Investigation on wear characteristic of biopolymer gear

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Abstract. Polymer is widely used in many mechanical components such as gear. With the world going to a more green and sustainable environment, polymers which are bio based are being recognized as a replacement for conventional polymers based on fossil fuel. The use of biopolymer in mechanical components especially gear have not been fully explored yet. This research focuses on biopolymer for spur gear and whether the conventional method to investigate wear characteristic is applicable. The spur gears are produced by injection moulding and tested on several speeds using a custom test equipment. The wear formation such as tooth fracture, tooth deformation, debris and weight loss was observed on the biopolymer spur gear. It was noted that the biopolymer gear wear mechanism was similar with other type of polymer spur gears. It also undergoes stages of wear which are; running in, linear and rapid. It can be said that the wear mechanism of biopolymer spur gear is comparable to fossil fuel based polymer spur gear, thus it can be considered to replace polymer gears in suitable applications.

1. Introduction
Polymer has been chosen to replace steel in various application such as gearing due to its mechanical advantages and economical value. Its ability to operate with a little lubrication, low noise operation and light weight material are some of the advantages [1-6].

The abundance of polymer from the non-renewable source which is fossil fuel have raised problems such as disposing and recyclability. This brings about the emergence of biopolymer made from natural resource and more environmentally friendly. The usage of biopolymer in the gearing section has not yet gained traction which is what this paper target to overcome. Despite the same function, polymer gear does not behave as same as its counterpart, the steel gears even in the designing stage. They even have specific standards which are found in [7-9]. For polymer and engineering polymer gears, several types of research have been conducted which focuses on gear life [10], the effect of temperature[11-13] and the failure methods [14-17].

However, research on biopolymer gear is not yet available during the time of research. This research focuses on identifying the wear mechanism of biopolymer gear and whether it is comparable to fossil fuel based polymer gear. In this research, the following were used to identify wear mechanism and the failure of biopolymer gear; tooth fracture, tooth deformation, debris and weight loss. This method was also used by [12, 16, 18-20] in their research to identify failure of polymer gear.
2. Methodology
The gears were designed in SolidWorks and followed the geometry shown in Table 1. The gears were then produced using injection moulding process. The parameters of injection moulding process are seen in Table 2. The test was done on a dedicated test rig seen in Figure 1.

| Name                        | Symbol | Pinion | Gear |
|-----------------------------|--------|--------|------|
| Module                      | m      | \( \frac{d_1}{z_1} = \frac{d_2}{z_2} \) | \( m = 2 \) |
| Tooth                       | z      | \( z_1 = \frac{d_1}{m} \) | \( z_2 = \frac{d_2}{m} \) |
| Pressure angle              | a      | 20°    |      |
| Face width                  |        | 15mm   |      |
| Reference pitch circle      | \( d \) | \( d_1 = 25 \times 2 = 50\text{mm} \) | \( d_2 = 30 \times 2 = 60\text{mm} \) |
| Tooth tip circle diameter   | \( d_a \) | \( d_{a1} = d_1 + 2h_a \) | \( d_{a2} = d_2 + 2h_a \) |
|                          | \( d_{a1} = 50 + 2(2) = 54\text{mm} \) | \( d_{a2} = 60 + 2(2) = 64\text{mm} \) |
| Root circle diameter        | \( d_f \) | \( d_{f1} = d_1 - 2h_f \) | \( d_{f2} = d_2 - 2h_f \) |
|                          | \( d_{f1} = 50 - 2(2.5) = 45\text{mm} \) | \( d_{f2} = 60 - 2(2.5) = 55\text{mm} \) |
| Addendum                    | \( h_a \) | \( h_a = m \) | \( h_a = 2 \) |
| Dedendum                    | \( h_f \) | \( h_f = h_a + c \geq 1.25 \times m \) | \( h_f = 2 + 0.5 = 2.5 \) |
| Tip and root clearance      | \( c \) | \( c = h_f - h_a \geq 0.25 \times m \) | \( c = 2.5 - 2 = 0.5 \) |
| Tooth depth                 | \( h \) | \( h = h_a + h_f \geq 2.25 \times m \) | \( h = 2 + 2.5 = 4.5\text{mm} \) |
|                          | \( a = \frac{d_1 + d_2}{2} = m\left(\frac{z_1 + z_2}{2}\right) \) | \( a = \frac{50 \pm 60}{2} = 2\left(\frac{25 \pm 30}{2}\right) = 55\text{mm} \) |
| Centre distance             | \( a \) | \( a = \frac{50 \pm 60}{2} = 2\left(\frac{25 \pm 30}{2}\right) = 55\text{mm} \) | \( a = 2A_\Delta \tan 20 \) |
| Backlash                    | \( b_c \) | \( b_c = 2(55.05 - 55) \tan 20 = 0.36 \times 10^{-3}\text{meter} \) |
The gear pair were run on different RPM to create the effect of different speed. The gears were run to a certain amount of revolutions. The conditions are 500, 1000, and 1500 RPM. Each pair undergoes the test for 2 hours and a non-load and 10N load condition. The standard practice to test gear fatigue is at $1 \times 10^6$ however this result is for preliminary and to determine whether the conventional method to investigate wear characteristic in polymer gear is applicable for biopolymer gear.

The surrounding area of testing was then investigated to determine the presence of debris. Then the gears are inspected visually to detect fracture and crack formation on the tooth region, including tip and root.

The microstructure before and after the test was then studied using a microscope. The weight reduction of gears is also recorded using a digital scale.

3. Results and discussion

3.1. Weight Loss

Table 3 and 4 shows the weight loss and its rate. Figure 2 and 3 shows the graph of weight loss. The steeper the gradient indicates that the gear loses weight much faster. The slower RPM have a much steep curve compared to the higher speed. This can be explained by the effect of the gear pump as seen in [13, 16, 21-23]. When meshing, the space between the gears or backlash creates an air pocket which helps to improve the heat distribution. A much faster gear pair will distribute more heat to the surrounding, helping it to regulate the temperature. If too much heat is produced, the gear may undergo thermal deformation. The teeth may become soft, and flakes occurs which is explained in 3.3.

The weight loss is contributed by the debris formed during the test. The chipping of tooth also influences the weight reduction. The weight loss can be grouped into three stages; running in wear, where the wear occurs for a short time but high, followed by linear wear, where the wear is small but progressively increase and finally rapid wear, where the wear causes deformation leading to gear failure.

Table 2. Injection Moulding Parameter.

| Parameter                  | Value |
|----------------------------|-------|
| Screw Temperature, °C      | 160   |
| Dosage Stroke, mm          | 25, 35|
| Injection Speed, mm/s      | 75    |
| Injection Pressure, Bar     | 210   |
| Cooling time, second       | 110   |
| Back Pressure, Bar         | 50    |

Figure 1. Test rig for polymer gear.
Table 3. Weight Loss of Non-Load Gear Pair.

| Pair No. | Biopolymer Gear | Weight Before → After | % of Weight Loss | Gradient |
|----------|-----------------|------------------------|------------------|----------|
| 500 RPM without load for 60,000 revs |
| Pair 1   | Driver          | 24.389 → 24.290        | 0.4059           | $-1.65 \times 10^{-6}$ |
|          | Driven          | 37.3370 → 36.340       | 2.6702           | $-1.66 \times 10^{-5}$ |
| 1000 RPM without load for 120,000 revs |
| Pair 2   | Driver          | 24.399 → 24.348        | 0.2090           | $-4.25 \times 10^{-7}$ |
|          | Driven          | 37.455 → 37.345        | 0.2945           | $-9.16 \times 10^{-7}$ |
| 1500 RPM without load for 180,000 revs |
| Pair 3   | Driver          | 24.390 → 24.370        | 0.0820           | $-1.11 \times 10^{-7}$ |
|          | Driven          | 37.342 → 36.380        | 2.5761           | $-4.00 \times 10^{-6}$ |

![Graph](image)

Figure 2. Weight loss of non-load gear pair.

The percentage of weight loss for driven gear is much higher compared to the driver gear as it carries the load. Even without a load attached at the shaft, the shaft itself is also a load as power is needed to turn it.

The slower RPM have a higher percentage of weight loss, this is due to more debris produced. A slower RPM reduces the heat transfer rate, therefore contributing to the amount of debris produced. The gradient for gear Pair 2 does not follow the trend of other pairs. This can be caused by the defect of product during production process or misalignment of test equipment. Since the data sampling is not enough the result was taken, however for future works more pair will be tested for each parameter giving more valid data to be selected.
Table 4. Weight Loss of 10N Load Gear Pair.

| Pair No. | Biopolymer Gear | Weight Before → After | % of Weight Loss | Gradient |
|----------|----------------|------------------------|------------------|----------|
|          |                | 500 RPM with load for 60,000 revs |                |          |
| Pair 4   | Driver         | 24.581 → 24.563         | 0.0732           | $-3.00 \times 10^{-7}$ |
|          | Driven         | 37.582 → 37.538         | 0.1170           | $-7.33 \times 10^{-7}$ |
|          |                | 1000 RPM with load for 120,000 revs |                |          |
| Pair 5   | Driver         | 24.487 → 24.477         | 0.0408           | $-8.33 \times 10^{-8}$ |
|          | Driven         | 37.132 → 37.067         | 0.1750           | $-5.41 \times 10^{-7}$ |
|          |                | 1500 RPM with load for 180,000 revs |                |          |
| Pair 6   | Driver         | 24.466 → 24.458         | 0.0326           | $-3.33 \times 10^{-8}$ |
|          | Driven         | 37.120 → 37.067         | 0.1427           | $-2.20 \times 10^{-7}$ |

3.2. Tooth fracture and deformation

The gears were checked for any fracture and deformation after completing their cycles. It was found that only several pairs undergo tooth fracture and deformation. Figure 5 shows tooth fracture occurring on the biopolymer gear.
3.3. Debris formation
Debris and flake formation on the surrounding area of the gear test is due to the gear disintegrating caused by the temperature rise. The flakes mostly come from the meshing of gear pair where the tooth tip of driver gear is digs out the softened material on the tooth of the driven gear which is also found in [14].

These flakes influence the weight reduction of the gear. When the scraping is severe, it may lead to the teeth deformation and finally fracture of the said teeth. These can be reduced by implementing several steps. First is by ensuring the gear profile is accurate. This can be done by having an accuracy test on the gears. Second is checking the tooth contact. The contact can be checked by applying a gear marking compound dedicated for testing the contact of the gear. The backlash of the gears also plays an important role in reducing the temperature and tooth damage. This can be checked using a dial gauge on the meshed gear at the teeth pitch region, root, and tip. The backlash checking can be seen in Figure 4.

By increasing the speed and adding load, the heat produced is increased, which leads to more debris formation. The debris formed can be seen in Figure 6.

3.4. Microstructure condition
The surface was studied before and after testing to get a better understanding of the surface condition resulting from the test. The main area of interest is the pitch line, where the contact of teeth is at the maximum.
From the resulting images, it was seen that the surface becomes smooth due to the contact. The materials in contact experience higher temperature and softening may occur in that region. This leads to the smooth region on the pitch section.

![Surface condition of driver gear](image1)

![Surface condition of driven gear](image2)

**Figure 7.** Microstructure condition of gear tooth surface before test.

![Surface condition of driver gear with running condition of 1000 RPM with 10N load](image3)

![Surface condition of driven gear with running condition of 1000 RPM with 10N load](image4)

![Surface condition of driver gear with running condition of 1500 RPM with 10N load](image5)

![Surface condition of driven gear with running condition of 1500 RPM with 10N load](image6)

**Figure 8.** Microstructure condition of gear tooth surface after test.

Surface seen in Figure 8 a) is much smoother compared to b) which is caused by the wear is higher in b). Since the RPM is lower, less heat is released to the surrounding during the test, causing the material to soften. This makes the surface mush easier to wear compared to surface in Figure 8 b).
4. Conclusions

During this experiment, the wear characteristic of biopolymer gear is investigated. Methods used in this experiment to characterize wear was widely used in the polymer gear research field. Weight loss was used by [11, 14, 19], tooth fracture and deformation as a failure was studied by [15, 24], [16, 18, 25] used debris formation to study failure and gear microstructure was studied by [26, 27]. From those research, it can be concluded that the methods used to determine wear for polymer gear are also viable for biopolymer gear.

The wear formed on the biopolymer gear can be identified by visual examination on the gear tooth for crack and deformation. The debris formed also indicates that wear is occurring on the gear pair. The weight loss of gears is also an indication of wear. By using a microscope, the microstructure image can be investigated to prove the wear is occurring on the gear pair.

It can be noted that the methods above can be used to determine wear of biopolymer gear. The gears undergo three stages of wear; running in, linear and final rapid wear. The wear debris increase as the gear approaches final wear period.

Weight loss is due to gear tooth contact which causes friction and heat. Gear will undergo moisture loss and debris formation leading to the weight loss. Running temperature affects the material as at a certain temperature; the material will start to degrade and causing the gear to fail. For future improvements, more load value will be used and the frequency of weight recording will be increased, and the running temperature of the gears will be observed.

From these results, the biopolymer gears can be considered as an alternative to be used in application where polymer gears are used. By using biopolymer gears, the application can be more sustainable and environmental friendly.

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