24 | 24 | 24 | 24 | 24 |
| 32        | 1  | 32 | 26| 25 | 25 | 25 | 25 | 25 | 25 | 25 |

Figure 2. Schematic of gear test rig: 1. Motor 2. Load coupling 3. Bearing block 4. Test spur gear 5. Generator 6. Standard spur gear 7. Torque sensor 8. Base plate
2.4. Wear measurement
Severe wear of the gear tooth is one of the gear failure modes, which leads to a gradual increase in sound and vibration of the assemble unit. For extensive investigation of wear behaviour in plastic gear, a wear measurement was carried out to determine the amount of materials removed or worn away after the gears have been tested for a period of running time as specified in Table 3.8. In this research, the material worn away is expressed as weight (mass) loss. Weight measurement was taken from both driving and driven gear by using Shimadzu precision balance (model ATY224) just before and after each test to evaluate the weight loss. The difference in weight before and after gear performance test represents the weight loss in gram (g) caused by wear. For further understanding the wear failure mechanism, the optical photograph of the tested gears was also observed.

2.5. Gear performance analysis
All the experimental results obtained from the wear measurement of each gear made from unfilled PP and bamboo-based PP composites were then systematically and statistically analyzed by main effects analysis and ANOVA.

3. Results and discussion
3.1 Main effects analysis
By using the results in Table 4, the main effects analysis of testing parameters including the bamboo loading percentage (A), the gear meshing gap (B), the speed (C), the load (D), as well as the running time (E), are presented in the form of a graphical display to demonstrate the impact of variation in testing parameters on wear behaviour of the gear produced (see Figure 3).

Figure 3 clearly shows that the total weight loss of the meshing gear studied is significantly affected by the adjustments of the testing parameters. In this case, the variations in the gear meshing gap, the speed, the load, and the running time, as well as the percentage of bamboo filler loading in the gears, have different effects on the wear behaviour of the meshing gears. Any changes in parameters can lead to an improvement or a deterioration in gear quality. Plastic gears are known to fail in a number of ways, including wear, which needs to be minimized during the gear running. It is important to understand the wear characteristics, particularly the way in which such gear wear is related to the contact conditions during gear running [9-10]. From Figure 4.22, it can be concluded that the percentage of bamboo loading in the gear is significant parameter, because the slope gradient is very big. Compared to that in an unfilled PP gear, the addition of 5 wt% of bamboo filler has a great impact in minimizing the wear during the gear running.
Figure 3 also shows that lower speeds minimize the wear behaviour in the gear meshing. With loading, the opposite trend occurs. The wear of the meshing gear decreases with higher loads. For the meshing gap and the running time, the total weight loss for both running gears at 3.1 mm and 30 minutes of running time, respectively, showed the least amount of wear. Repeated gear tooth loading contributes to subsequent deformation of gear teeth, due to hysteresis heating during the gear running. Friction between the mating gear teeth resulting from the gear meshing gap selected during the gear running generates the heat and propagates hysteresis effects. This heat, generated due to friction as well as hysteresis loss, also increases with increasing gear rotational speed, which then results in wear failure gear teeth and on the surface.

3.2 Analysis of variance (ANOVA)
For further investigation into the effect of different testing parameters on the wear behaviour of the optimized unfilled PP and bamboo-based PP gears produced, the ANOVA is also performed. The relative contributions of the gear meshing gap, the speed, the load, the running time, as well as the bamboo loading percentage, to the wear behaviour of the gears, are measured. By adopting similar procedures to those followed in the previous experiments, the quantities such as DOF, sums of squares, variances, F-Ratios, and percentage contributions, are computed and presented in Table 3.

| Column | Parameters | DOF | Sum of squares | Variances | F-Ratio | Percent |
|--------|------------|-----|----------------|-----------|---------|---------|
| A      | Bamboo loading (%) | 6   | 3.7650E-04     | 6.2750E-05 | 1.5800   | 37.85   |
| B      | Gear meshing gap (mm) | 3   | 5.8430E-05     | 1.9477E-05 | 0.4904   | 5.87    |
| C      | Speed (Hz) | 3   | 1.1604E-05     | 3.8680E-06 | 0.0974   | 1.17    |
| D      | Load (%) | 3   | 1.8046E-04     | 6.0155E-05 | 1.5146   | 18.14   |
| E      | Running time (min) | 3   | 1.0261E-05     | 3.4204E-06 | 0.0861   | 1.03    |
| All others/error | 9   | 3.5745E-04     | 3.9717E-05 | 1.3594   | 35.94   |
| Total  |            | 27  | 9.9471E-04     | 1.0000E+00 | 1.0000   | 100.00  |

In analysing the results in the gear performance testing, the 10% rule, where a parameter is considered insignificant when its influence is less than 10% of the highest parameter influence, is implemented [8]. From the results of ANOVA in Table 3.19, the bamboo loading percentage appears to be the key parameter affecting the wear in an engaged gear pair. The percentage contribution of the bamboo loading percentage is 37.85%, the highest of all the process parameters, followed by the load and the gear meshing gap. While, speed and running time are insignificant, as their percentages are less than 10% of the highest parameter influence, which is 3.785%.
Table 4. Wear measurement results.

| Test | Bamboo loading (%) | Gear meshing gap (mm) | Speed (Hz) | Load (%) | Running time (min) | Weight loss (g) |
|------|--------------------|----------------------|------------|----------|-------------------|-----------------|
|      |                    |                      |            |          |                   | Driver Gear     |
| 1    | 0                  | 3.0                  | 12         | 0        | 30                | 0.0116          |
| 2    | 0                  | 3.1                  | 13         | 5        | 40                | 0.0115          |
| 3    | 0                  | 3.2                  | 14         | 10       | 50                | 0.0159          |
| 4    | 0                  | 3.3                  | 15         | 15       | 60                | 0.0022          |
| 5    | 5                  | 3.0                  | 12         | 5        | 40                | 0.0014          |
| 6    | 5                  | 3.1                  | 13         | 0        | 30                | 0.0033          |
| 7    | 5                  | 3.2                  | 14         | 15       | 60                | 0.0017          |
| 8    | 5                  | 3.3                  | 15         | 10       | 50                | 0.0027          |
| 9    | 10                 | 3.0                  | 13         | 10       | 60                | 0.0013          |
| 10   | 10                 | 3.1                  | 12         | 15       | 50                | 0.0019          |
| 11   | 10                 | 3.2                  | 15         | 0        | 40                | 0.0081          |
| 12   | 10                 | 3.3                  | 14         | 5        | 30                | 0.0035          |
| 13   | 15                 | 3.0                  | 13         | 15       | 50                | 0.0021          |
| 14   | 15                 | 3.1                  | 12         | 10       | 60                | 0.0021          |
| 15   | 15                 | 3.2                  | 15         | 5        | 30                | 0.0025          |
| 16   | 15                 | 3.3                  | 14         | 0        | 40                | 0.0059          |
| 17   | 20                 | 3.0                  | 15         | 0        | 60                | 0.0052          |
| 18   | 20                 | 3.1                  | 14         | 5        | 50                | 0.0022          |
| 19   | 20                 | 3.2                  | 13         | 10       | 40                | 0.0022          |
| 20   | 20                 | 3.3                  | 12         | 15       | 30                | 0.0025          |
| 21   | 25                 | 3.0                  | 15         | 5        | 50                | 0.0071          |
| 22   | 25                 | 3.1                  | 14         | 0        | 60                | 0.0033          |
| 23   | 25                 | 3.2                  | 13         | 15       | 30                | 0.0026          |
| 24   | 25                 | 3.3                  | 12         | 10       | 40                | 0.0042          |
| 25   | 30                 | 3.0                  | 14         | 10       | 30                | 0.0024          |
| 26   | 30                 | 3.1                  | 15         | 15       | 40                | 0.0027          |
| 27   | 30                 | 3.2                  | 12         | 0        | 50                | 0.0041          |
| 28   | 30                 | 3.3                  | 13         | 5        | 60                | 0.0109          |

4. Conclusion
The Taguchi technique’s OA and main effects analysis was recommended as a way of efficiently optimizing the cutters geometry in studying the feasibility of using bamboo fillers in plastic gear manufacturing related to wear behaviour. The main effects plot showed that A₁, B⁴, C⁴, D¹ and E² was identified as the optimal parameters setting that statistically results in minimum wear behaviour in plastic gear testing performance. The bamboo loading percentage appears to be the key parameter affecting the wear in an engaged gear pair with the percentage contribution of 37.85%. The results indicated that bamboo can be potentially used as a practical and economical filler in plastic gear material reinforcement as well as in minimizing the cost of raw material in general.
5. References

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