# DEVELOPMENT OF TEST EQUIPMENT TO STUDY LIFE, FRICTION AND WEAR PERFORMANCE FOR POLYMER GEARS IN AUTOMOTIVE APPLICATIONS

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Final report submitted in partial fulfillment of the requirements to close the grant

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# ABSTRAK

Bahan polimer secara meluas digunakan dalam pemacu mesin dan mekanisme kerana kelebihan mereka ke atas logam: sifat-sifat mekanik tertentu yang tinggi dan prestasi tribological, pelinciran diri, rintangan yang tinggi untuk memberi kesan memuatkan dan redaman, rintangan kepada minyak dan bahan kimia, nisbah saiz-berat yang tinggi , kadar pengeluaran yang tinggi dalam kes pengeluaran besar-besaran, dan keselamatan yang tinggi. Kajian ini adalah bertujuan untuk mereka bentuk gear biopolimer dan gear polimer dengan mengkaji tingkah laku haus gear biopolymer dan gear polimer. Gear dihasilkan daripada Asid Polylactic (PLA) dan Acrylonitrile Butadiene Styrene (ABS) yang menjalani proses pembuatan melalui proses pengacuan suntikan. Selepas proses pembuatan, gear ini diuji dengan menggunakan gear ujian pelantar dengan RPM yang berbeza selama 4 jam. Parameter yang diubah untuk eksperimen ini adalah RPM dan beban. Pertama, gear diuji dengan bahan dan RPM yang berbeza. Tiga jenis RPM yang digunakan bagi experiment ini adalah 500 RPM, 1000 RPM , dan 1500 RPM. Eksperimen kedua ialah menggunakan bahan gear yang berbeza dan RPM yang berlainan tetapi dengan penambahan beban sebanyak 10N. Eksperimen ketiga adalah untuk mengetahui tahap ketahanan gear dan untuk membandingkan gear biopolimer dengan gear polimer. Terdapat 4 jenis ciri kegagalan untuk dikaji dalam eksperimen ini iaitu pembentukan serpihan gear, pemantauan keadaan permukaan mikrostruktur, kerosakan haba dan kehilanggan berat.

# ABSTRACT

Polymer materials are widely employed in drives of machines and mechanisms owing to their advantages over metals: high specific mechanical properties and tribological performance, self-lubrication, high resistance to impact loading and its damping, resistance to oils and chemicals, high size-weight ratio, high production rates in case of mass production and high safety. This study is aim to fabricate biopolymer gear and polymer gear by study the wear behavior of biopolymer gear and polymer gear. These gear are produced from Polylactic acid (PLA) and Acrylonitrile Butadiene Styrene (ABS) which undergo fabrication process by injection molding process. After fabrication process, the gears are tested by using gear test rig with different RPM for 4 hours. Parameters that are varied for this experiment is RPM and load. First experiment is testing the gear with different material and different RPM. Three different RPM are been used for this experiment which are 500 RPM, 1000 RPM, and 1500 RPM. Second experiment is using the different gear material and different RPM but with added 10N load. Third experiment is to know gear durability and to compare biopolymer gear and polymer gear. There are four type of failure characteristics to study in this experiment which are gear wear debris formation, microstructure surface condition monitoring, weight loss and thermal damage.

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# CHAPTER 1

# INTRODUCTION

## 1.1 Project Background

This thesis aim are to fabricate and study wear properties of biopolymer gears and polymer gears. The gears are produced from Polylactic acid (PLA) and Acrylonitrile Butadiene Styrene (ABS) which undergo fabrication process by using injection moulding process. After fabrication process, gear is tested by using gear test rig with different gear material and RPM for 4 hours. Parameters that are varied for this experiment is RPM and load. First experiment is testing the gear with different materials and different RPM. Three different RPM are been used for this experiment which are 500 RPM, 1000 RPM and 1500 RPM. Second experiment is using the different gear material and different RPM but with added 10N load. Third experiment is to know the gear durability and to compare the biopolymer gear with polymer gear. There are four type of failure characteristics to study in this experiment which are gear wear debris formation, microstructure surface condition monitoring, weight loss and thermal damage.

## 1.2 Problem statement

Polymer are now widely used as substitute material for steel gear in low load devices. Its failure differs from gears made of steel, thus it is important to categorize the failures shown by polymer gears. Several previous studies noted that wear debris formation, microstructure surface condition monitoring, weight loss and thermal damage can be used in detecting failure of polymer gear.

This thesis reviews the failure characteristics of biopolymer gear and polymer gear. All failure characteristics of gear will be studied such as wear on the gear and weight loss from the gear.

## 1.3 Objective

Objective of this thesis are:

1. To develop the test gears from the biopolymer (Polylactic Acid) and polymer (Acrylonitrile Butadiene Styrene)
2. To compare and analyse the wear properties of biopolymer gear and polymer gear

## 1.4 Scope

The scope of this thesis is to fabricate biopolymer gear by using PLA and polymer gear by using ABS and study wear properties of biopolymer gears and polymer gears.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction


Figure 2-1 Types of failure characteristics for polymer gear

## 2.2 Wear

There are many types of failure that can be categorized under wear, such as crack or breaking, tooth thickness reduction and debris formation. Each review will include all known wear formation of polymer gear.

### 2.2.1 Wear debris formation

Acetal gear were found to have different failure compared to Nylon gear as reported by K. Mao et al [8]. Polymer gear wear can be divided into three stages; running in, linear and final rapid wear as shown in Table 1. The wear debris size increases as the gear approaches final wear period. When Acetal gears were tested in the high range load, 10 – 16.1 N.m, the wear debris formed immediately after the test started. When Nylon gears were tested at high load, 10 N.m, it fractures after going through running in and linear wear period. The gear made from Acetal failed by melting and in Nylon by fracture as shown in Figure 2.2

The same result was also obtained by W. Li et al [9] in their research where the test gears were paired with different materials. Acetal gear started to melt at load torques higher than 9 N.m and fracture occurs when load is 10 N.m and above. However, the wear performance improved when it is paired with dissimilar material where Acetal as the driver gear and Nylon as the driven gear, this pair showed the highest performance from other pairs which can be seen in Figure 2.3.

Table 2-1 Stages of polymer gear wear

| Phase | Explanation |
|---|---|
| Running in wear | Occurs for a short time but the amount of wear is high |
| Linear wear | Low amount of wear can be seen but is progressive |
| Final rapid wear | High wear rate but small amount of debris, indicating debris is due to deformation undergone by the polymer gear caused by thermal effects |

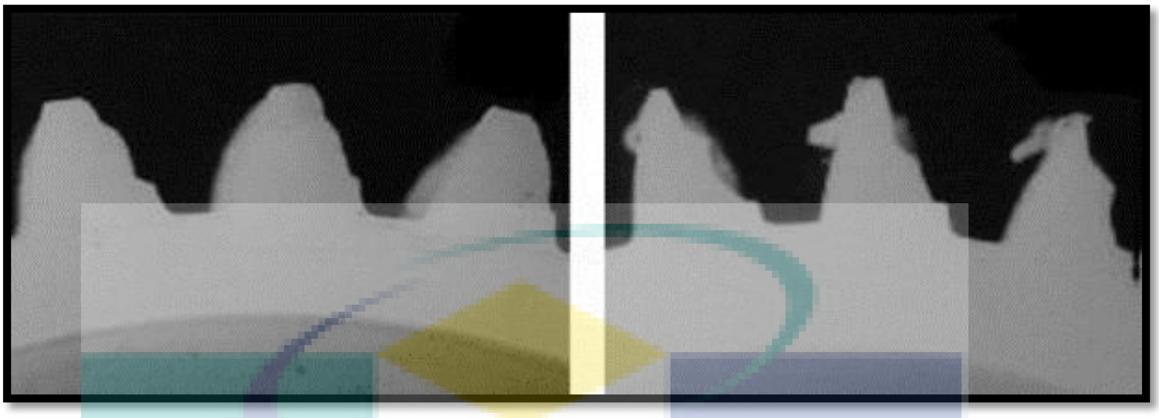




Figure 2-2 Wear on polymer gears with module 2 mm and 30 gear tooth [8]

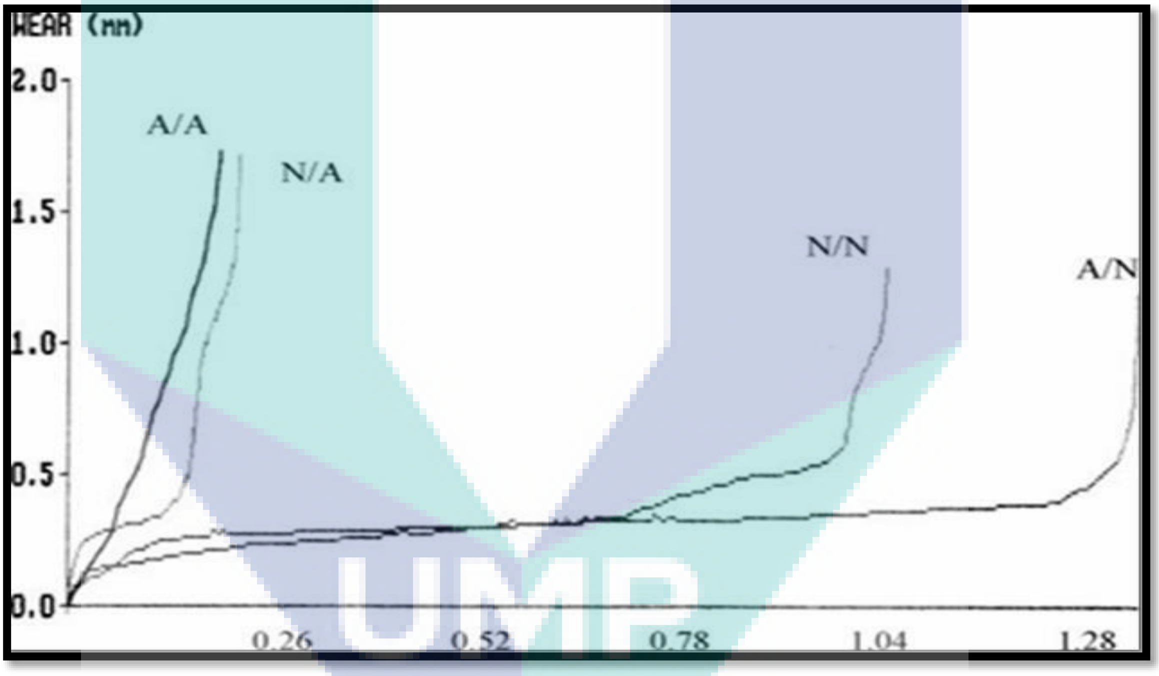




Figure 2-3 Results on Nylon/Acetal (N/A), Acetal/Nylon (A/N), Acetal/Acetal (A/A) and Nylon/Nyon (N/N) gear pairs [9]

### 2.2.2 The wall thickness

Wear rates for Acetal gear produced by machine cut and injection moulding are independent to the manufacturing process as reported by K. Mao et al [10]. The gears undergo testing at load 6 – 9 Nm at 100 rpm and undergo wear in three phases. The running-in and linear phase produced little wear debris, but in the rapid wear period, wear debris increased and so does the wear rate. After about 33% of tooth thickness removed, the gear started to fail. An incremental step loading (load is incrementally added without changing the test gears) was used and it was compared to the conventional procedure (test gears is changed for every load value). The result obtained showed that the incremental step loading test produces adequate result and can be completed within hours compared to conventional testing which takes up weeks. It was also noted that bending occurred when the material is momentarily melted causing it to jump out of mesh. The repeated motion of sliding at addendum and dedendum region produced heat caused by the friction of the tooth surface leading to adhesive wear.

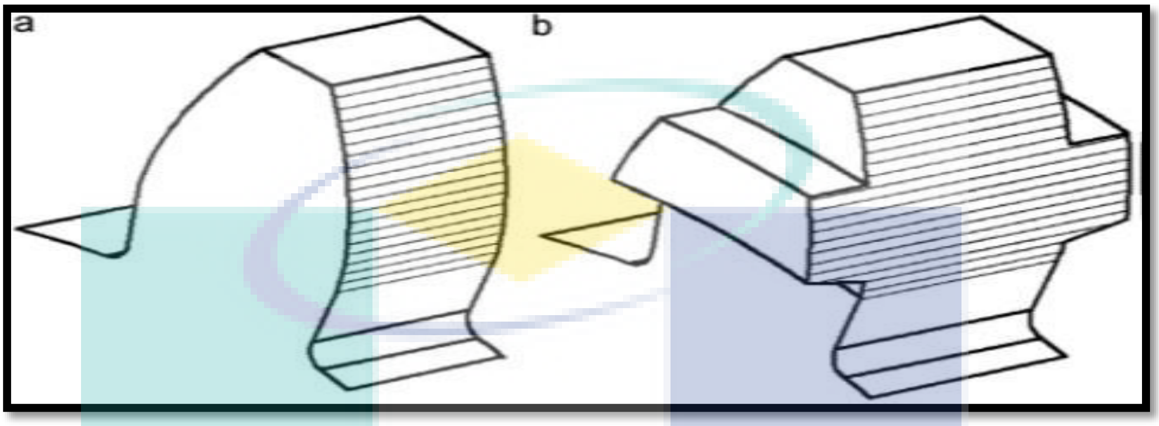
The various types of failure in unreinforced and reinforced Nylon 66 gear was studied by S. Senthilvelan and R. Gnanamoorthy [11] using tooth thickness and weight loss measurement technique. Unreinforced and reinforced Nylon 66 gears were meshed with a stainless steel (SS316) gear. Fig. 4 shows the deformation of teeth region undergone by the glass reinforced Nylon 66 gear. Reinforced gears showed a uniform material loss compared to unreinforced gears because glass fibre have better adhesion to the matrix compared to carbon fibre. Wear of tooth flank region in glass reinforced fibre is caused by softening of material and scraping by opposing stainless steel gear tooth. The wear occurred is due to the low thermal resistance of the material. In the case of carbon fibre reinforced gear, no appreciable tooth deformation was present due to high stiffness and good thermal resistance of the material. This result was obtained at the test parameter of 1000 rpm rotational speed and loads ranging from 1.5 N.m to 3 N.m.

Figure 2-4 Tooth thickness reduction due to scraping of steel gear tooth [11]

### 2.2.3 Cracks

Cracks often occur at the root of the tooth and will propagate causing tooth breakage. The effect of rotational speed on the performance of unreinforced and glass reinforced Nylon 6 was studied by S. Senthilevan and R. Gnanamoorthy [12]. The glass fibre reinforced gear showed improvement in mechanical strength and thermal deformation. They noted that the performance of gears was influenced by the load applied. The performance was only influenced by speed at the higher load condition. Gear root tooth crack and tooth wear were observed occurring at lower load, 8 MPa for both materials. When the load is higher, plastic deformation occurs on the unreinforced gear and at 15 MPa deformation starts to occur in glass fibre reinforced gear. At low stress levels, gear tooth root cracking and tooth wear was the main factor of failure, and in the higher stress level, deformation of material at high temperature causes failure. Modification on gear tooth made from Nylon 6 was reported by H. Imrek [13] and the failure for each design was studied. The tooth was modified as seen in Fig. 5 so that the single mesh area was increased thus reducing the load and temperature of the area. This reduces the wear rate and improves the overall teeth temperature. The unmodified gear showed cracking at the pitch area in Fig. 5 while in modified gear, cracking occurred at tooth roots.

Modification of gear tooth was also studied by H. Duzcukoglu [14] where holes are introduced to the tooth body of the gear. This serves as a cooling mechanism and to improve the heat distribution. Gears with modification shown smooth wear transition compared to unmodified gears. As the tooth load increases, the tooth profile wear becomes more noticeable at the tooth root and tooth tip region. It was concluded that wear occurs due to softening and detachment of material from the contact area and with the modification, the damage is delayed with the help of increased heat transfer from the gear. The effect of different hub type on the spur gear performance was studied by S. Senthilvelan and R. Gnanamoorthy [15] using gears made from Nylon 66 and reinforced with carbon fibre. The hub was made from Nylon 66 and in cylindrical or spline shape. At 15 MPa of bending stress, both unreinforced and reinforced gears showed wear at tooth surface and flank. When the bending stress is at 20 MPa, the gear fitted with cylindrical hub failed at the gear and hub joint at 2 x 105 cycle and the gear with spline hub showed wear characteristics such as cracks at tooth root region. The failure between circular hub and gear is caused by the joint failure meanwhile in spline hub and gear the failure is caused by the gear tooth. The failure for unreinforced and reinforced gear were the same in the spline hub.




Unmodified Modified

Figure 2-5 Gear profile models, arrow indicates crack propagation [13]

Unmodified Modified

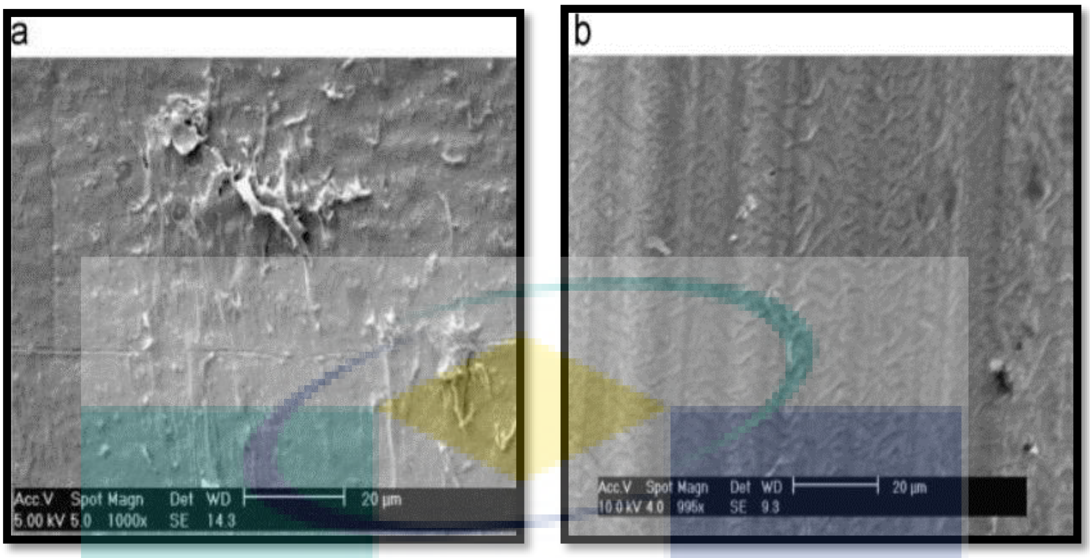
Figure 2.5:

### 2.2.4 Microstructure Surface Condition Monitoring

This method is used to detect micro crack or deformation on the gear surface which are not visible with naked eye. With the introduction of composite polymer, this method becomes more important as it is capable to inspect the fibre structure and alignment.

Scanning electron micrograph (SEM) was used by A. R. Breeds et al [16] in order to study the surface condition. Three major interest region were dedendum, addendum, and pitch line. With the help of SEM, they were able to detect large pits or scoops of material were removed at the dedendum, smooth surface due to wear at addendum caused by sliding and rolling motion of gears and the formation of a ridge at pitch line caused by rolling. An SEM examination around the gear tooth pitch and root areas were conducted by K. Mao et al [10] to determine whether wear occurs at that region. From the gear mesh theory, there is nearly zero friction around the pitch point, however the images from SEM showed otherwise. This shows that SEM can also be a reliable method to detect failure in polymer gears. Figure 2.5 shows the difference of wear occurring at the tip and pitch point of the gear.

The effect of fibre orientation was analysed using SEM by S. Sentilvelan and R. Gnanamoorthy [11]. A perpendicular aligned fibre orientation showed better performance where it helps slowing the crack growth, thus improving the gear life. In the glass reinforced gear, matrix nylon material was found adhered to the protruded glass fibre on the fracture surface. The cracked surface showed few cavities and nearly flat. This is due to the better adhesion of glass fibre and nylon matrix. Molten smeared layers were also seen on the surface. A high number of cavities were observed in the carbon reinforced gear cracked surface due to the poor adhesion between carbon fibres and nylon matrix. Molten material was absent due to better thermal properties of the carbon fibre reinforced Nylon 66. The fibre orientation is influenced by the gate location and tooth geometry. Both glass and carbon reinforced show poor wear resistance compared to unreinforced gear at the investigated condition. Molten material can be seen on the unreinforced Nylon 66 in Figure 2.6 and on glass fibre reinforced Nylon 66 in Figure 2.7 There was no molten material present on carbon fibre reinforced Nylon 66. However, cavities are present on both glass fibre and carbon fibre reinforced Nylon 66 in Figure 2.7.




Wear at tip                                        Wear at pitch

Figure 2-6 SEM image of wear on polymer gear occurring at tip and pitch [10]

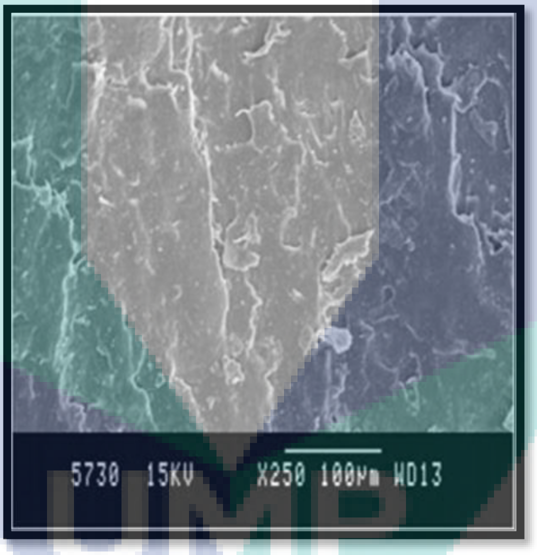
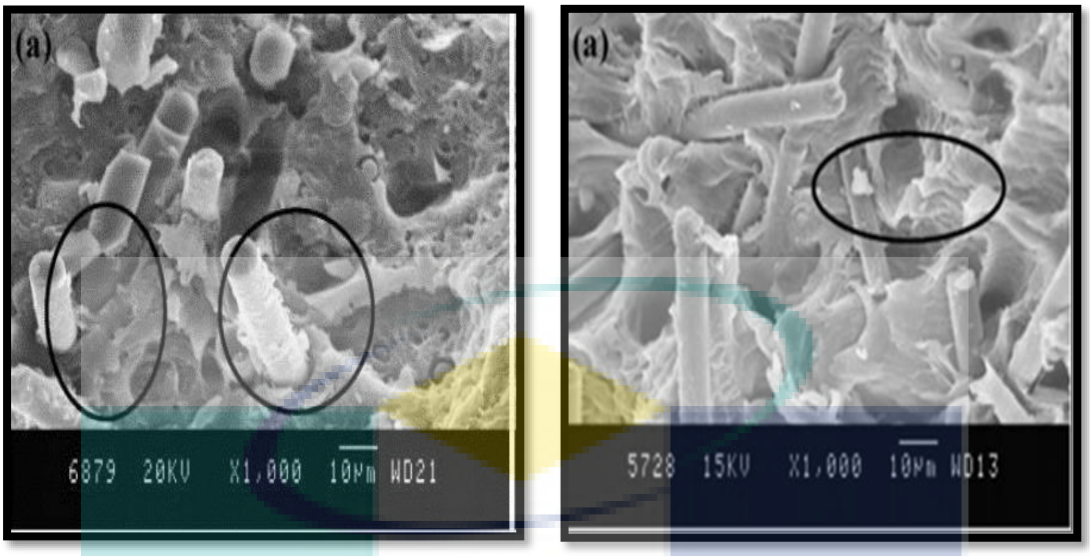



Figure 2-7 Surface condition of unreinforced Nylon 66 [11]




Glass Fibre Reinforced Nylon 66 Carbon Fibre Reinforced Nylon 66

Figure 2-8 Surface condition of polymer gear [11]

The surface of loading tooth was inspected by H. Duzcukoglu et al [17] to determine the presence of transverse crack. It was found that the transverse cracked occurred due to thermal softening caused by accumulated heat. These cracks shall merge and grow resulting removal of material in the shape of flakes. The possibility of controlling wear by applying coatings on tooth flanks were studied by K. Dearn et al [18]. Five types of coating were used; PTFE, boron nitride, molybdenum disulphide and graphite to protect the gear. SEM was used to study the surface of each gear with different coatings. PTFE and graphite provide most optimum protection as it lowers the friction between gear teeth, reduces running temperature and subsequently the wear of gears. However, it is possible that the coating will lose its effectiveness as the protection film wears over time.

### 2.2.5 Weight loss

This characteristic was found to be acceptable if gears were made using pure polymer. However, if it is made from composite, it become less reliable as the weight is affected by the composition of fibre and moisture or water presence. This was shown by N. A. Wright and S. N. Kurenka where they introduced a pair of control gear in their research [19]. They stated that the weight loss from running test can be considered as one of the method to determine failure, if only the material used does not have a high affinity for water. They noted that Polyamide 66 absorbs a significant amount of water, therefore the introduction of control gears and it was placed on the drive gearbox. They calculated the weight loss by subtracting the weight loss by control gear from the total measured weight loss by the test gear.

The weight loss method was used by C. H. Kim [20] to determine the wear volume of both Nylon and Acetal pinion. The pinion had three design, a solid gear tooth body, a drilled hole on the gear tooth body and a hole inserted with steel pin. The hole type and insert type showed less wear rate than the solid one. In the Nylon gear, hysteric heat loss was decreased by the hole in the tooth, while in the steel pin type, heat is absorbed and distributed by the pin. Both design led to decrease in wear rate and degradation of Nylon material. In the case of Acetal pinion, the variation of cross section increased the specific wear rate. The decrease of cross section area led to deformation and plastic flow on the Acetal pinion. This will lead to severe wear due to interference and severe contact between the Acetal pinion and steel driver gear. The wear rate in Nylon pinion decreased by over 30% and an increase in service life by 415%. While the Acetal pinion, it causes increase in wear, therefore this method can only be applied to visco-elastic material only.

The wear resistance of carbon nanotube reinforced Acetal gear was studied by S. Youseff [21] by determining the weight loss of the gear. It was then compared to results from previous research [22]. The results showed that the average wear resistance of Acetal reinforced with carbon nanotube compared to Acetal improved significantly. Spur gear improved by 28%, helical gear by 35%, bevel gear by 44% and lastly worm gear up to 47%.

### 2.2.6 Thermal Damage and Temperature Detection Using Thermal Camera or Temperature Sensor

In this method, temperature of the gears is taken during or after they were tested. Some researcher also used data acquisition system to record the operating temperature. This failure detection method is essential as different loads will influence the running temperature and affect the material properties when it reaches the glass transition temperature or the melting temperature.

The failure mode of polymer and polymer composite was found to be different as shown by S. Sentilvelan and R. Gnanamoorthy [11]. The gears were made from Nylon and reinforced with carbon or glass fibre. They also found that the surface temperature of unreinforced gear was higher compared to reinforced gear. In the reinforced Nylon, carbon reinforced had a lower temperature than glass reinforced. The reinforced gears lower temperature was contributed by a better tooth stiffness, lower friction and good thermal properties. A high tooth stiffness prevents tooth deflection which contribute to less unwanted contact between tooth surfaces which causes heat. The improved heat dissipation ability increased the gears life considerably. The introduction of cooling holes was reported by H. Duzcukoglu [17] in order to decrease thermal damage. Three design of gears were studied, first is unmodified, the second gear had a hole drilled at the pitch point of the gear tooth and the third design have holes at the pitch point and on the body of the tooth as seen in Figure 2.8. The temperature was detected using a non-contact infrared temperature sensor and recorded on a PC by using data acquisition system. The first design failed at the vicinity of the pitch diameter, caused by softening. This was due to the gear inability to emit heat which was accumulated during the running process. As the load increases, the thermal damage also increased. This causes the material to soften and severe tooth deformation occurs. In the second design, partial thermal softening at the pitch region and tooth root region was observed. The amount of thermal damage was reduced by using this design, however, there is still damage on the surface of the loading tooth. For the third design, only thermal damage initiation was observed at the high load, 18.1 N.m. The heat produced in each design is from the friction between the driver and driven gear. The result from heat produced affecting the gear tooth can be seen in Figure 2.8.

Figure 2-9 Tooth condition for each design when the load is at 6.1 N/mm [17]

A design in which an internal hole or steel pin inserts are introduced to the tooth body was presented by C. H. Kim [20] to improve heat transfer process and stress concentration. Temperature of the tooth surface was measured and investigated using a non-contact type temperature sensor. Three load value was used, which are 9.8N/mm, 19.6 N/mm and 29.4 N/mm. At first load value, the hole type pinion had the lowest temperature value but have a higher fluctuation. The steel insert pinion has a slightly higher temperature, but the temperature maintained. When the load is 19.6 N/mm, the insert type pinion showed better performance than the others. At the highest test load, fracture can be seen from all types of design. The insert type took the longest time before failing followed by hole type and lastly solid type. It can be noted that the decrease in tooth temperature will result in better life and reduction of wear.

Polymer gear can fail in two typical ways, fatigue or sudden melting as reported in the research by A. Pogacnik and J. Tavcar [23]. A new multilevel accelerated testing procedure was proposed by the authors and the results which are life span and gear temperature were compared with a calculation procedure. The temperature was recorded using a thermal camera and the materials were PA 6, PA 6 with 30% glass fibres and Polyacetal. The maximum gear temperatures and load levels are different for every pair of materials. PA6/PA6 pair generated the highest temperature due to the high coefficient of friction. POM/PA6 pair gives the lower temperature due to lower coefficient of friction. The melting of gears was a consequence of overload and an increase in temperature. By avoiding problematic material combination, the failure due to thermal characteristic can be avoided.

The effect of different surface roughness was studied by J. Mertens and S. Sentilvelan [24] where three different value of coefficient of friction studied. Three stainless steel gear with coefficient of friction 3.8-4.1μm, 2.5-2.8μm and 1.9-2.2 μm was mated with polypropylene gear. The surface temperature of test gear was measured using a non-contact infra-red sensor. The frictional values of the surface are influenced by the hardness and micro geometry of the stainless steel gear. When a polymer slides on steel, adhesion and deformation occurs, contributing to the friction between those two surfaces. At a higher load, the surface interaction will increase, causing the friction, wear and temperature to increase which can be seen in Figure 2.9. Polymer gear will generate more heat when meshed with surfaces having a high friction coefficient thus affecting the performance of the polymer gear. It can be seen that Gear A have the highest friction followed by B and C which relates to the higher temperature produced by A and followed by B and C at each load.

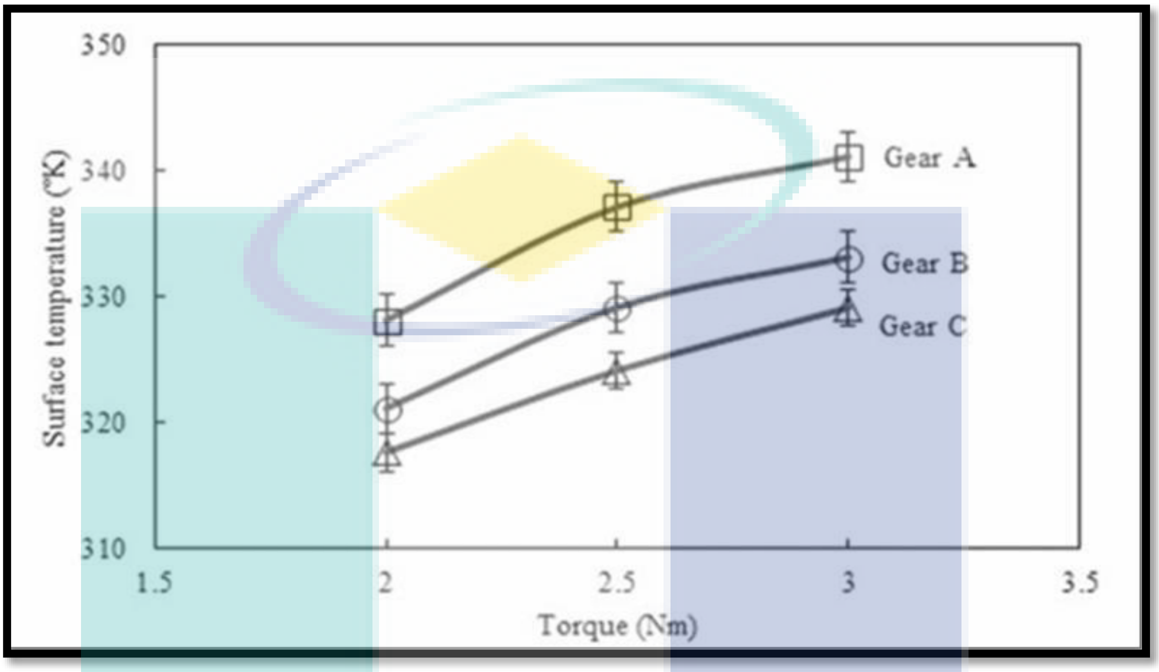



Figure 2-10 Comparison of surface temperature for test gears [25]

### 2.2.7 Rolling and Sliding

There are two type of contact that is conformal contact non-conformal or counter-formal contact. Conformal contact occurs when contact is made over an extended area and test pieces are shaped accordingly in order to allow full face contact. Non-conformal or counter formal contact happens when contact is nominally made at a point or along a line. When gear teeth in mesh, non-conformal line contact is made.

The type of contact can be simplified into two component during the meshing cycle between two gear teeth; roll and slide. The extent of each component is different for the driving gear and the driven gear and varies throughout the cycle. During the meshing cycle the contact conditions at a point of contact are often described in terms of slip ratio (i.e. ratio of sliding velocity to average rolling velocity), load, radii of curvature and sliding speed. The rolling direction is from root to tip on the driving gear and from tip to root on the driven gear. However, in the root of the driving gear, the sliding direction is opposite to rolling, while at the tip it is the same. Figure 2.10 show the sliding direction in the driver is always from the pitch line outwards. Conversely, on the driven gear, sliding speed is from root and tip inwards to the pitch line. This leads again to sliding direction being opposite to rolling at the root and the same as rolling at the tip. A situation, where sliding speed is opposite to rolling is known as “approach action” whereas co-directional sliding and rolling is known as “recess action”. Approach action is sometimes considered to be more damaging than recess action and consequently, modifications to gear profiles have been attempted in order to increase the proportion of the meshing cycle which is subject to recess action.

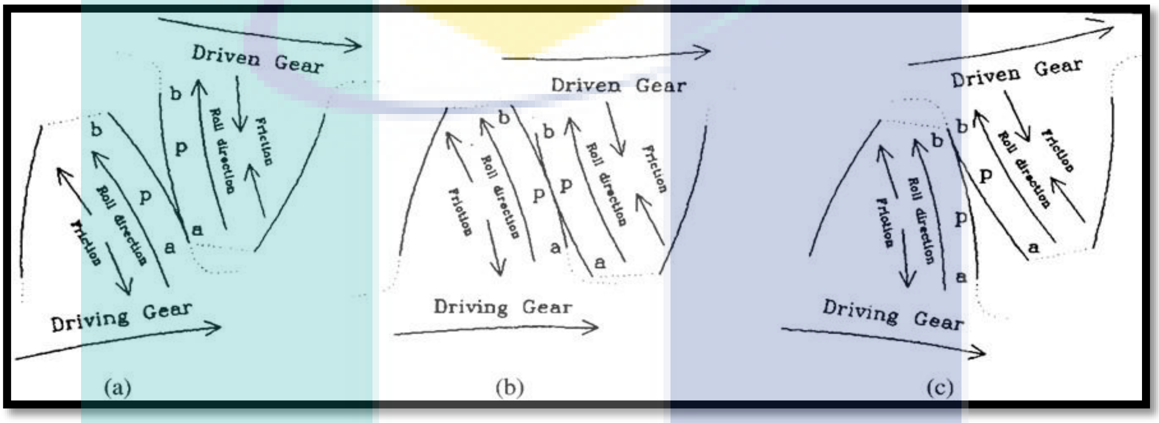



Figure 2-11 Sliding direction in the driver is always from the pitch line outwards [19]

# CHAPTER 3

# METHODOLOGY

## 3.1 Introduction

In this chapter, it will be discuss about the method and process fabrication of gear and the experiment that need to study wear behaviour of biopolymer gear and polymer. Objective of this project methodology is to show the flow of the project from fabrication of gear until the gear testing.

For the beginning of the process, gear will be produced by using injection moulding process. Then the process will be continuing with testing the gear on the test rig. The test equipment used for validate and test biopolymer gears and polymer gears to study wear and durability of the gear. Already available and set the alignment in the injection molding machine. Biopolymer gear and polymer gear will be produced by injection molding process.

## 3.2 Flow Chart at Methodology

Methodology flow chart acts as process flow for the guideline in this project. As a result, biopolymer gear and polymer gear will be produce from the injection molding process without have troubleshoot during the process. Figure 3.1 illustrates the flow chart for the methodology of this project.

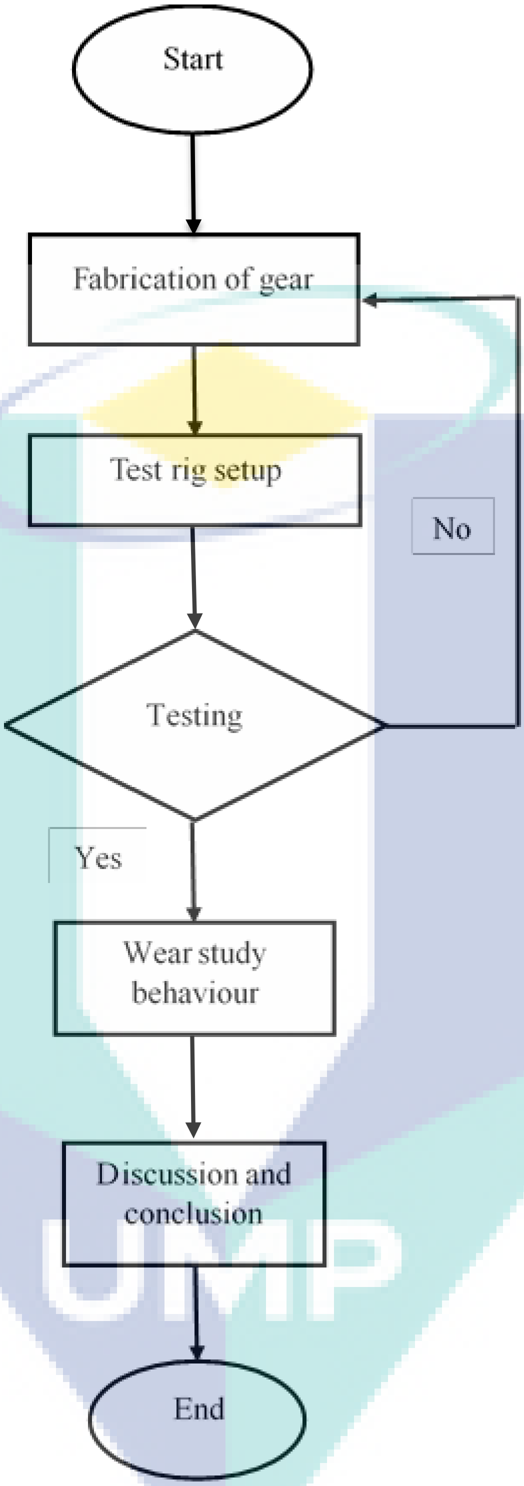



Figure 3-1 Flow chart

## 3.3 Mould

The dimension of the mould is 250mm length, 200mm height and 250mm width.

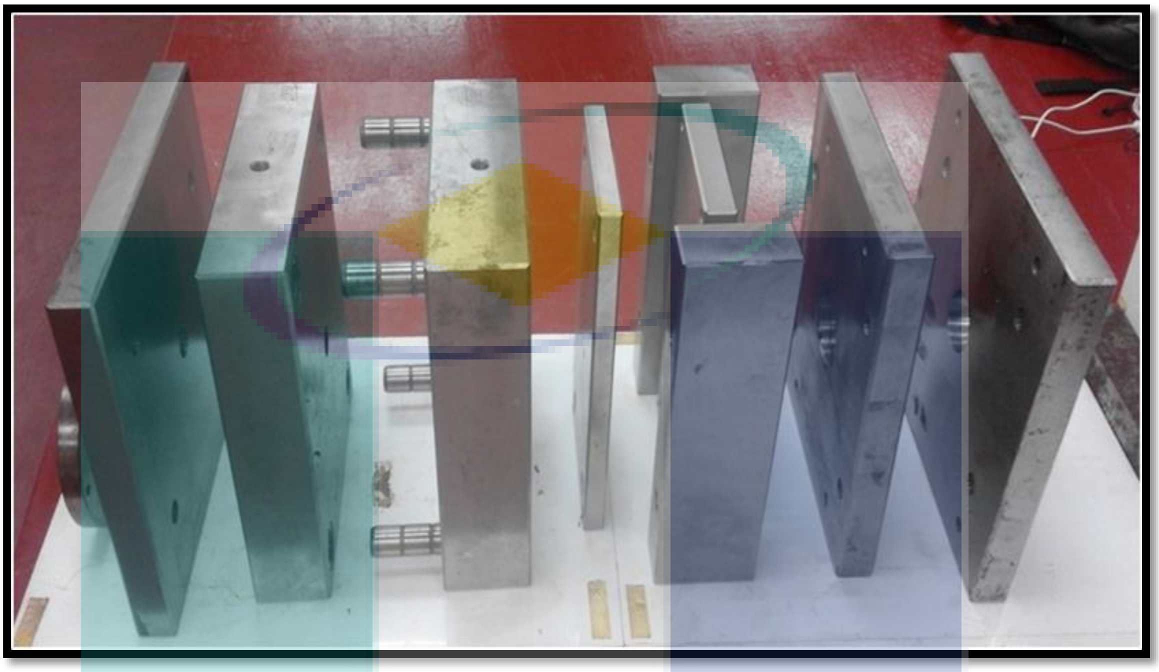


Figure 3-2 Exploded view of mould before assembly

Figure 3-3 Gear insert

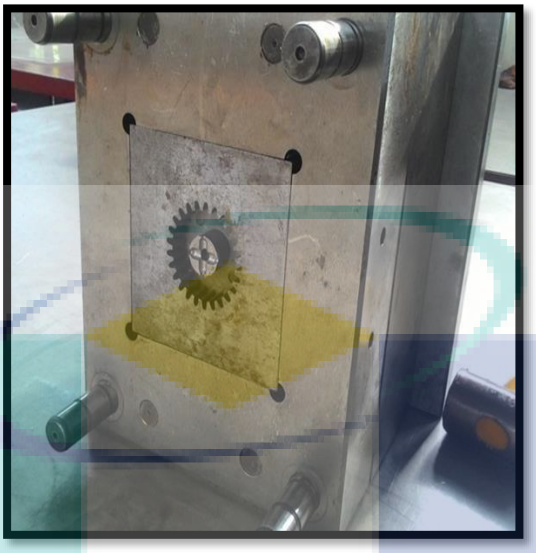


Figure 3-4 Mould assembly

### 3.4 Injection Moulding Process

The locating rings fit at top plate and will have aligned with injection moulding machine nozzle centre. It will be references to aligned mould with injection moulding machine.

Table 3-1 Parameter setting for this process is:

| Test gear | | Biopolymer (PLA) | Polymer (ABS) |
|---|---|---|---|
| Screw temperature (ºC) | | 160 | 260 |
| Dosage stroke (mm) | Driver | 25 | 25 |
| | Driven | 35 | 35 |
| Injection speed (mm/s) | | 75 | 50 |
| Injection pressure (Bar) | | 210 | 340 |
| Cooling time (s) | | 110 | 130 |
| Back pressure (Bar) | | 50 | -50 |

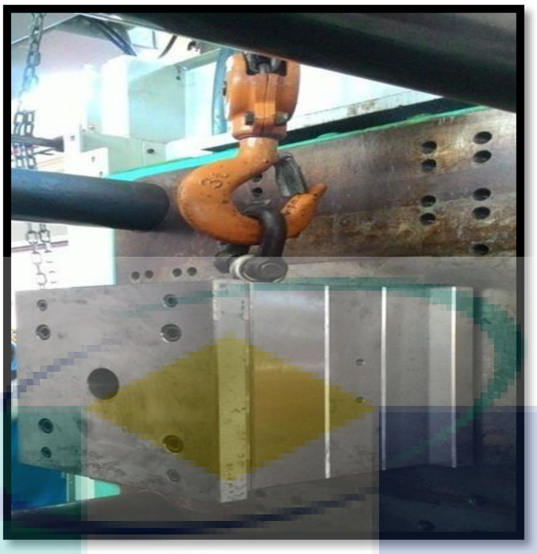


Figure 3-5 Mould was fit with the injection machine


Figure 3-6 Pressure and speed of injection for injection process

Temperature used in this process is around 40 to 160 °C for biopolymer and 40 to 255 °C for polymer which are included the temperature of mould, nozzle and machine.

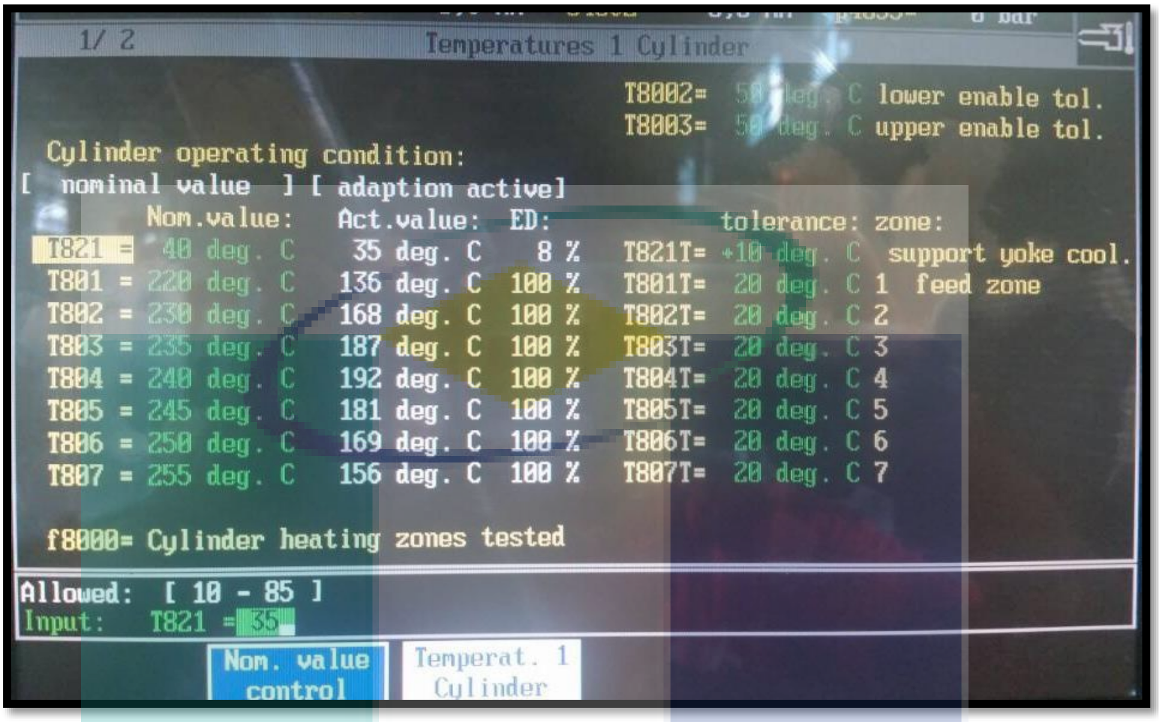



Figure 3-7 Temperature variance for injection process

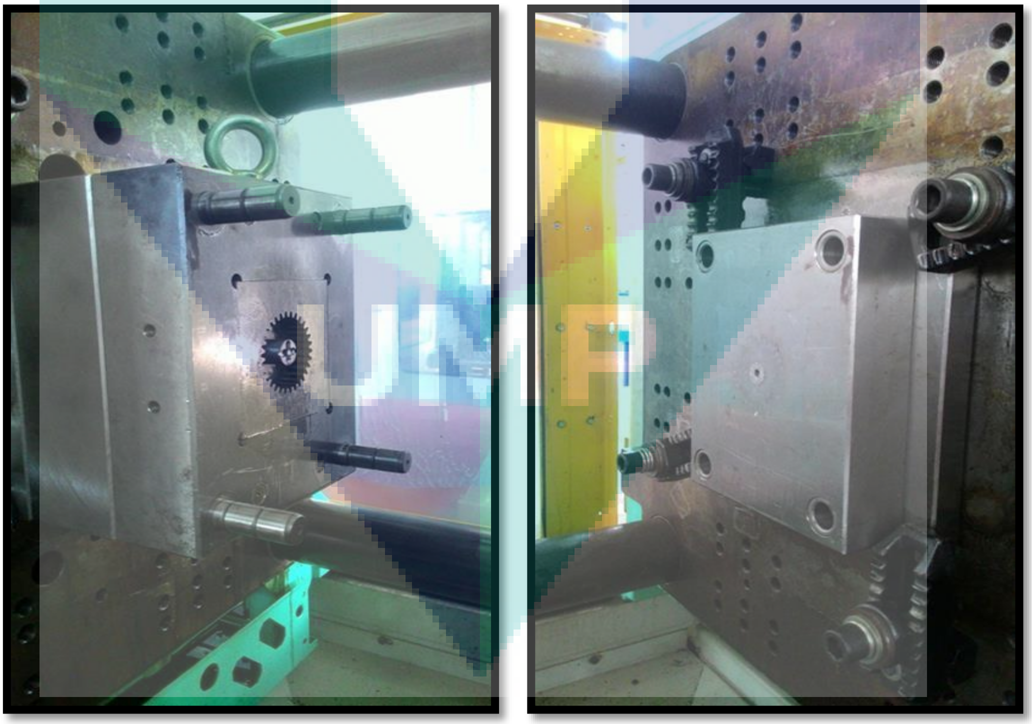


Figure 3-8 Mould was open during injection process

Material used for injection moulding process for gear fabrication is Polylactic acid pellets (PLA) and Acrylonitrile Butadiene Styrene (ABS). These two polymer are hygroscopic thermoplastic that easily absorb water from the atmosphere. Prior to injection molding process, PLA and ABS are drying first for 2 hours to prevent degradation.

Figure 3-9 Polylactid acid pellets (PLA)

Table 3-2 Mechanical properties of polylactic acid

| Properties | Polylactic acid (PLA) | Acrylonitrile Butadiene Styrene (ABS) |
|---|---|---|
| Degradation temperature | 190 °C | 370 °C |
| Density | 1100 (kg/m$^{-3}$) | 1070 (kg/m$^{-3}$) |
| Flexural modulus | 475 Mpa | 2500 Mpa |
| Flexural strength | 21 Mpa | 75 Mpa |
| Melting temperature | 165 °C | 260 °C |
| Tensile strength | 14 Mpa | 40 Mpa |
| Tensile elongation | 59 % | 30 % |
| Thermal conductivity | 0.13(W/(m. K)) | 2.34(W/(m. K)) |

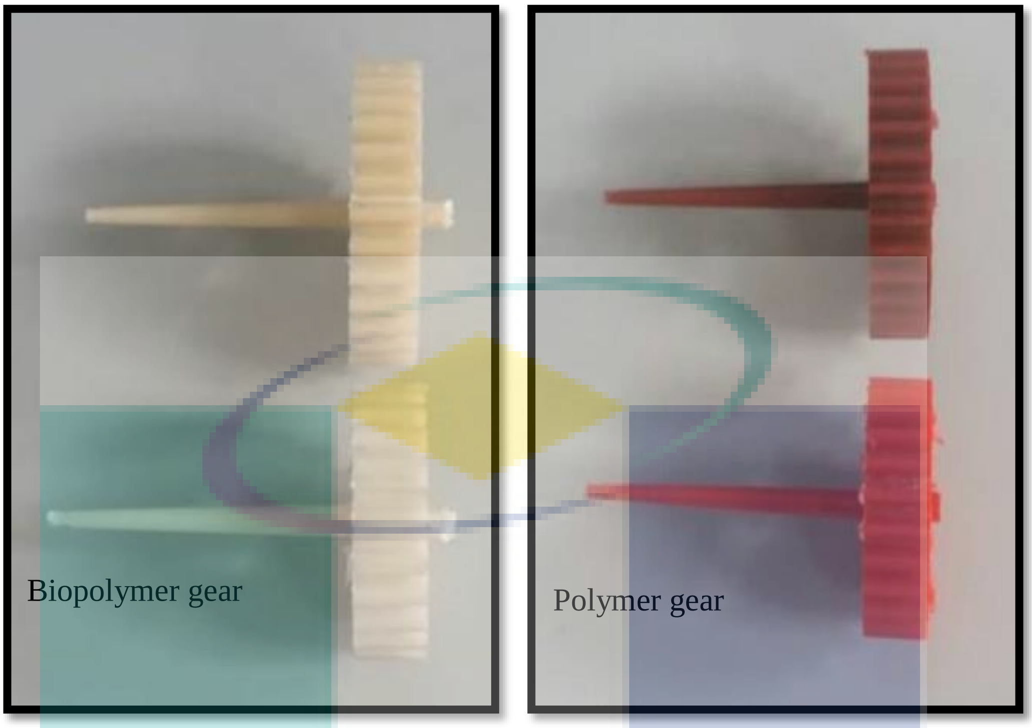



Figure 3-10 Gear produce after injection process

### 3.5 Fabrication of Motor Stand

#### 3.5.1 Bend Saw Machine

This bend saw machine was used when to cut the 150x100x100 mm steel cube to fabricate the motor stand.


Figure 3-11 Cutting of steel metal cube

Dimension of the plate that need after cut:

1. Motor stand: 146x65x92 mm

#### 3.5.2 Milling machine

Milling machine is used to get the good surface and dimension of stand after cut using bend saw machine. Used face mill method to get the flat surface of stand and exact dimension of motor stand. This process used constant spindle speed which is 350-450 rpm of tool.

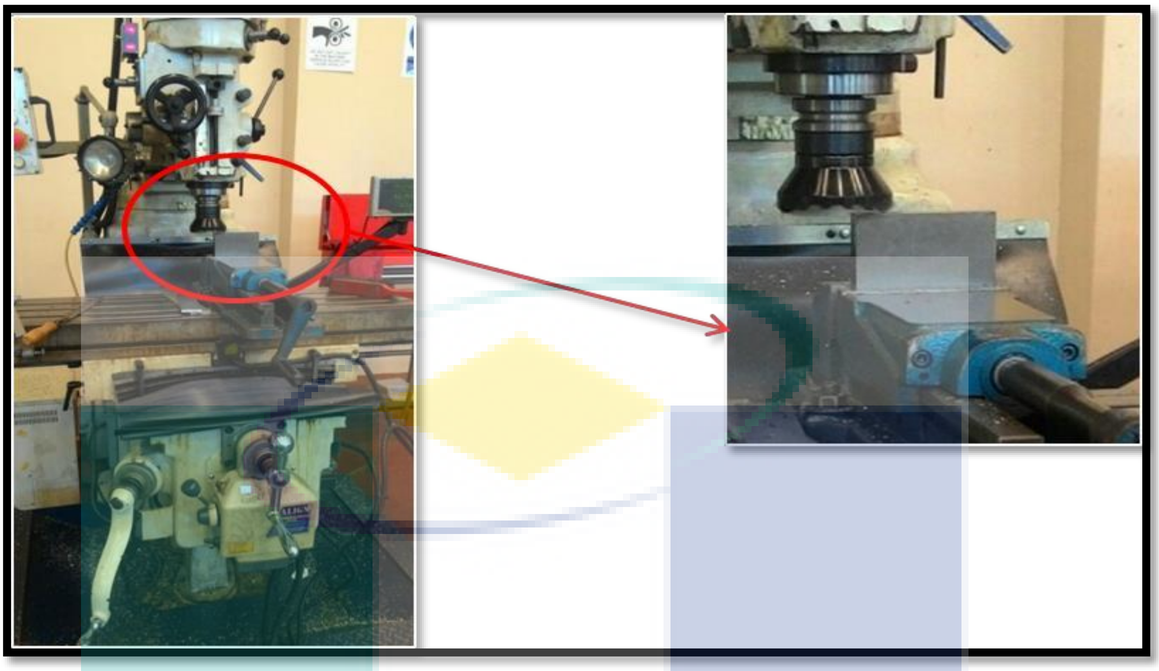


Figure 3-12 Face mill process for motor stand to get the actual dimension

### 3.6 Gear Test Rig

This test rig has table plate with dimension 600x250x30 mm. The slot on the table used for making the driven plate to be unfixed and can be changed.

Figure 3-13 Gear test rig with the load

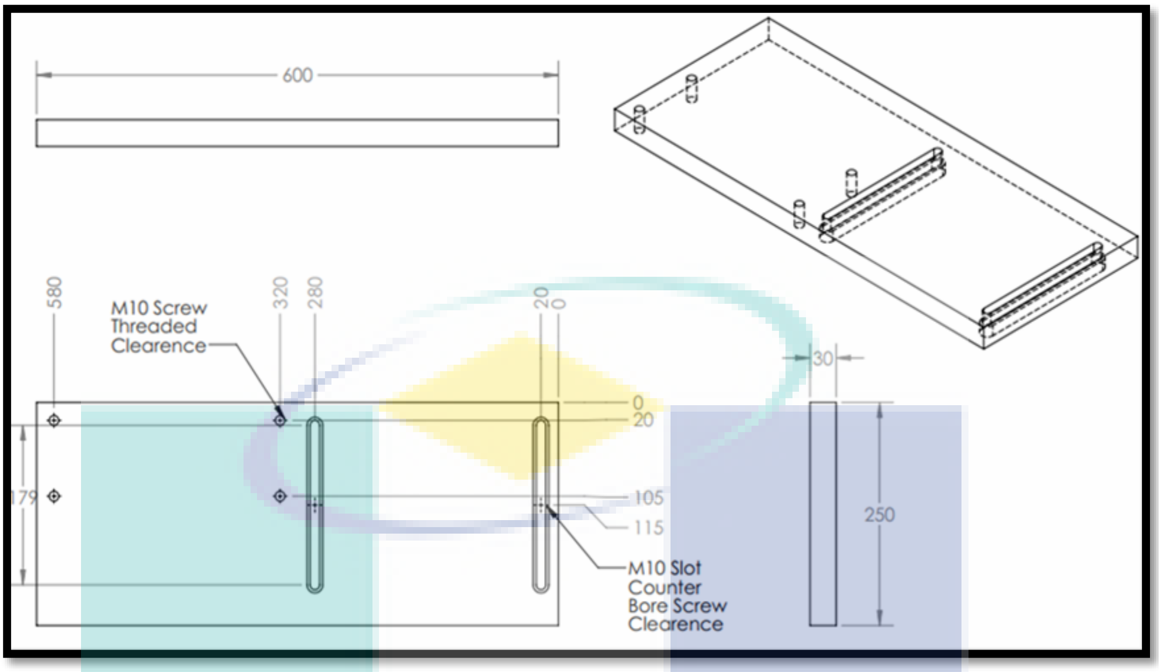



Figure 3-14 Drawing of table plate

The design also have two plate that is driver plate and driven plate that attached with table plate. The driver plate is fixed while driven plate of the test rig can be move depend on the size of the gears that are going to be used by using slot, bolt and nut.

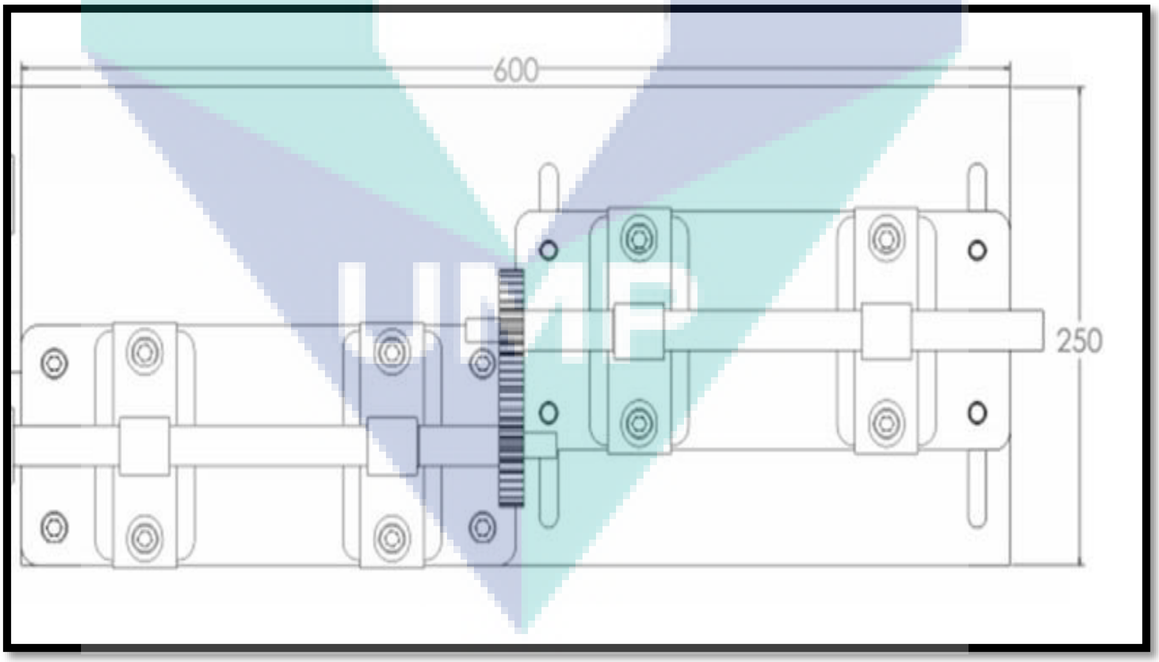



Figure 3-15 Top view of table plate

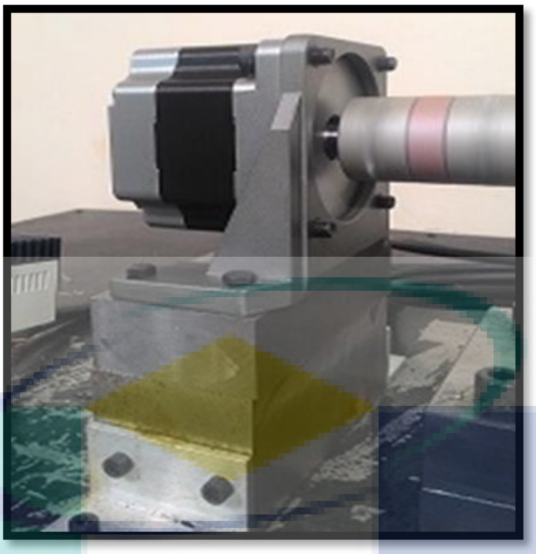


Figure 3-16 Motor

- Model - BMUD400-S
- Output - 0-240V 0.333Hz 2.0 A
- Power - 400W

Figure 3-17 Motor controller

- Model - BMUD400-S
- Input - 200-240V 50/60Hz 2.8A
- Output - 0-240V 0.333Hz 2.0A

• Power - 400W

## 3.7 Gear Meshing Assembly

### 3.7.1 Gear Tooth Contact Pattern

When gears operate near their maximum load capacity, very high contact pressure occurs at the mesh interference where it can lead to wear and tear of the tooth.It is very important to check the surface contact before run the experiment. Contact pattern checks require painting some or all of the teeth of at least one member with gear marking compound and rotating the gears to see how they contact in the marking compound. Permatex Perussian Blue been painted on the teeth surface by using colour brush. This procedure is strictly needed to be done to aid precision fitting of gear tooth and prevent distraction to get a good result

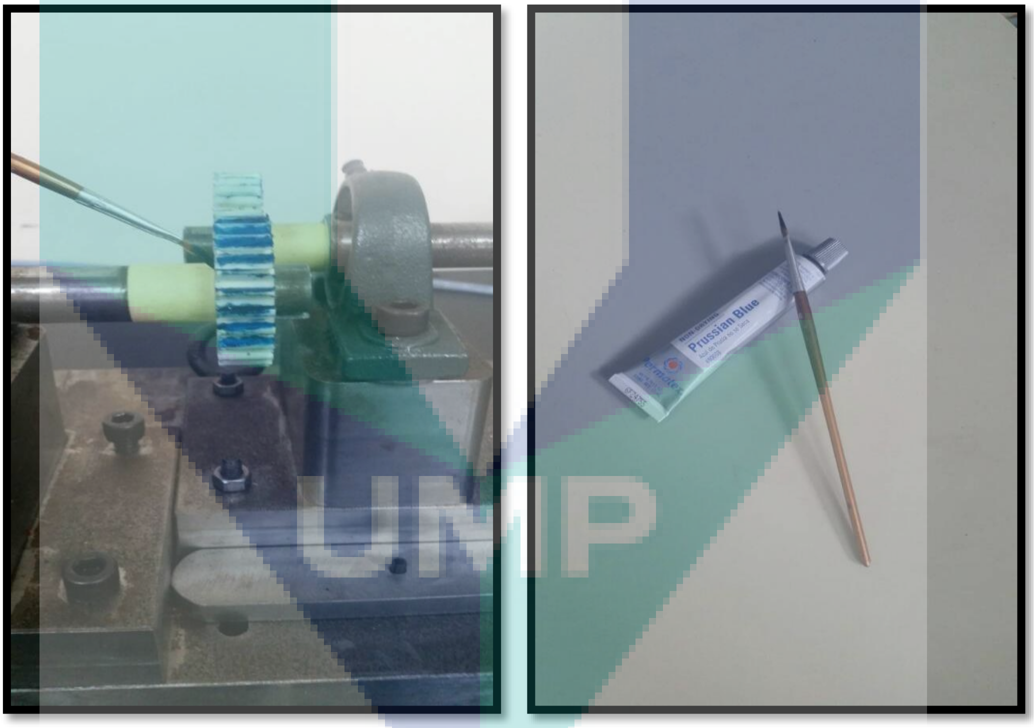



Figure 3-18 Painted process by using Non-drying Permatex Prussian Blue colour

### 3.7.2 Checking Backlash

Backlash can be checked using a dial test indicator applied to a tooth on one member of the mesh and moving that member back and forth while holding the other member still.

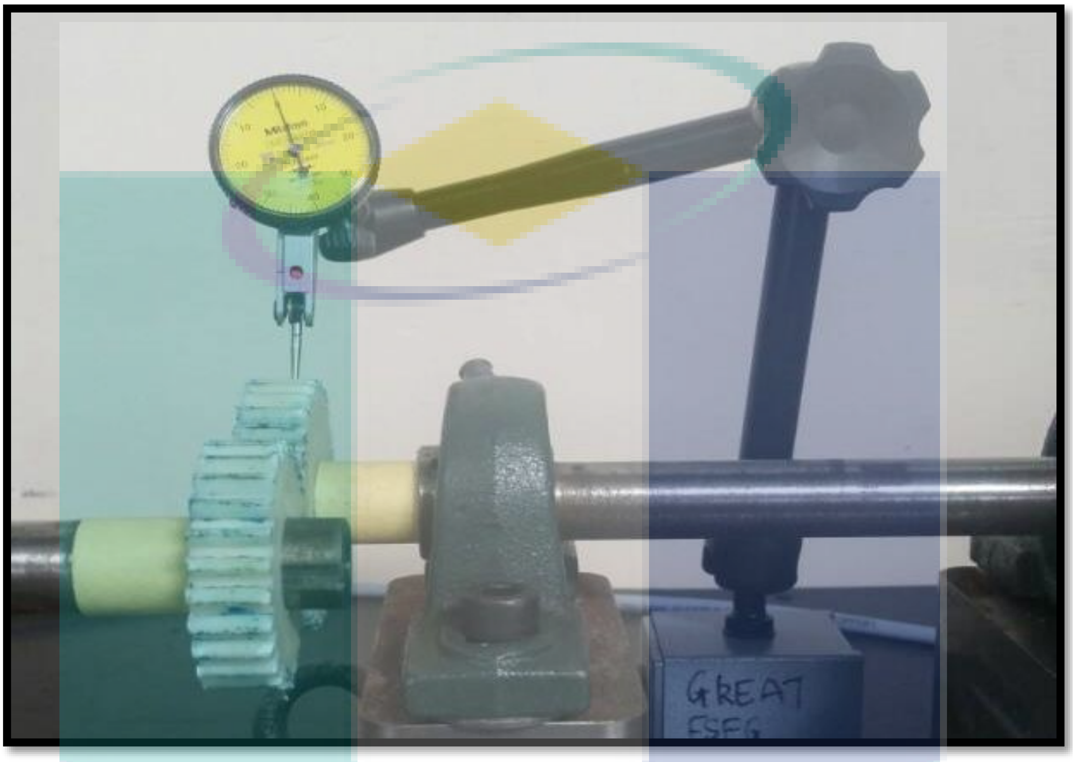



Figure 3-19 Dial test indicator been used to check the gear backlash

### 3.7.3 Gear Centre Distance

In order to make sure that the assembly process is perfect, gear centre distance is needed to be consider by doing some calculation. By doing this, the gear alignment can be checked in order to get an identical surface contact.

| Name | Symbol | Pinion | Gear |
|---|---|---|---|
| Module | $m$ | $m = \frac{a_1}{z_1} = \frac{a_2}{z_2}$<br>$m = 2$ | |

| | | | |
|---|---|---|---|
| Tooth | $z$ | $z_1 = \frac{d_1}{m}$<br>$z_1 = 25$ | $z_2 = \frac{d_2}{m}$<br>$z_2 = 30$ |
| Pressure angle | $a$ | $20°$ | |
| Face width | | $15mm$ | |
| Reference pitch circle diameter | $d$ | $d_1 = z_1 m$<br>$d_1 = 25 \times 2 = 50mm$ | $d_2 = z_2 m$<br>$d_2 = 30 \times 2 = 60mm$ |
| Tooth tip circle diameter | $d_a$ | $d_{a1} = d_1 + 2h_a$<br>$d_{a1} = 50 + 2(2) = 54mm$ | $d_{a2} = d_2 + 2h_a$<br>$d_{a2} = 60 + 2(2) = 64mm$ |
| Root circle diameter | $d_f$ | $d_{f1} = d_1 - 2h_f$<br>$d_{f1} = 50 - 2(2.5) = 45mm$ | $d_{f2} = d_2 - 2h_f$<br>$d_{f2} = 60 - 2(2.5) = 55mm$ |
| Addendum | $h_a$ | $h_a = m$<br>$h_a = 2$ | |
| Dedendum | $h_f$ | $h_f = h_a + c \geq 1.25 \times m$<br>$h_f = h_a + c \geq 1.25 \times 2 = 2.5$ | |
| Tip and root clearance | $c$ | $c = h_f - h_a \geq 0.25 \times m$<br>$c = h_f - h_a \geq 0.25 \times 2 = 2.5 - 2 = 0.5$ | |

| | | |
|---|---|---|
| Tooth depth | $h$ | $h = h_a + h_f \geq 2.25 \times m$<br><br>$h = h_a + h_f \geq 2.25 \times 2 = 4.5mm$ |
| Centre distance | $a$ | $a = \frac{d_1 \pm d_2}{2} = m\left(\frac{z_1 \pm z_2}{2}\right)$<br><br>$a = \frac{50 + 60}{2} = 2\left(\frac{25 + 30}{2}\right) = 55mm$ |

Table 3-3 Calculation process to get the gear centre distance

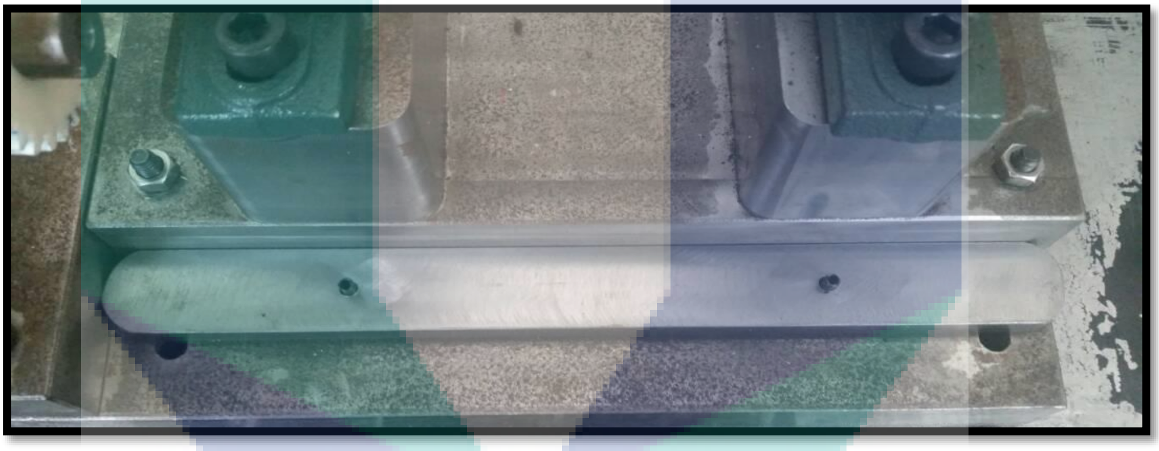


Figure 3-20 Locking plate as the marking point for the gear centre distance

## 3.8 Wear Analysis

### 3.8.1 Microstructure Surface Condition Monitoring

Vickers microscope is used to analyse gear surface microstructure before after the experiment.

Figure 3-21 Vickers microscope

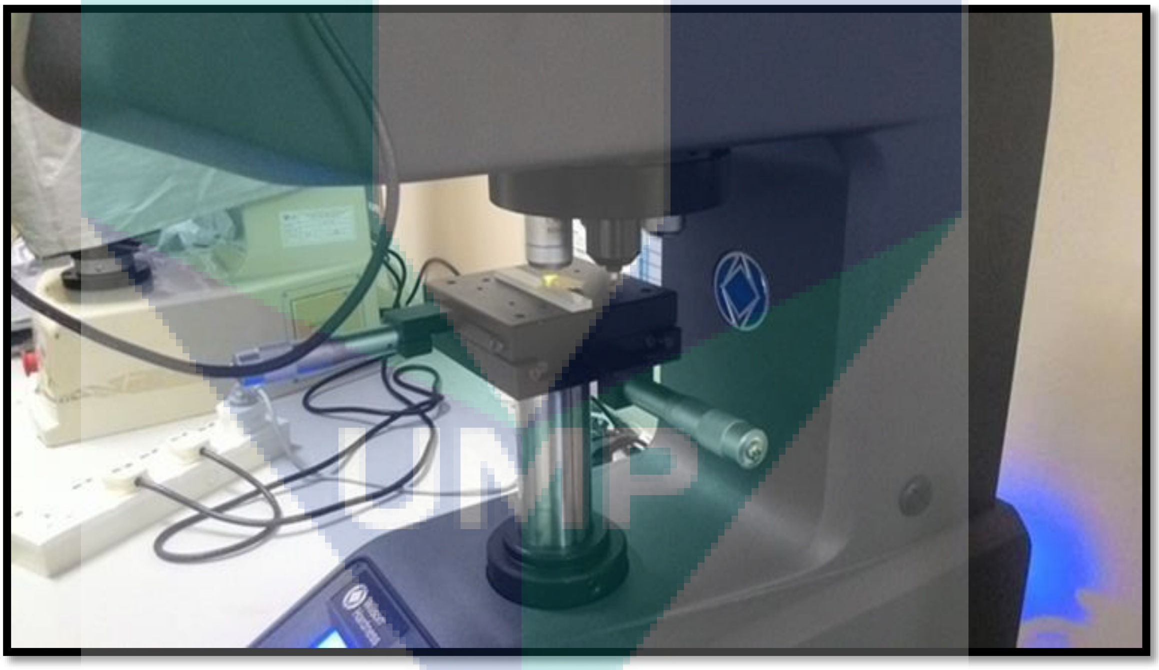


Figure 3-22 Microstructure analyse

Surface microstructure is monitor on the desktop by using WIN-Control software.


Figure 3-23 Microstructure monitoring

### 3.8.2 Weight Loss

Weight of the gear is measured before and after testing. Weight balance is used to measure gear weight loss due until 3 decimal places that is more accurate.

Figure 3-24 Weight balance

## 3.9 Gear Testing

### 3.9.1 Gear test rig

Rpm set is 500 rpm, 1000 rpm and 1500 rpm by using motor controller.

Figure 3-25 Gear test rig


Figure 3-26 500 rpm


Figure 3-27 1000 rpm


Figure 3-28 1500 rpm

### 3.9.2 Running Load

Second testing is running with same rpm that is 500 rpm, 1000 rpm and 1500 rpm and with additional load of 10 Newton.

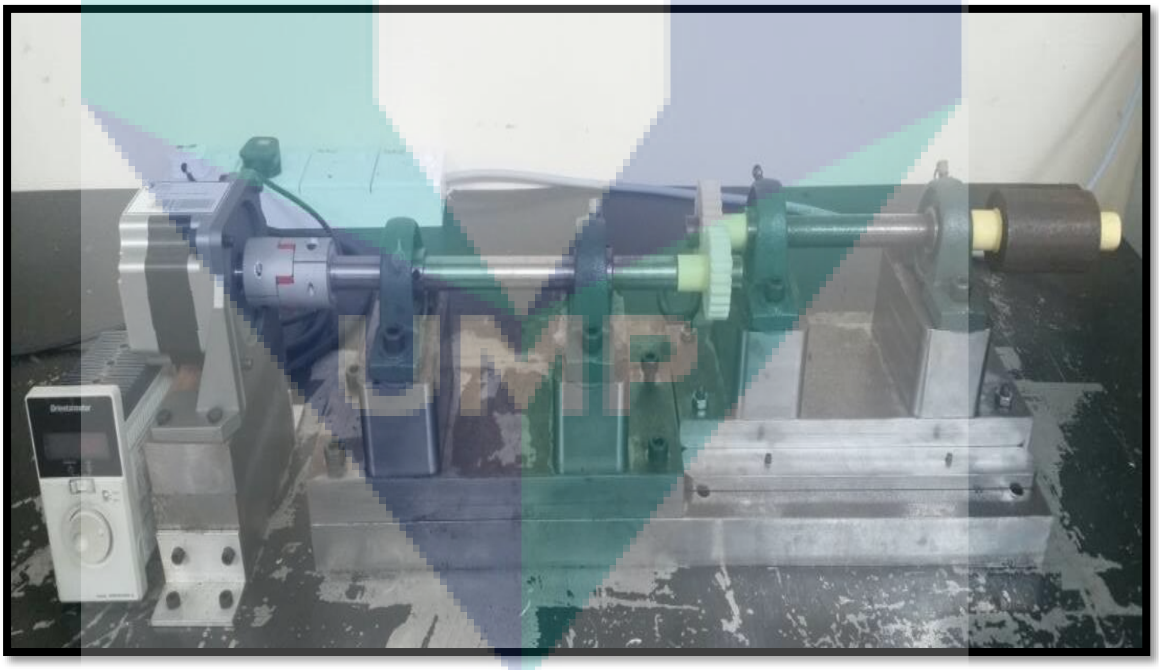


Figure 3-29 Test rig with load

# CHAPTER 4

# RESULTS AND DISCUSSION

## 4.1 Introduction

In this section shows the wear result from the gear testing by using gear test rig. The objective of the experiment is to study wear properties of tapioca based biopolymer gears. From the experiment, there are 3 types of wear failure that want to study that is surface wear that is wear debris formation, weight loss and microstructure surface condition. This section will discuss all 3 types of wear failure above. From the experiment, the result gain come from two experiment parameters. First is different rpm and second different rpm with added load.

## 4.2 Wear Debris and Crack Formation

Table 4-1 Gear set

| | Biopolymer | | Polymer | |
|---|---|---|---|---|
| Speed (RPM) | Unloaded | Loaded | Unloaded | Loaded |
| 500 | 1 pair | 1 pair | 1 pair | 1 pair |
| 1000 | 1 pair | 1 pair | 1 pair | 1 pair |
| 1500 | 1 pair | 1 pair | 1 pair | 1 pair |

This experiment use only one set of gear. It is because, this experiment take 4 hours to complete for 1 pair of gear set Below show the result of the experiment.

### 4.2.1 Actual Biopolymer Gear before the Experiment

Figure 4-1 Driving gear before the experiment

Figure 4-2 Driven gear before the experiment

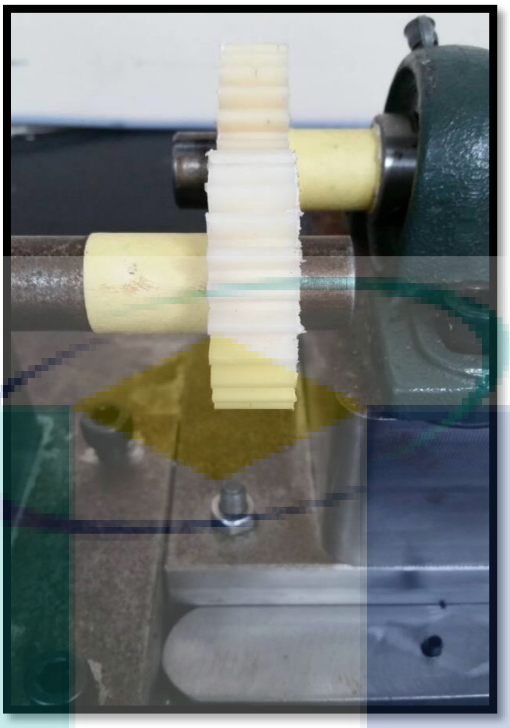


Figure 4-3 No Biopolymer debris formation before start the experiment

### 4.2.2 Biopolymer at 500 RPM without Load

Figure 4-4 Driving gear after test

Figure 4-5 Driven gear after test

### 4.2.3 Biopolymer at 1000 RPM without Load

Figure 4-6 Driving gear after experiment

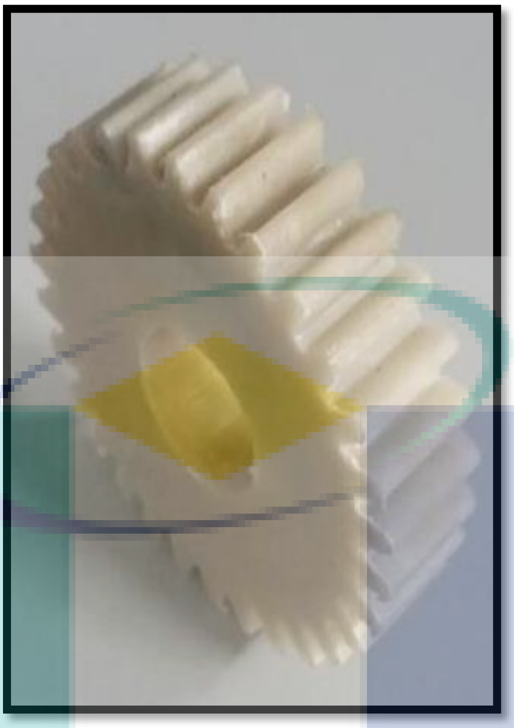


Figure 4-7 Driven gear after test

#### 4.2.4 Biopolymer at 1500 RPM without Load

Figure 4-8 Driving gear after experiment

Figure 4-9 Driven gear after test

### 4.2.5 Biopolymer at 500 RPM with Load

Figure 4-10 Driving gear after experiment

Figure 4-11 Driven gear after test

### 4.2.6 Biopolymer at 1000 RPM with Load

Figure 4-12 Driving gear after experiment

Figure 4-13 Driven gear after test

### 4.2.7 Biopolymer at 1500 RPM with Load

Figure 4-14 Driving gear after experiment

Figure 4-15 Driven gear after test

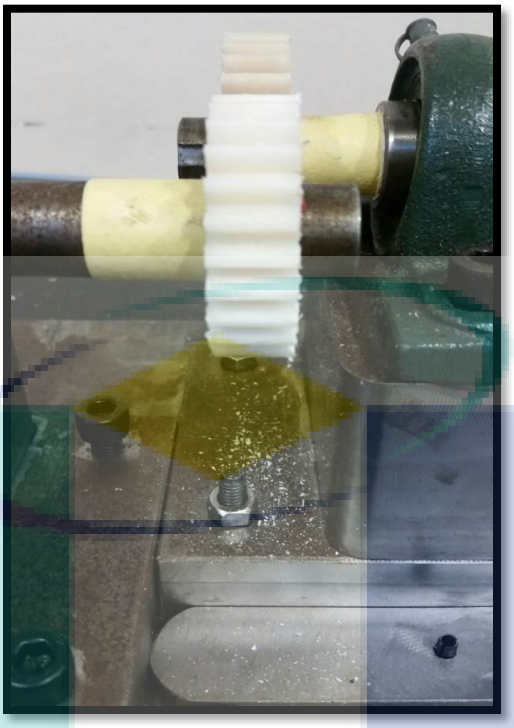


Figure 4-16 Debris formation after the experiment

### 4.2.8 Actual Polymer Gear before the Experiment

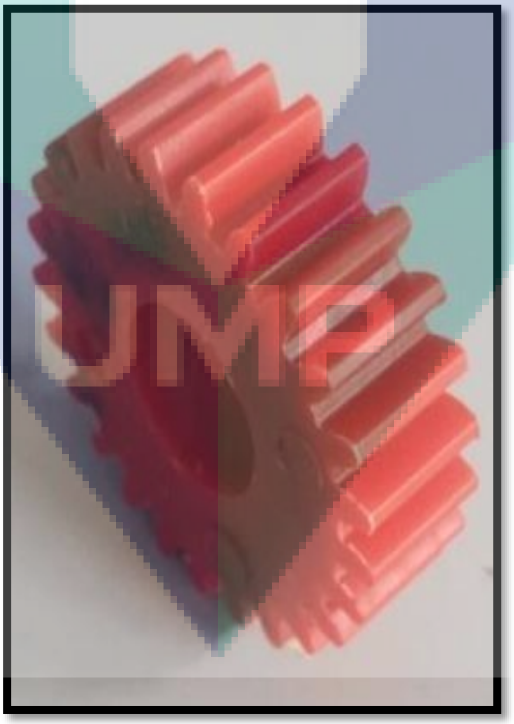


Figure 4-17 Driving gear before the experiment

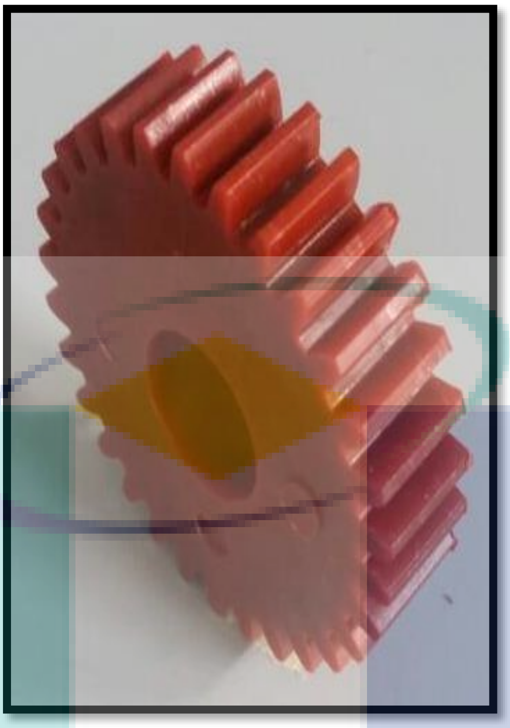


Figure 4-18 Driven gear before the experiment

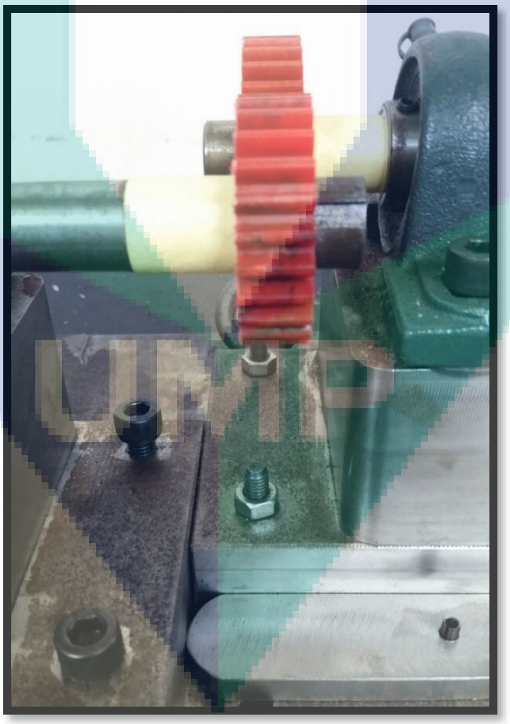


Figure 4-19 No Polymer debris formation before start the experiment

### 4.2.9 Polymer at 500 RPM without Load

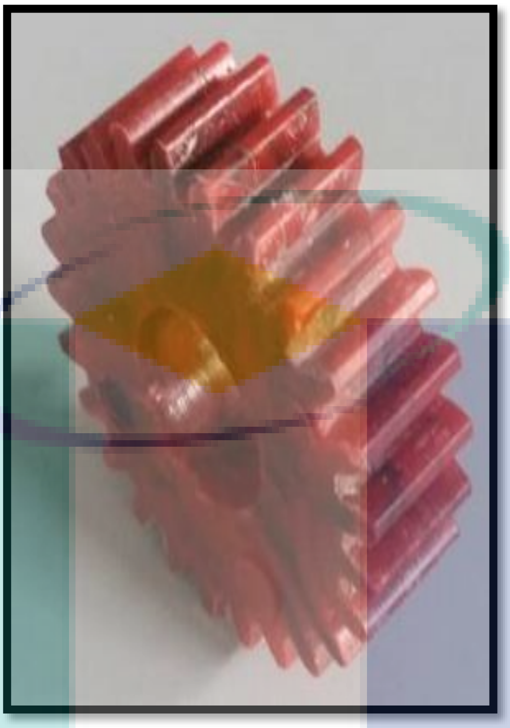


Figure 4-20 Driving gear after test

Figure 4-21 Driven gear after test (Scratching occur on tooth surface)

#### 4.2.10 Polymer at 1000RPM without Load

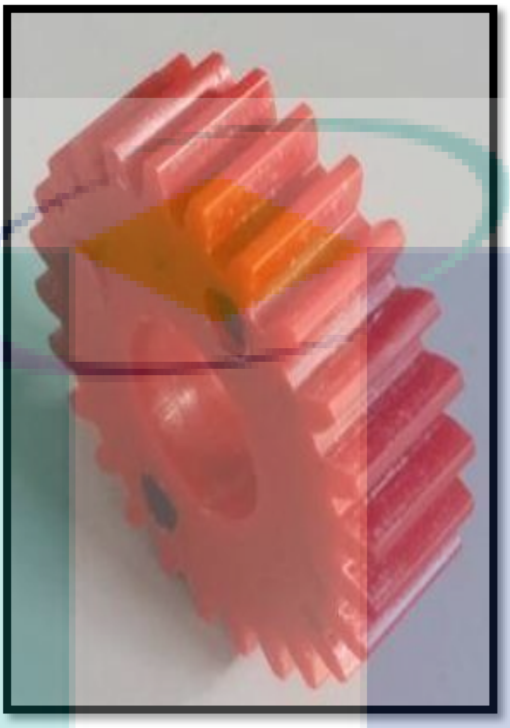


Figure 4-22 Driving gear after test

Figure 4-23 Driven gear after test (Ridging occur on tip surface)

#### 4.2.11 Polymer at 1500 RPM without Load

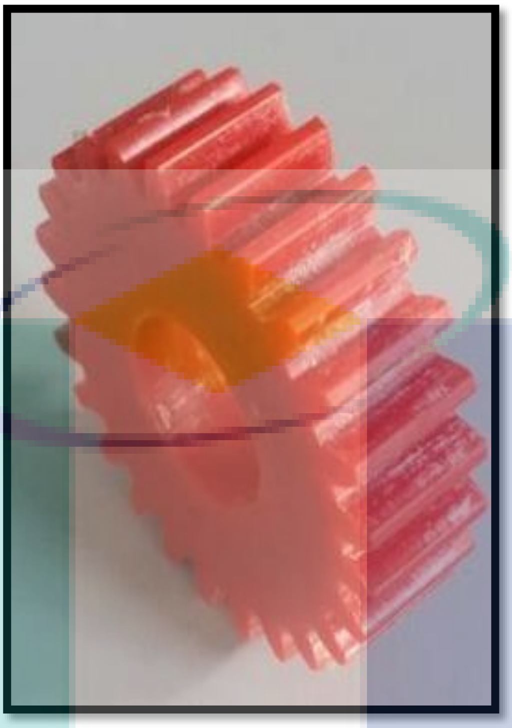


Figure 4-24 Driving gear after test (Some scratching occur on the tooth)

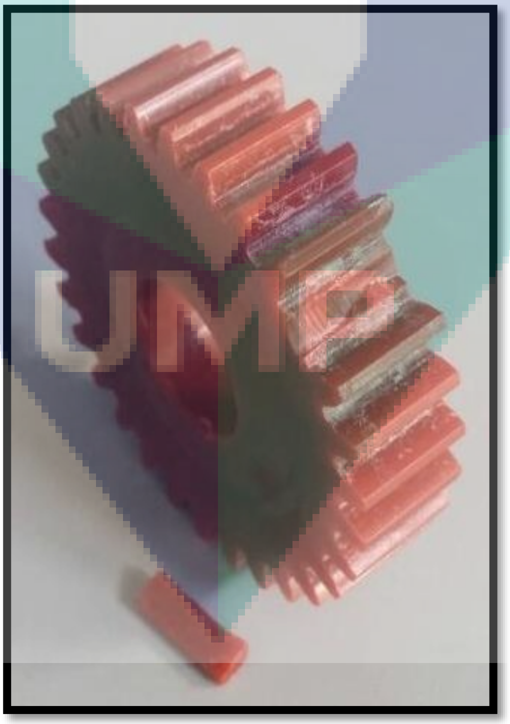


Figure 4-25 Driven gear after test (One of the tooth fracture)

#### 4.2.12 Polymer at 500 RPM with Load

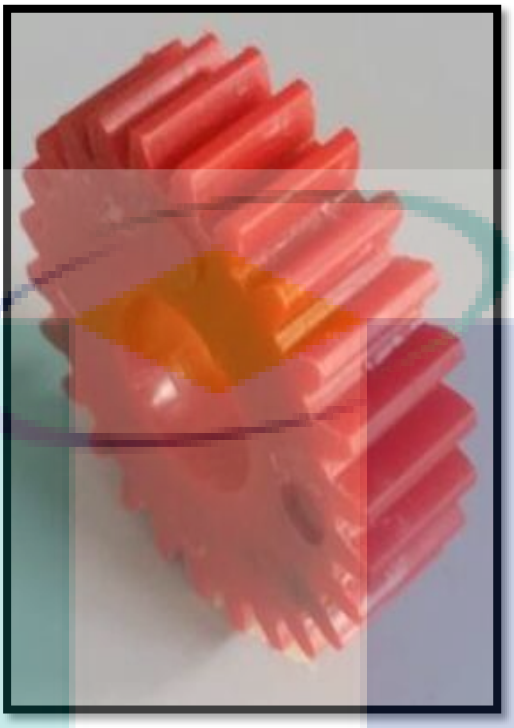


Figure 4-26 Driving gear after test

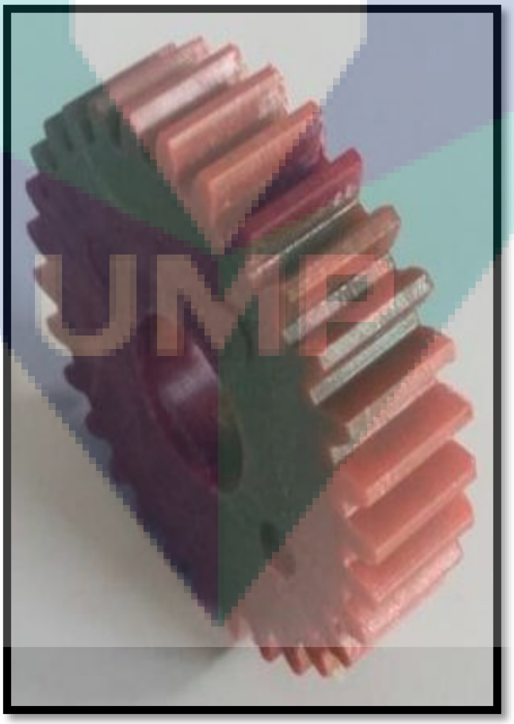


Figure 4-27 Driven gear after test

#### 4.2.13 Polymer at 1000 RPM with Load

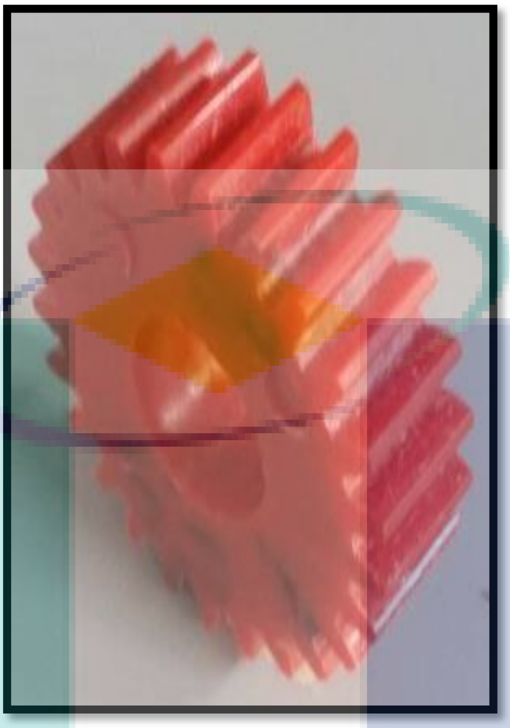


Figure 4-28 Driving gear after test (Svere scoring occur on the tooth)

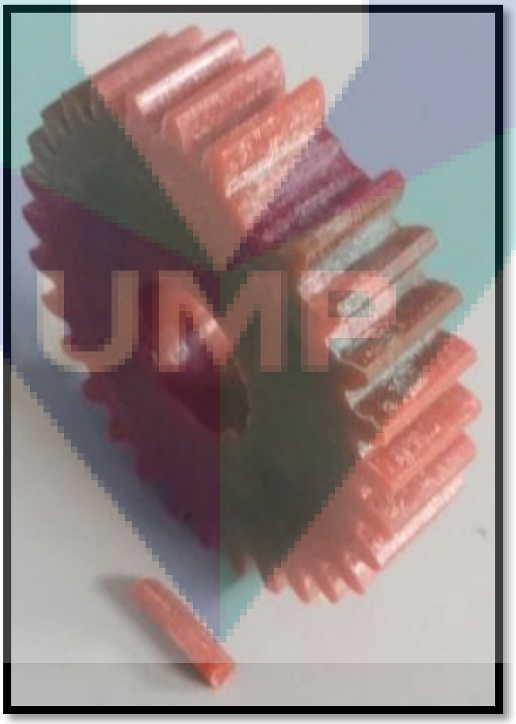


Figure 4-29 Driven gear after test (One of the tooth fracture)

### 4.2.14 Polymer at 1500 RPM with Load

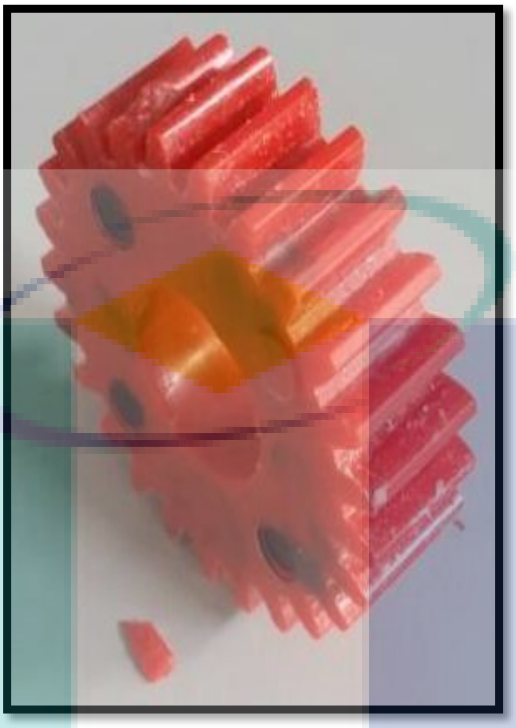


Figure 4-30 Driving gear after test (Overload breakage occur on one of the tooth)

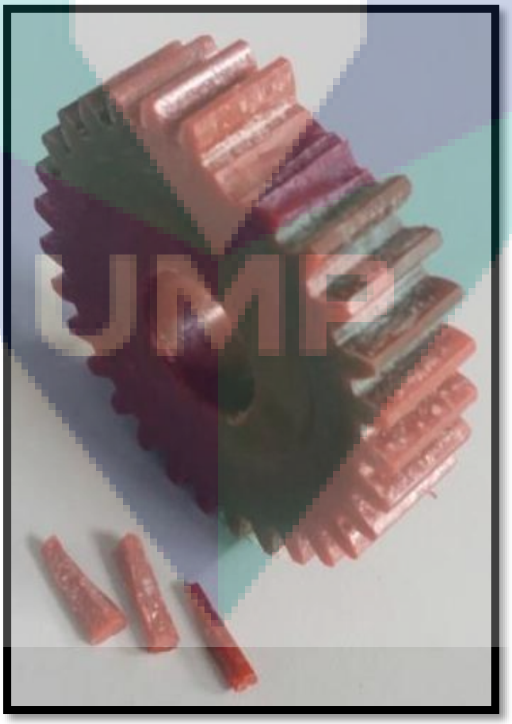


Figure 4-31 Driven gear after test (Two tooth have fracture and one of the tooth has split in two)

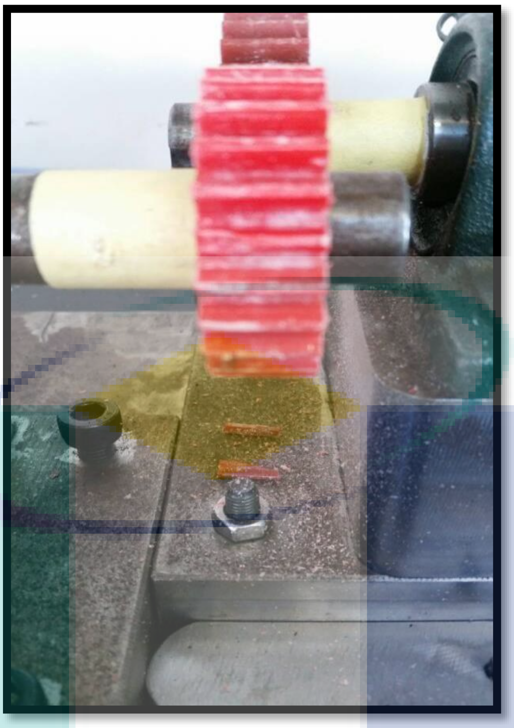


Figure 4-32 Debris formation after the experiment

## 4.3 Weight Loss

### 4.3.1 Weight Loss of the gear without Load

| | Biopolymer | % of Weight Loss | Polymer | % of Weight Loss |
|---|---|---|---|---|
| | 500 RPM w/o load | | | |
| Driving | 24.389 → 24.290 | 0.4059 | 24.339 → 24.319 | 0.0821 |
| Driven | 37.3370 → 36.340 | 2.6702 | 37.265 → 37.264 | 0.0002 |
| | 1000 RPM w/o load | | | |
| Driving | 24.399 → 24.348 | 0.2090 | 24.358 → 24.255 | 0.4228 |
| Driven | 37.455 → 37.345 | 0.2945 | 37.260 → 37.246 | 0.0375 |
| | 1500 RPM w/o load | | | |
| Driving | 24.390 → 24.370 | 0.0820 | 24.367 → 24.300 | 0.2749 |
| Driven | 37.342 → 36.380 | 2.5761 | 37.275 → 36.366 | 2.4386 |

Table 4-2 Weight loss of the Biopolymer and Polymer gear without Load

### 4.3.2 Weight Loss of the gear with Load

| | Biopolymer | % of Weight Loss | Polymer | % of Weight Loss |
|---|---|---|---|---|
| | 500 RPM with load | | | |
| Driving | 24.581 → 24.563 | 0.0732 | 24.367 → 24.359 | 0.0328 |
| Driven | 37.582 → 37.538 | 0.1170 | 37.246 → 37.239 | 0.0187 |
| | 1000 RPM with load | | | |
| Driving | 24.487 → 24.477 | 0.0408 | 24.344 → 24.333 | 0.0451 |
| Driven | 37.132 → 37.067 | 0.1750 | 37.293 → 37.034 | 0.6945 |
| | 1500 RPM with load | | | |
| Driving | 24.466 → 24.458 | 0.0326 | 24.378 → 24.344 | 0.1394 |
| Driven | 37.120 → 37.067 | 0.1427 | 37.243 → 36.311 | 2.5024 |

Table 4-3 Weight loss of the Biopolymer and Polymer gear with Load

### 4.3.3 500 RPM Driven without load

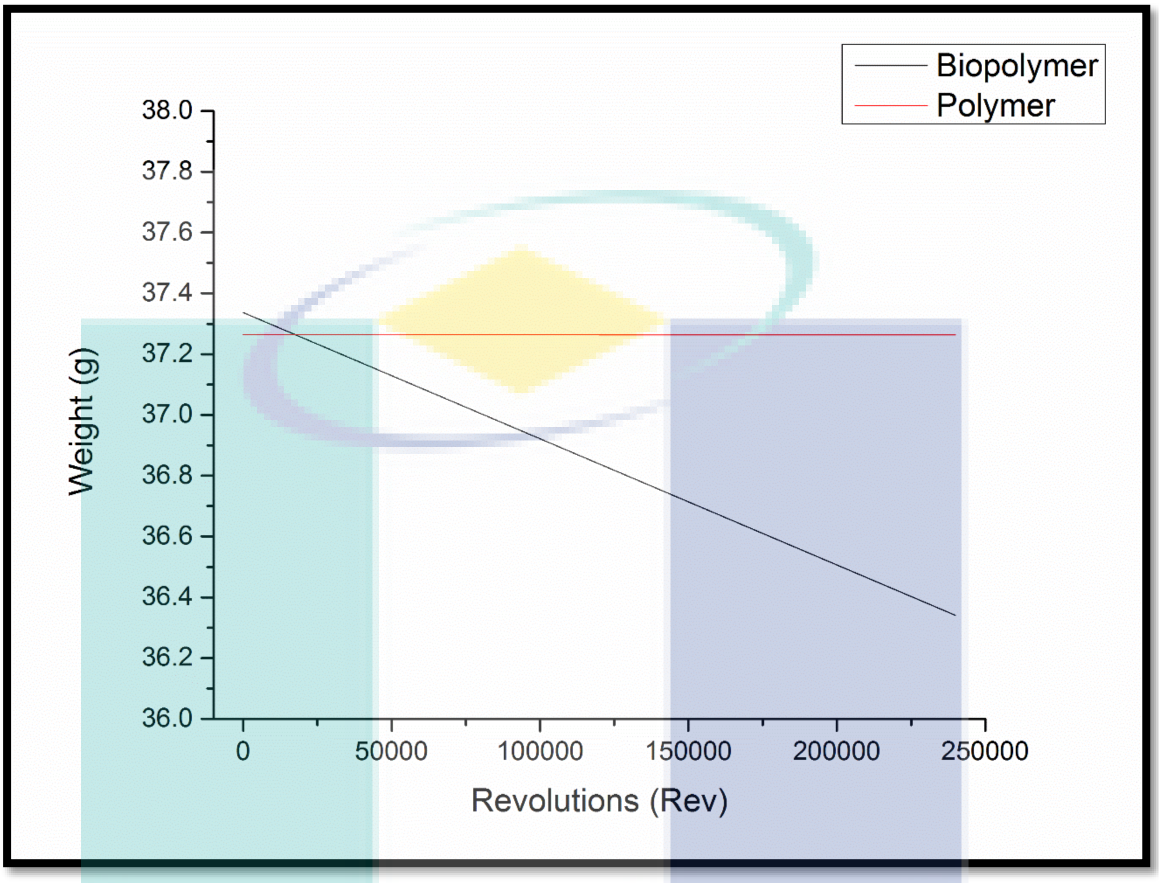



Figure 4-33 500 RPM Driven without load

### 4.3.4 500 RPM Driving without load

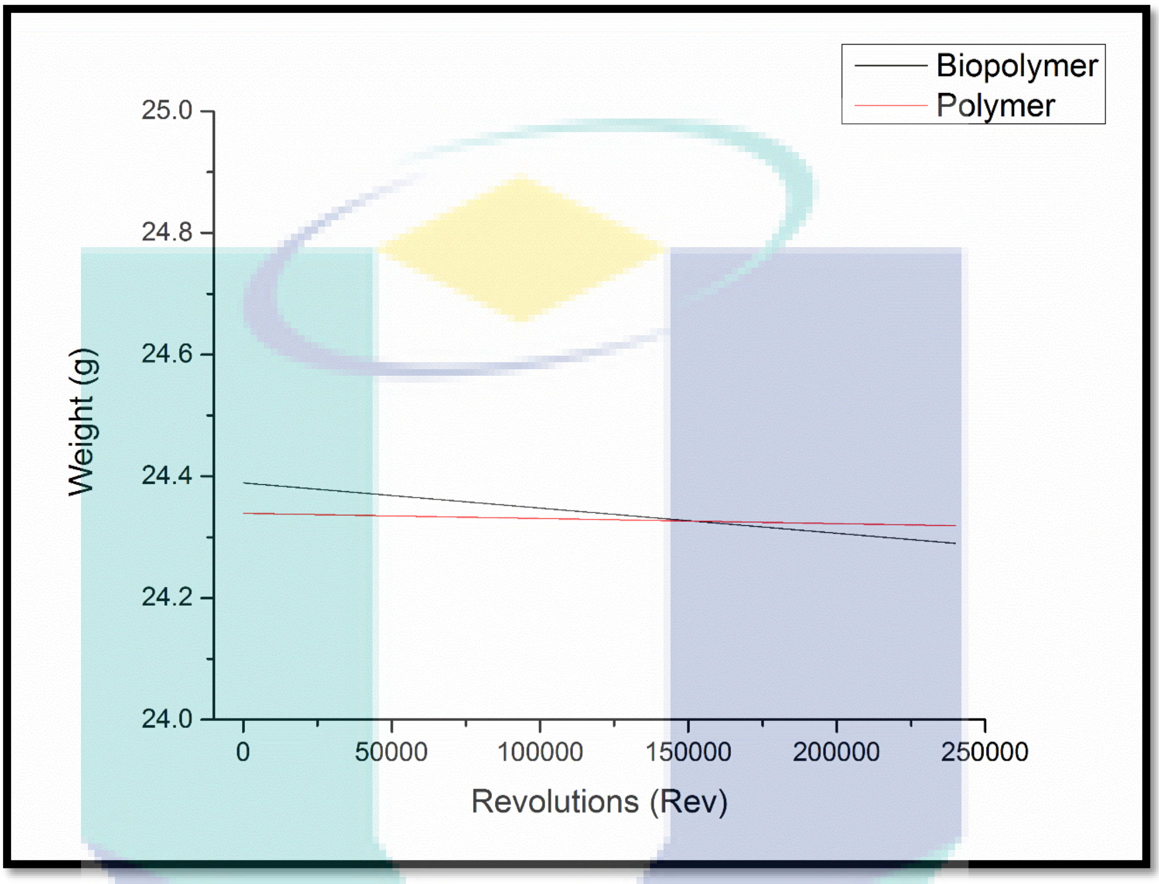



Figure 4-34 500 RPM Driving without load

### 4.3.5 500 RPM Driven with load

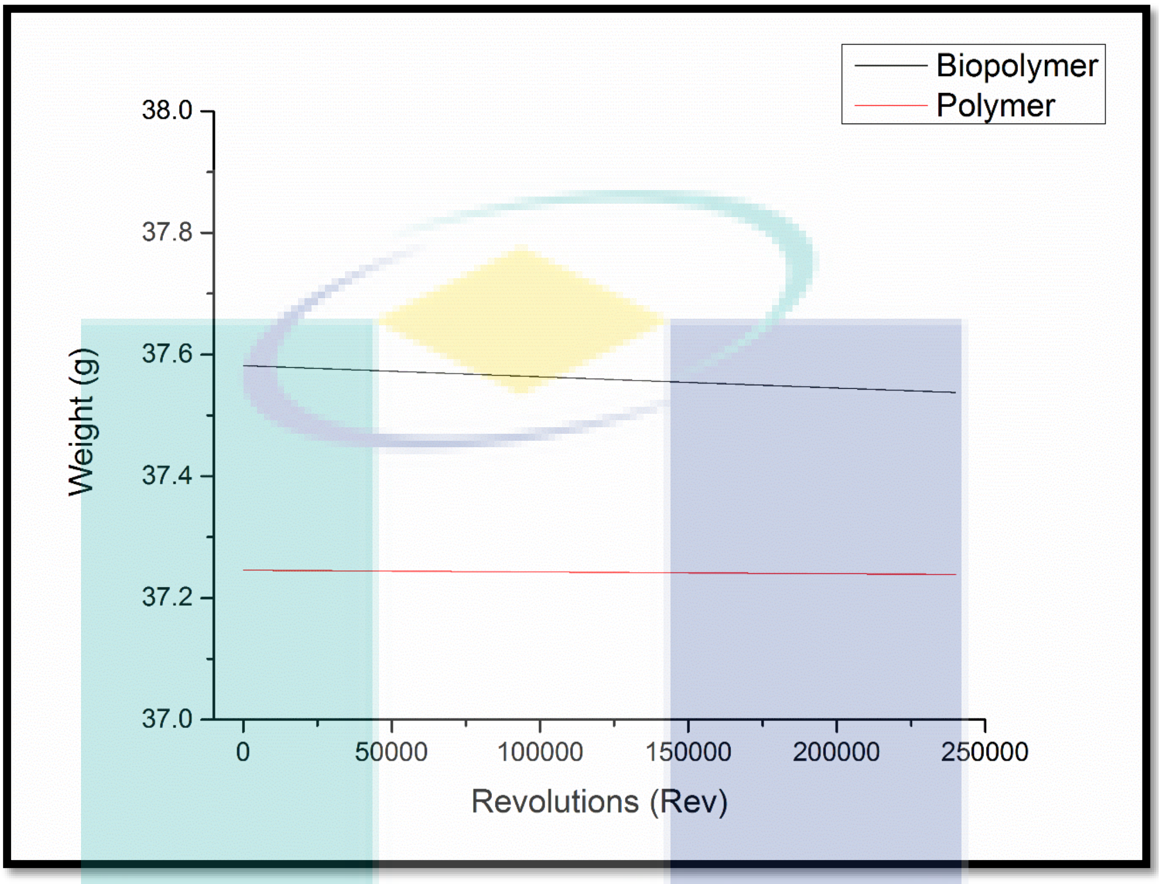



Figure 4-35 500 RPM Driven with load

### 4.3.6 500 RPM Driving with load

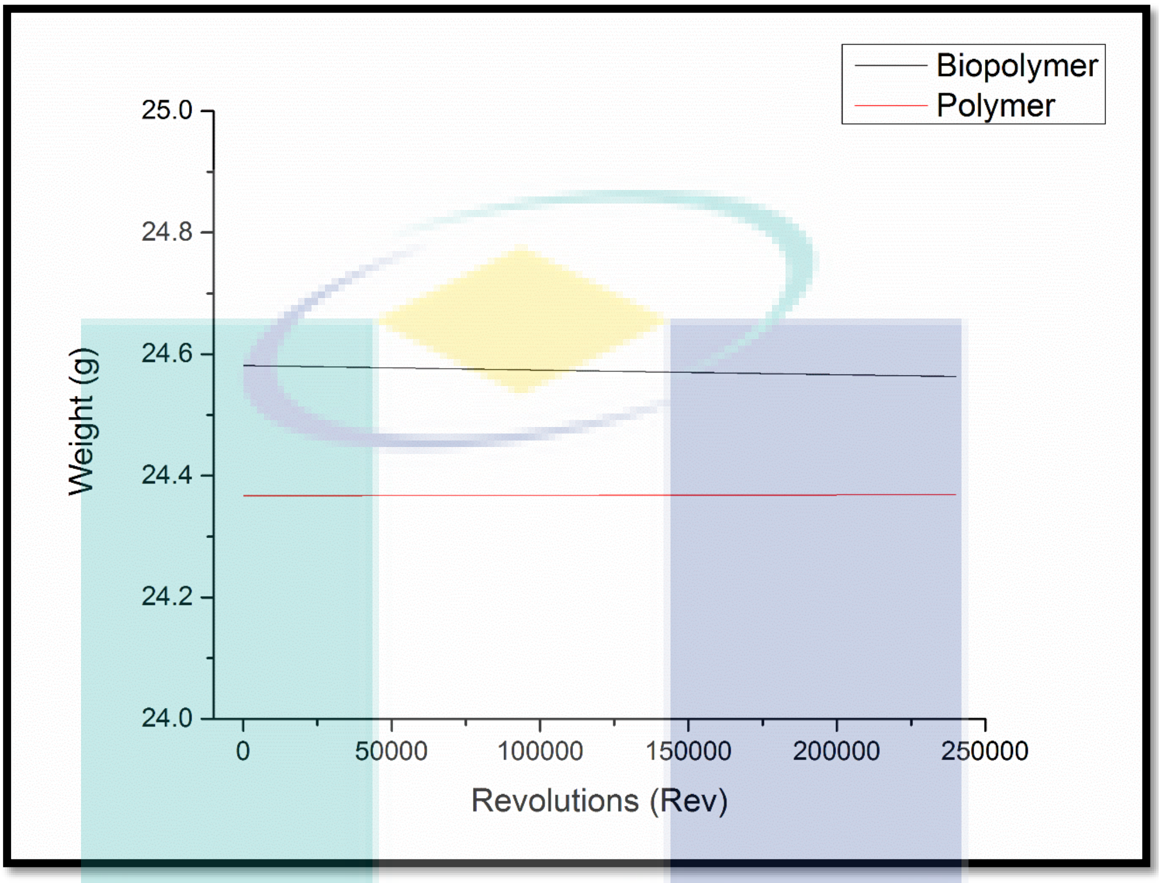



Figure 4-36 500 RPM Driving with load

### 4.3.7 1000 RPM Driven without load

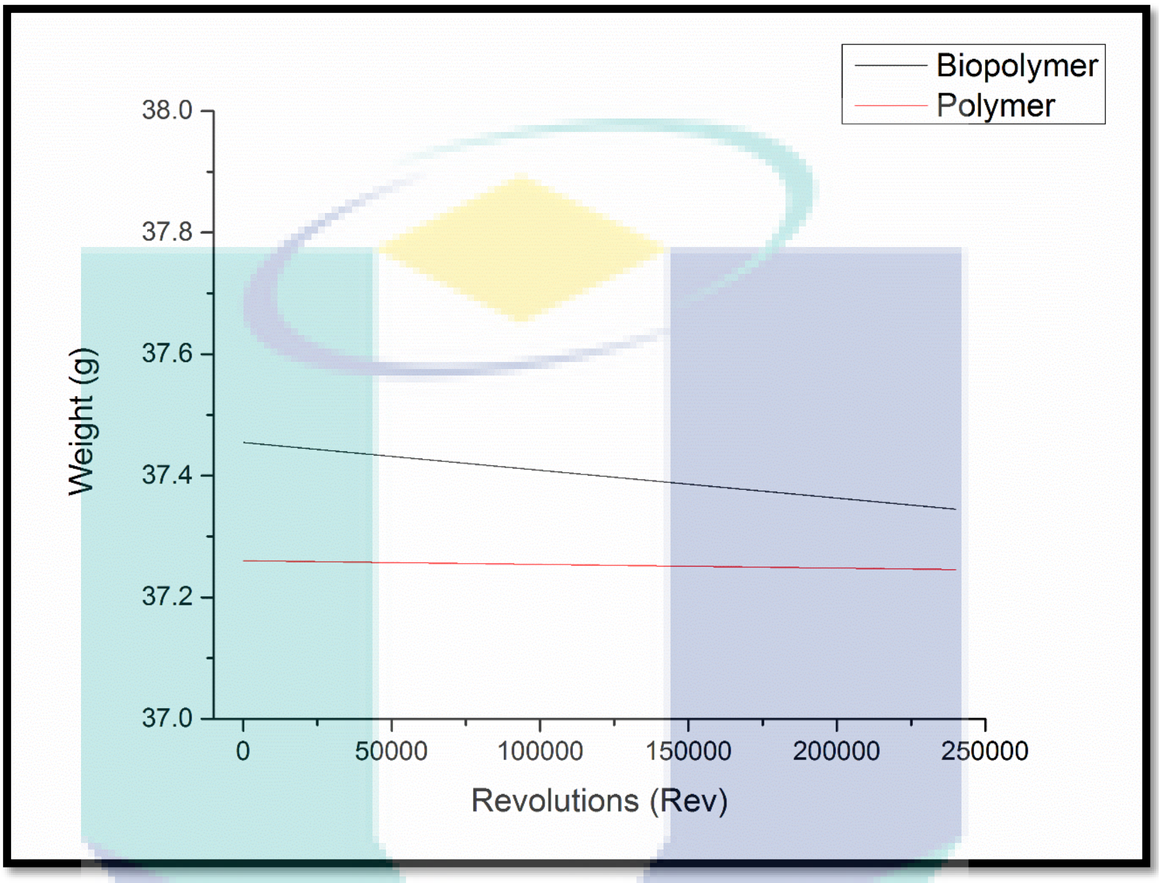



Figure 4-37 1000 RPM Driven without load

### 4.3.8 1000 RPM Driving without load

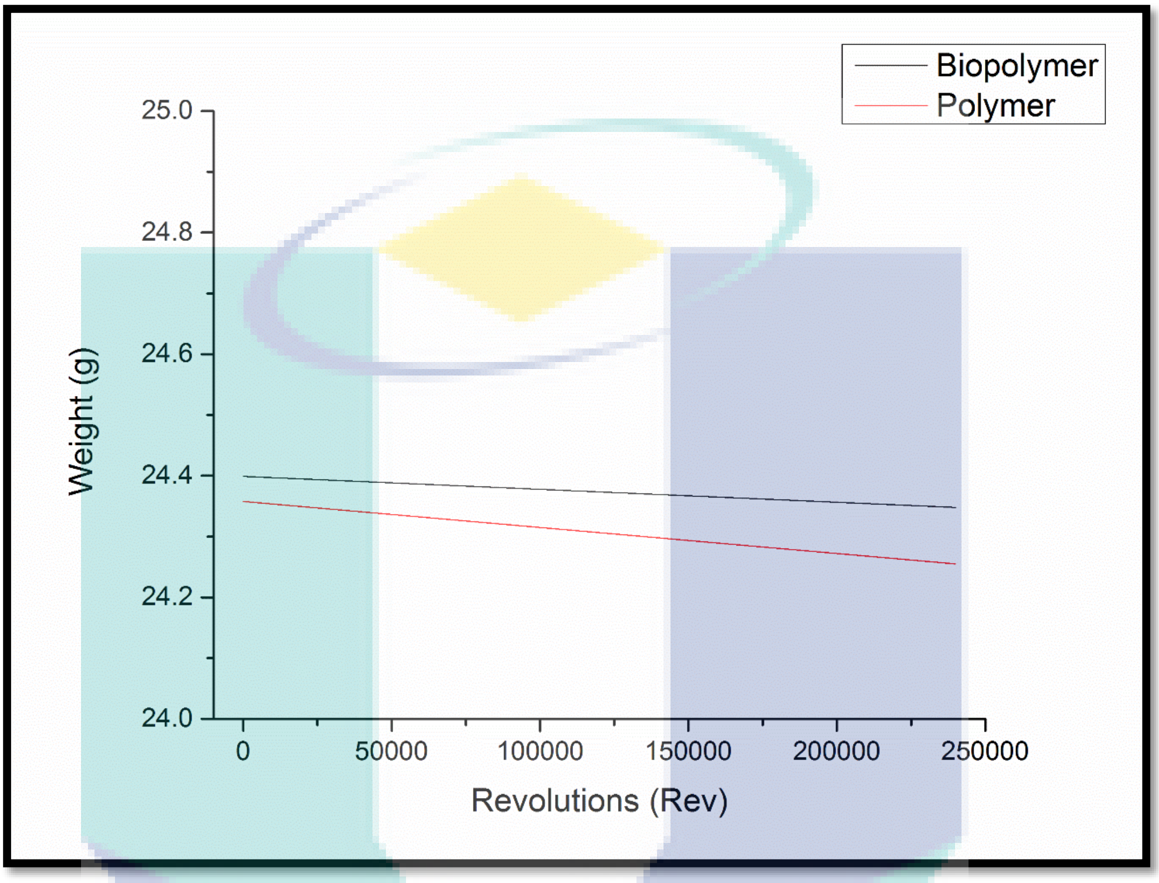



Figure 4-38 1000 RPM Driving without load

### 4.3.9 1000 RPM Driven with load

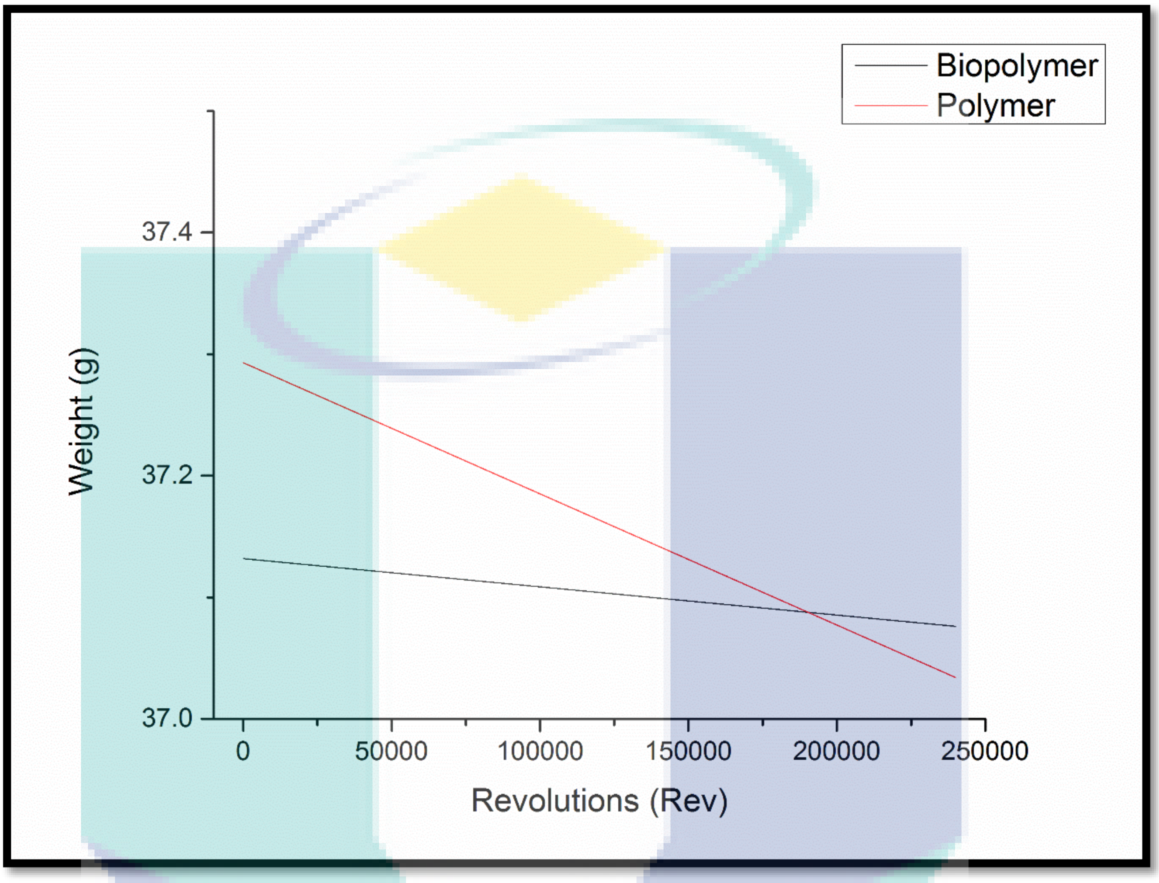



Figure 4-39 1000 RPM Driven with load

### 4.3.10 1000 RPM Driving with load

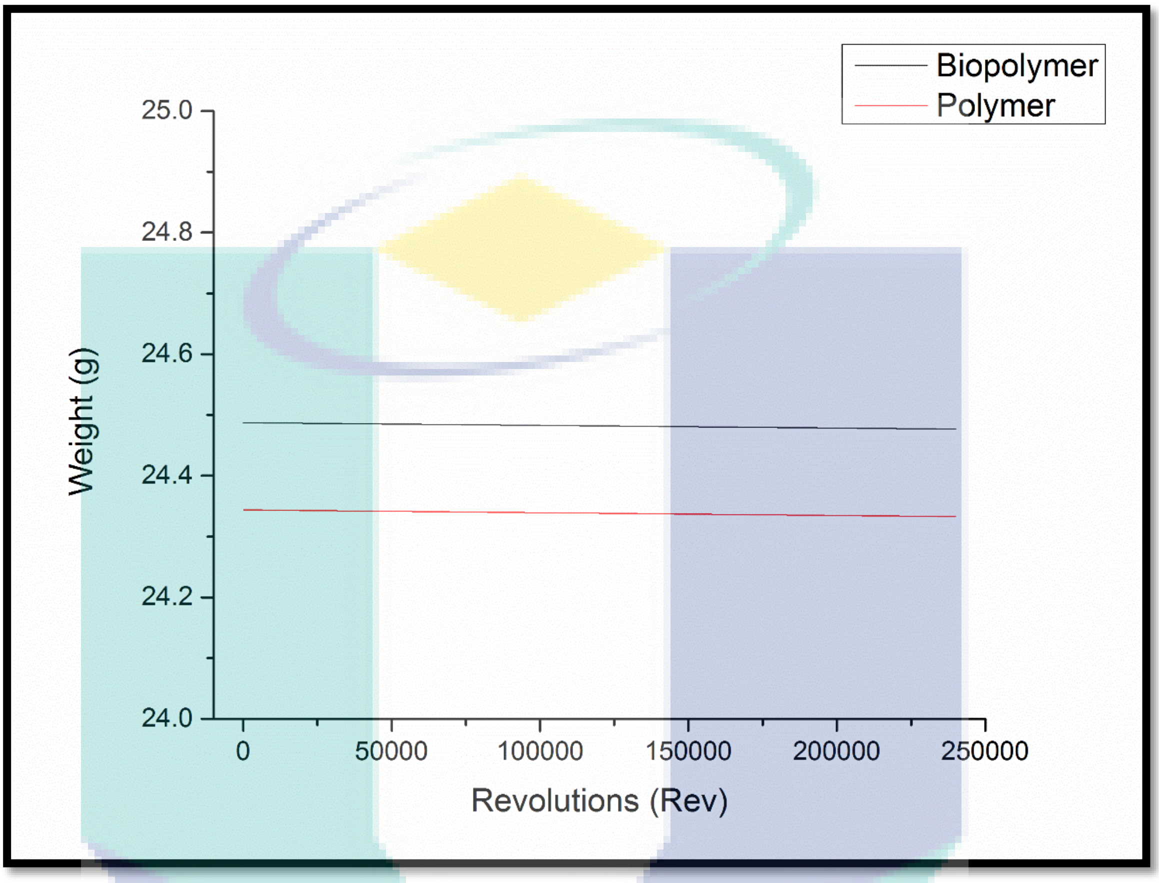



Figure 4-40 1000 RPM Driving with load

### 4.3.11 1500 RPM Driven without load

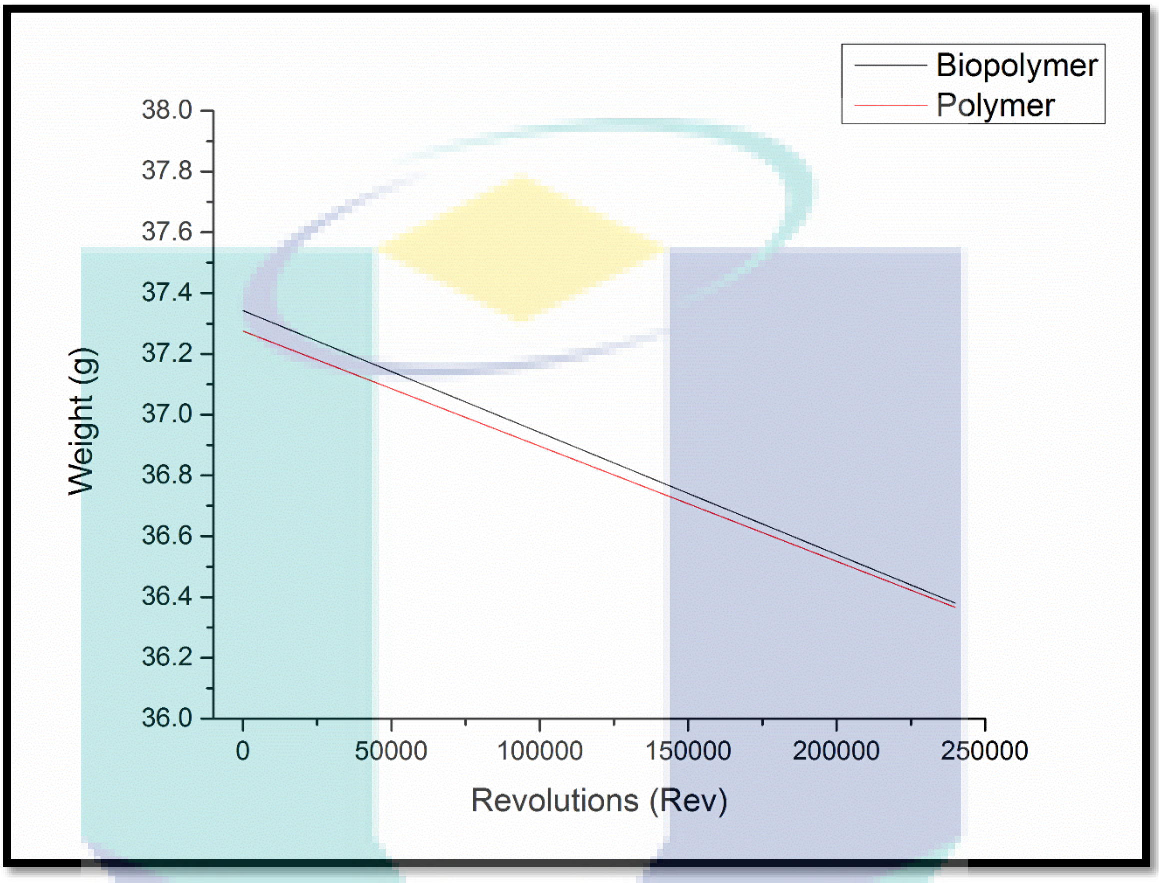



Figure 4-41 1500 RPM Driven without load

### 4.3.12 1500 RPM Driving without load

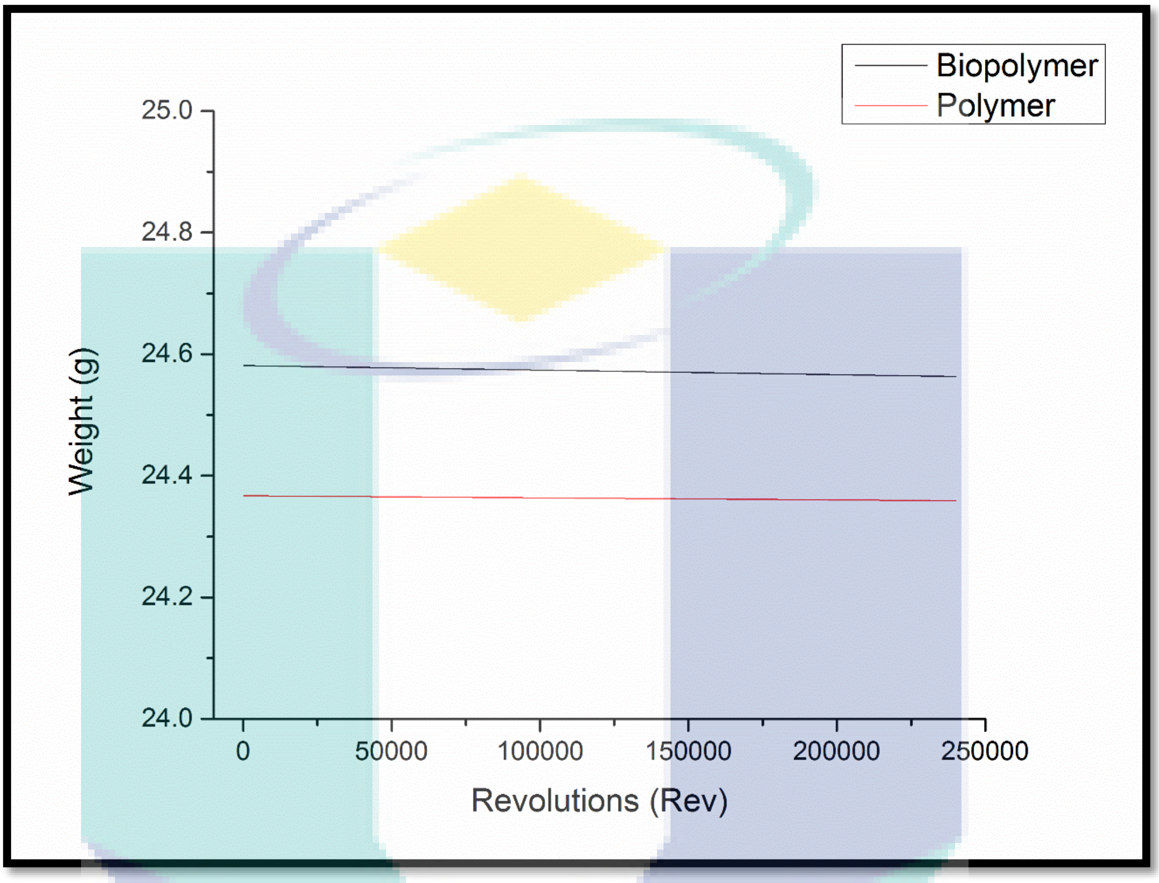



Figure 4-42 1500 RPM Driving without load

### 4.3.13 1500 RPM Driven with load

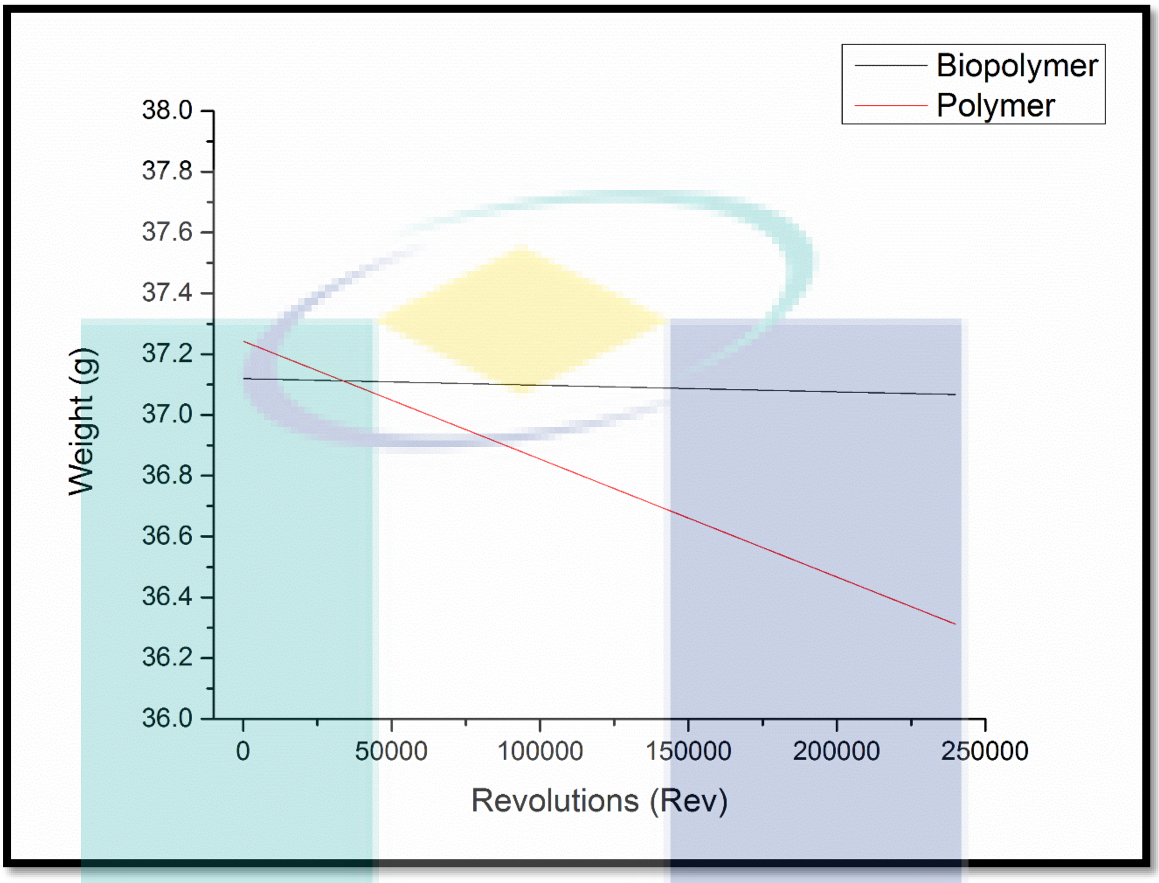



Figure 4-43 1500 RPM Driven with load

### 4.3.14 1500 RPM Driving with load

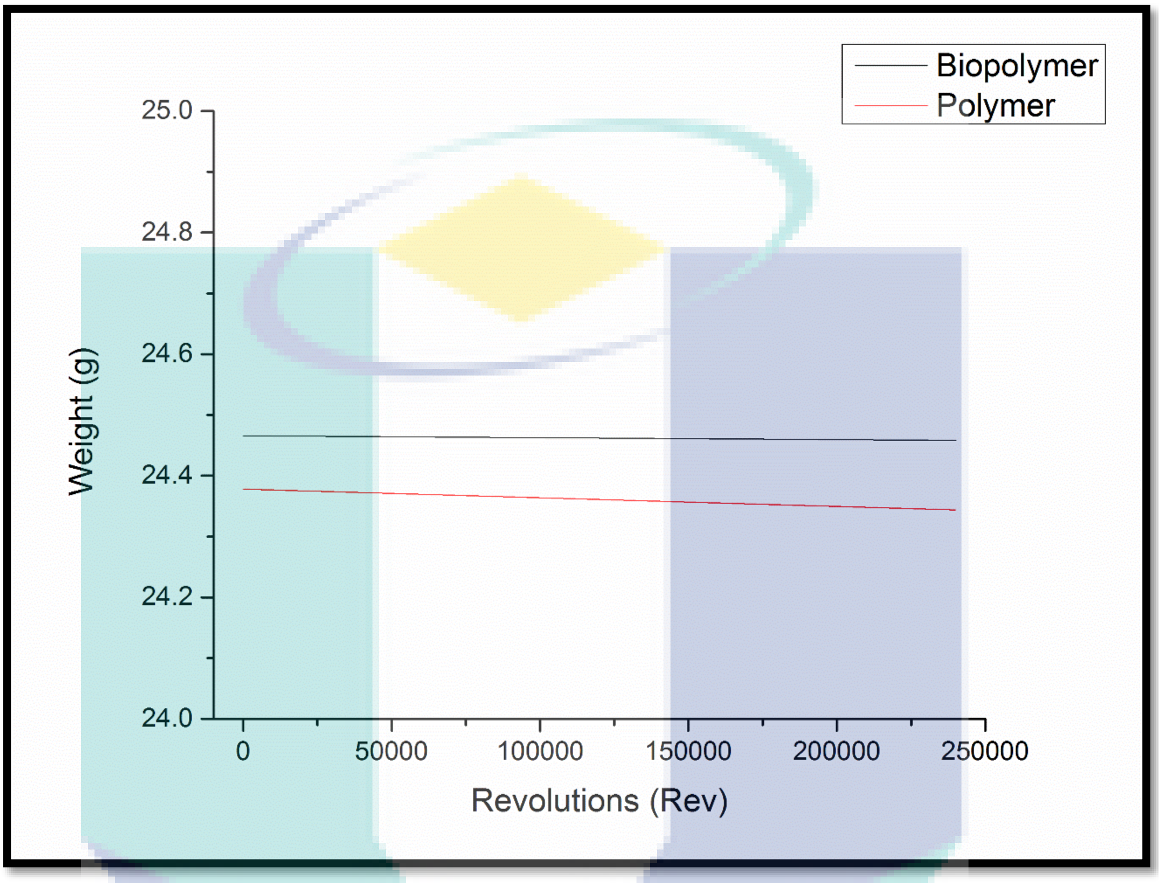



Figure 4-44 1500 RPM Driving with load

### 4.3.15 Different Speed Biopolymer Driven without load

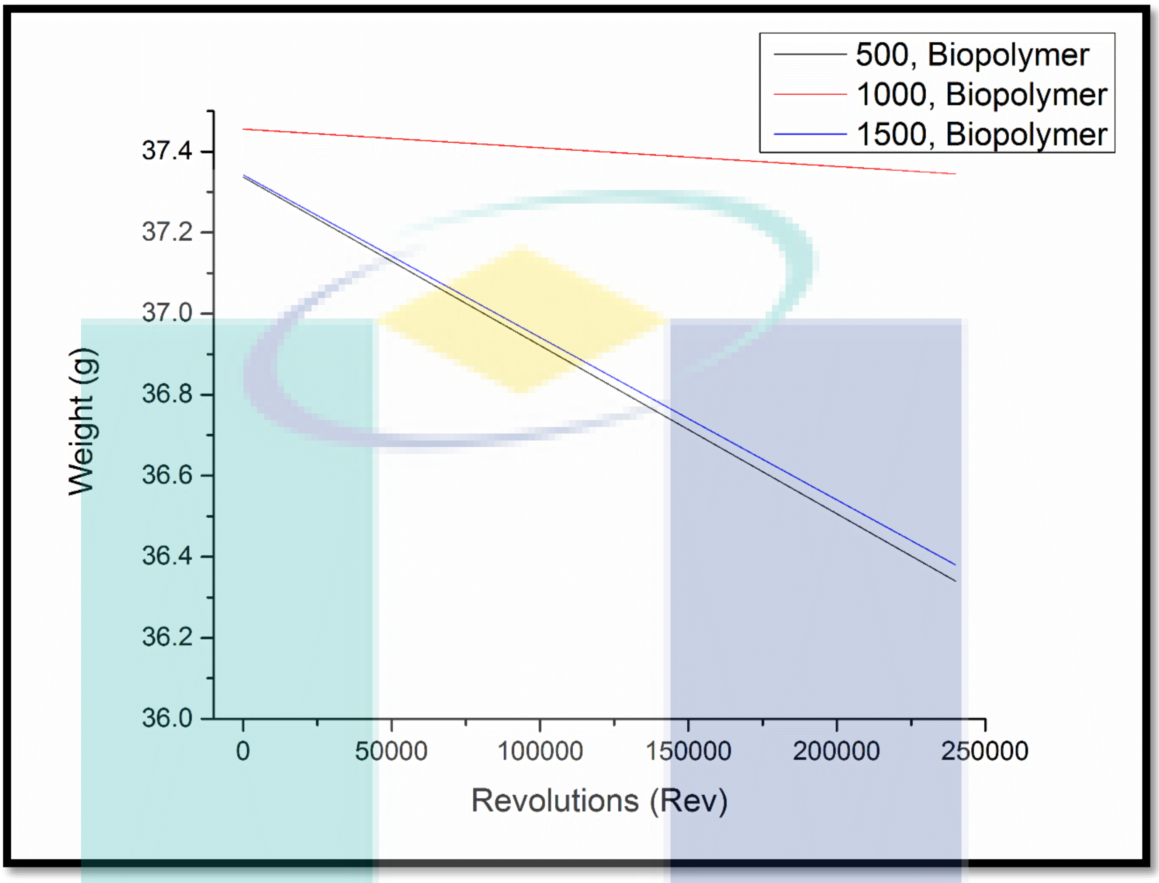



Figure 4-45 Different Speed Biopolymer Driven without load

### 4.3.16 Different Speed Biopolymer Driving without load

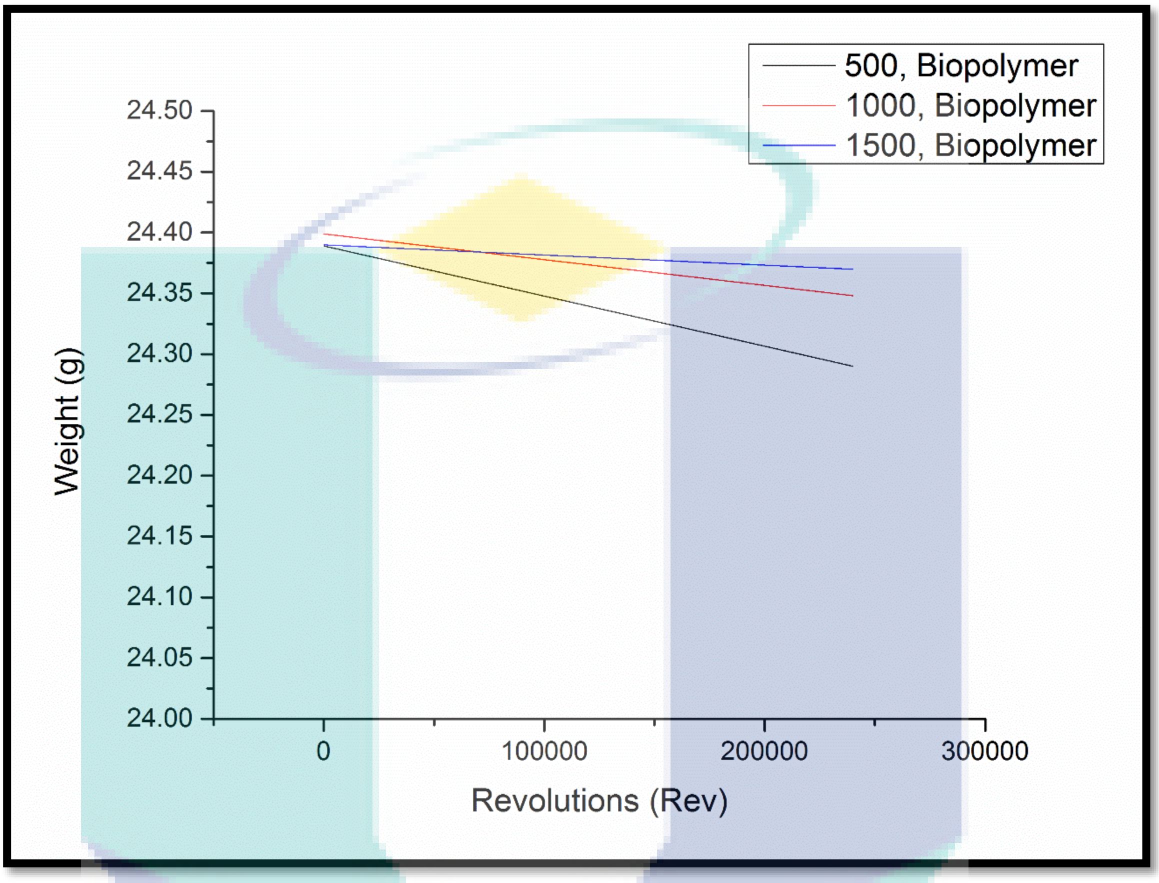



Figure 4-46 Different Speed Biopolymer Driving without load

### 4.3.17 Different Speed Biopolymer Driven with load

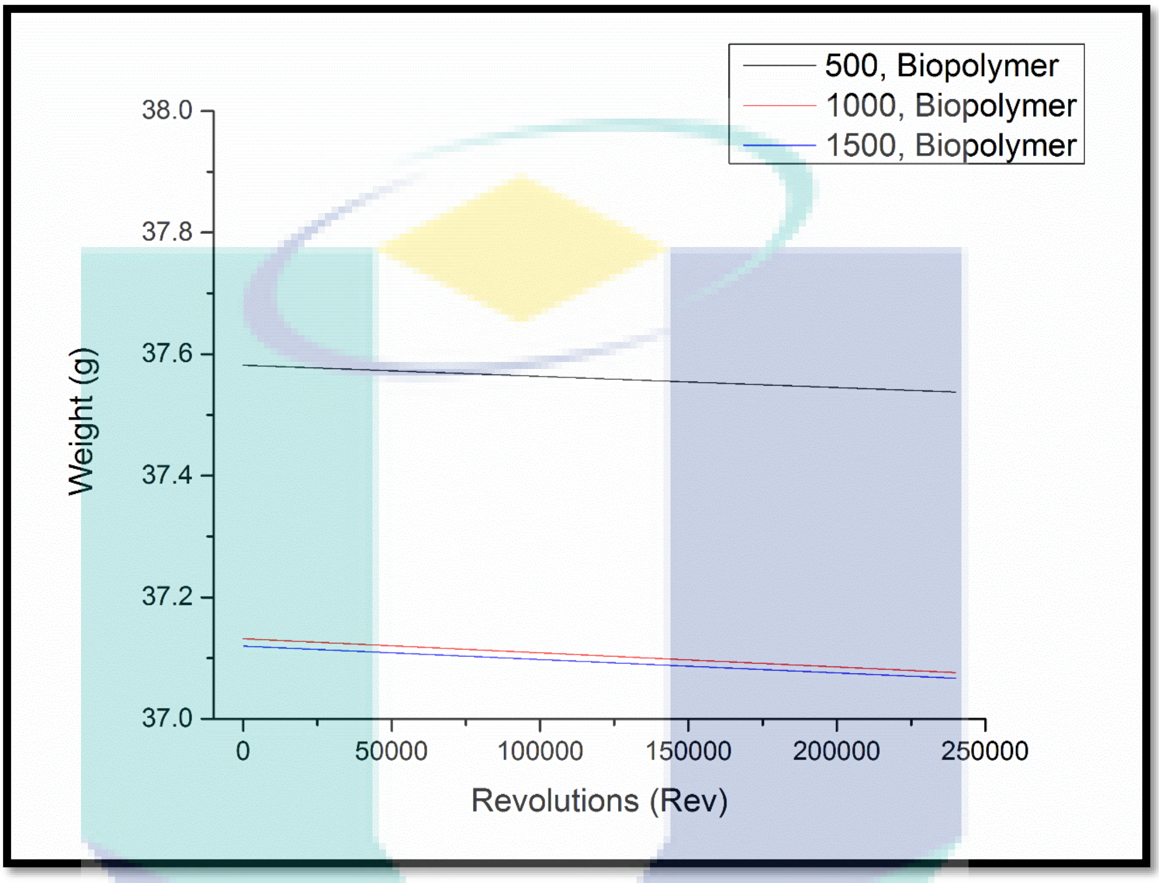



Figure 4-47 Different Speed Biopolymer Driven with load

#### 4.3.18 Different Speed Biopolymer Driving with load

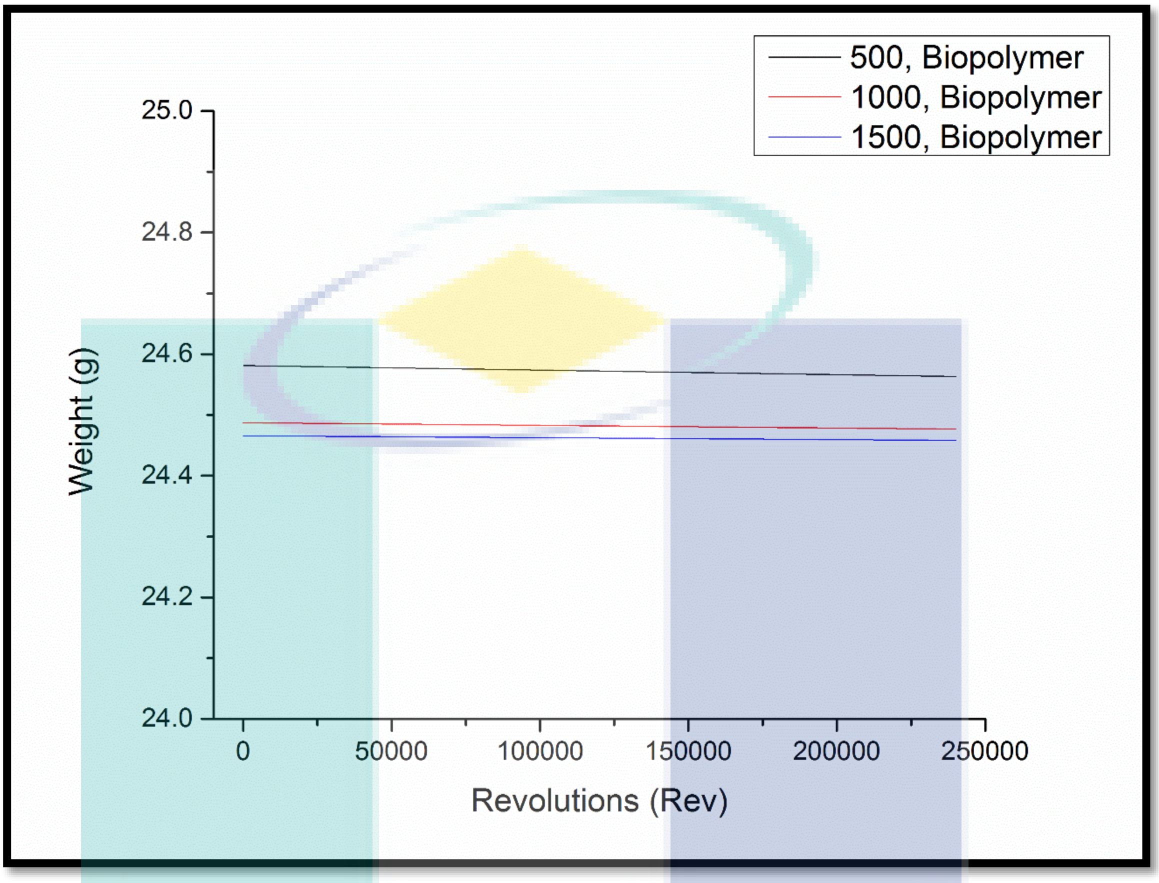



Figure 4-48 Different Speed Biopolymer Driving with load

### 4.3.19 Different Speed Polymer Driven without load

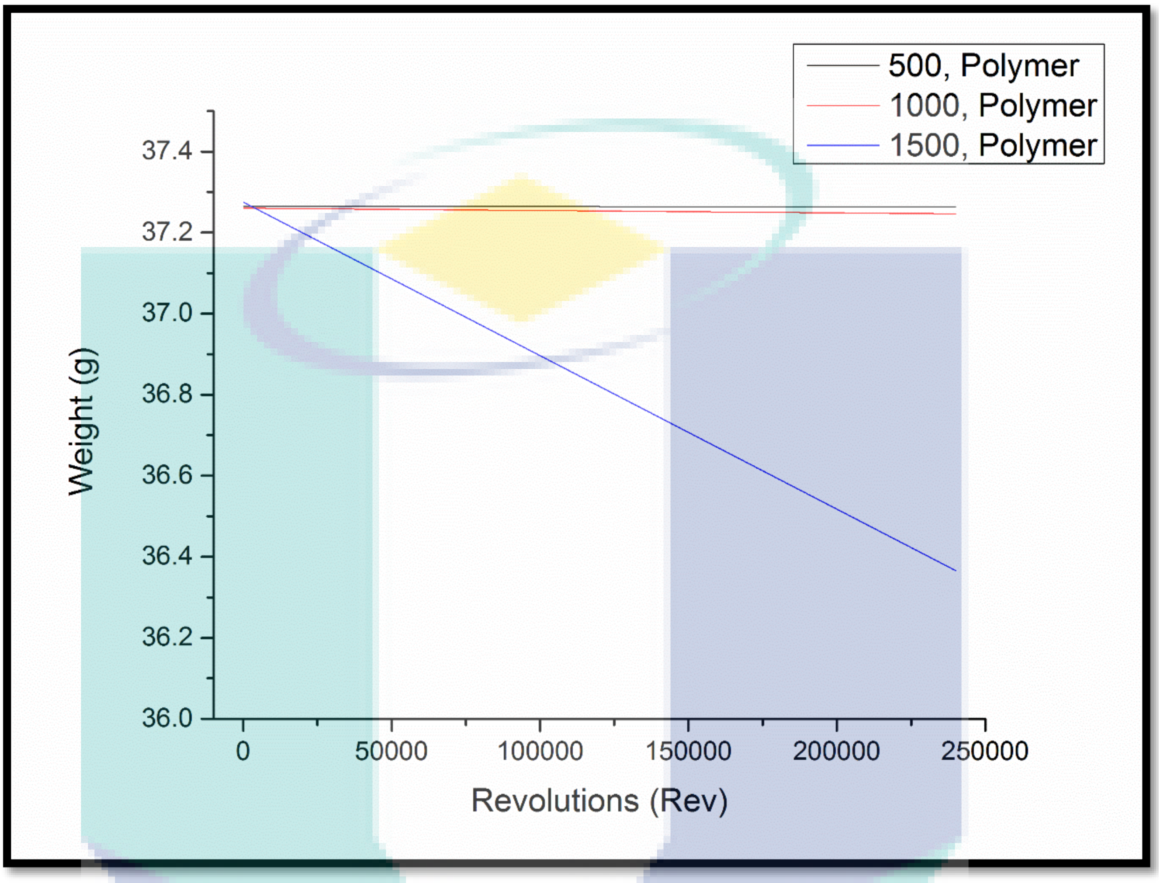



Figure 4-49 Different Speed Polymer Driven without load

### 4.3.20 Different Speed Polymer Driving without load

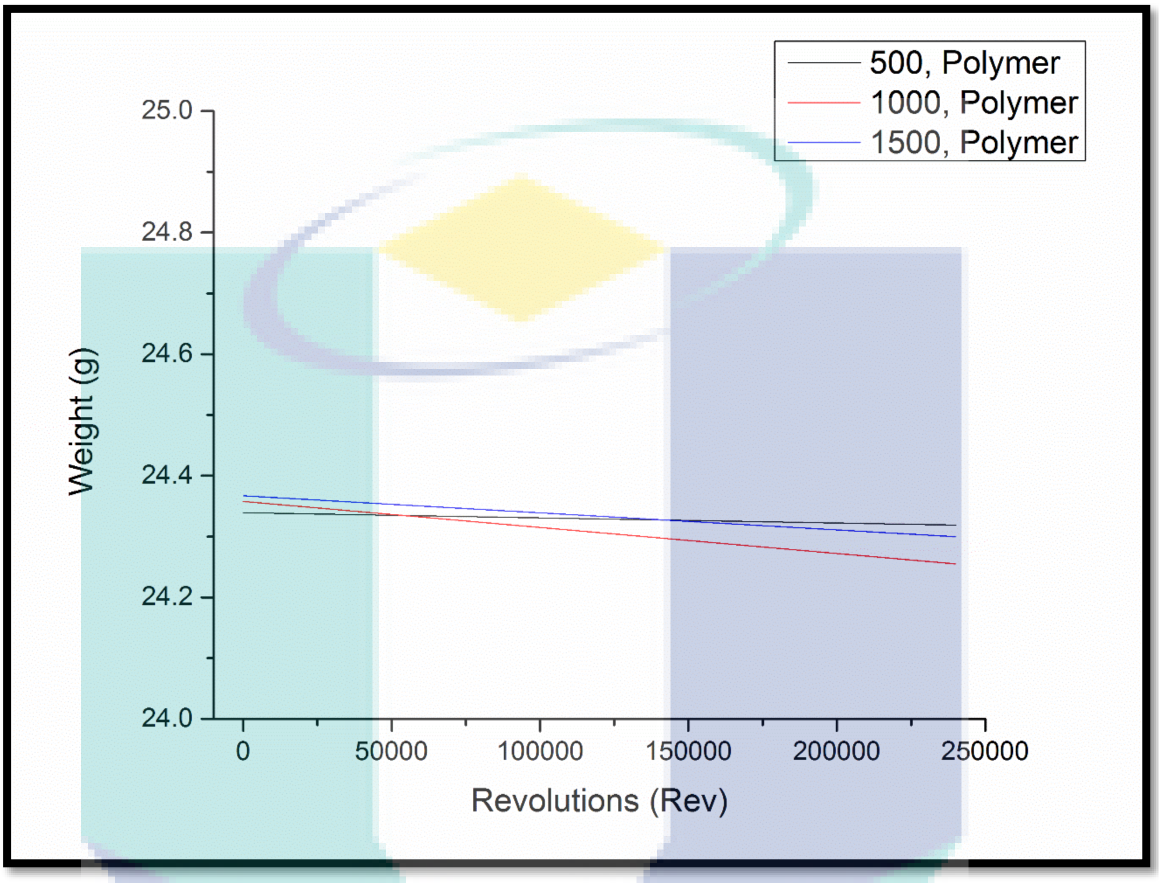



Figure 4-50 Different Speed Polymer Driving without load

### 4.3.21 Different Speed Polymer Driven with load

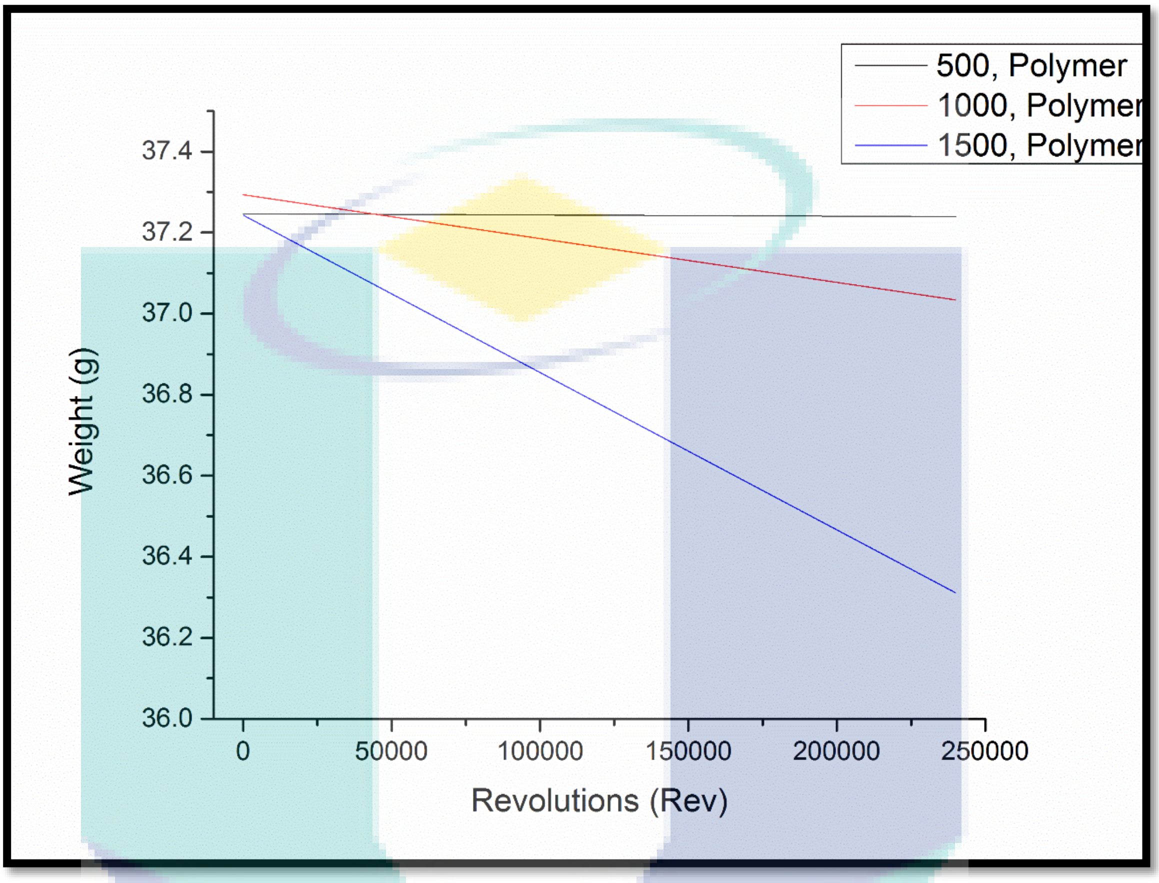



Figure 4-51 Different Speed Polymer Driven with load

### 4.3.22 Different Speed Polymer Driving with load

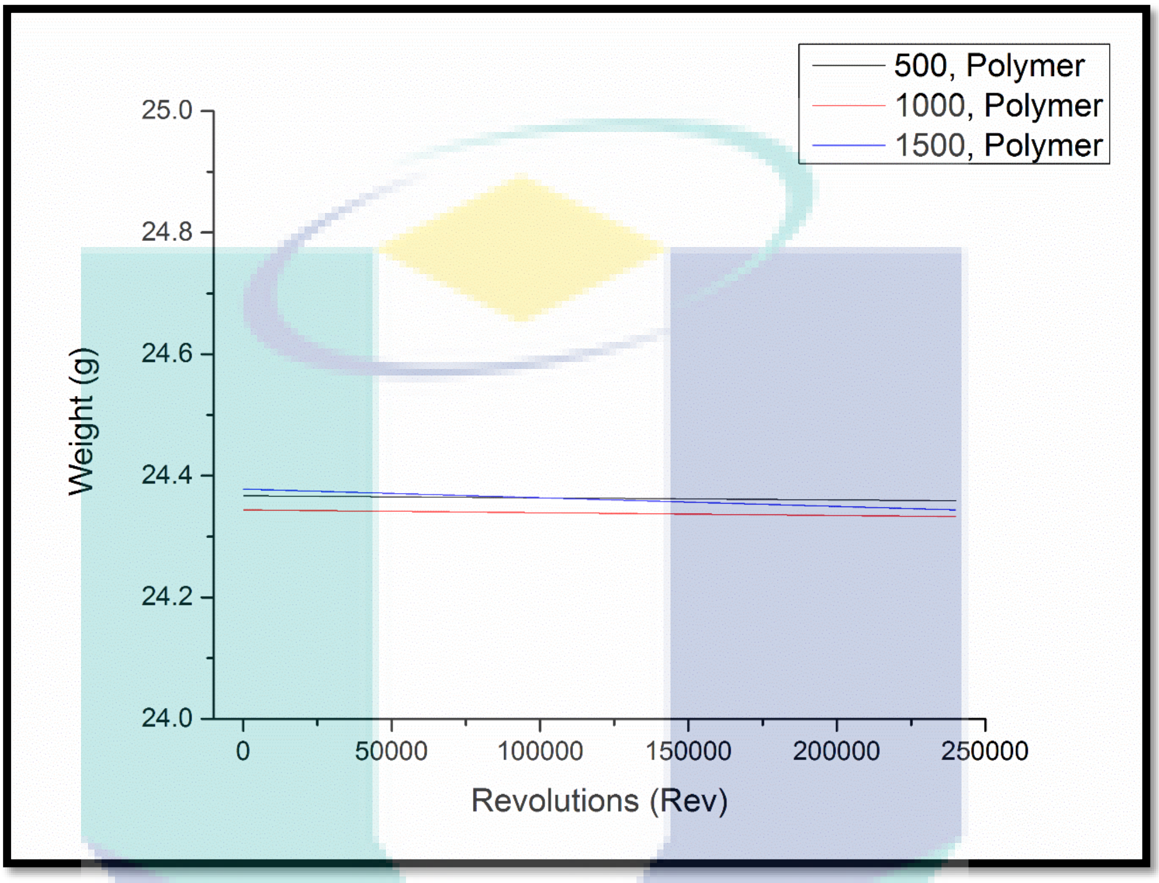



Figure 4-52 Different Speed Polymer Driving with load

# CHAPTER 5

# CONCLUSION

## 5.1 Introduction

The gears are validated on the test rig. The gear pair mesh properly without any interference and problem. The gear tooth mesh and contact with each other properly.

Based on the result, gears undergo wear such as debris formation, fracture and undergo three stage; running in, linear and final rapid wear. The wear debris increase as the gear approaches final wear period. When gears were testing with load the wear debris formed immediately after the test started. Gears start to fractures after going through running in and linear wear period. The wear debris increase as the gear approaches final wear period. Gear start to fracture at certain time during linear wear period until final wear period.

The result of weight loss is determined before and after gear testing. Gear weight loss were estimated and plot into graph to show the percentage of graph slope for 500 RPM, 1000 RPM and 1500 RPM. The graph show estimated weight loss of driving and driven gear. Weight loss is formed due to gear tooth contact which cause friction and heat. Gear will undergo moisture loss at running temperature and thus will produce heat.

Based all the results, it show that driven gear occur higher wear rate compared to driving gear. This is because driven gear act as load and driving gear act as effort. The larger force occur at driven gear thus produce wear. From the experiment it can conclude that detection of wear, weight loss is the most prominent method in order to detect failure in biopolymer and polymer gear. Most of the failures occurred due to the limitation of material, such as the load handling capability and thermal properties. In order to optimize the usage of polymer gear in applications, the operating parameters such as load and running temperature must be calculated beforehand so that the working environment of the gear is the most optimum.

## 5.2 Recommendation

For the recommendation, add material drying to decrease moisture content in material. Also, add resin and fibre with material to increase gear mechanical properties. Besides, fabricate keyway on the gear to improve gear locking mechanism.

# REFERENCES


1. R. L. Mort, Machine Elements in Mechanical Design: Pearson Education South Asia Pte Ltd, 2006.
2. J. L. Elmquist. (2014) Deciding When to Go Plastic. Gear Technology. 46 - 47.
3. A. G. M. Association, "Standard 1106-A97. Tooth Proportions for Plastic Gears," ed. Washington DC: American Gear Manufacturers Association.
4. B. S. Institution, "BS 6168. Specification for non-metallic spur gears," ed. London, 1987.
5. K. M. Marshek and P. K. C. Chan, "Qualitative analysis of plastic worm and worm gear failures," Wear, vol. 66, pp. 261-271, 1981/02/16 1981.
6. H. J. Watson, "5–Wear of gears," Tribology, vol. 2, pp. 212-216, 1969/11/01 1969.
7. B. A. Shaw, J. T. Evans, and T. F. Page, "Scanning electron acoustic microscopy imaging of sub-surface microcracks produced in gear fatigue," Journal of Materials Science Letters, vol. 13, pp. 1551-1554, 1994.
8. K. Mao, W. Li, C. J. Hooke, and D. Walton, "Friction and wear behaviour of acetal and nylon gears," Wear, vol. 267, pp. 639-645, 6/15/ 2009.
9. W. Li, A. Wood, R. Weidig, and K. Mao, "An investigation on the wear behaviour of dissimilar polymer gear engagements," Wear, vol. 271, pp. 2176-2183, Jul 29 2011.
10. K. Mao, P. Langlois, Z. Hu, K. Alharbi, X. Xu, M. Milson, et al., "The wear and thermal mechanical contact behaviour of machine cut polymer gears," Wear, vol. 332–333, pp. 822-826, 5// 2015.
11. S. Senthilvelan and R. Gnanamoorthy, "Damage Mechanisms in Injection Molded Unreinforced, Glass and Carbon Reinforced Nylon 66 Spur Gears," Applied Composite Materials, vol. 11, pp. 377-397, 2004.
12. S. Senthilvelan and R. Gnanamoorthy, "Effect of rotational speed on the performance of unreinforced and glass fiber reinforced Nylon 6 spur gears," Materials & Design, vol. 28, pp. 765-772, // 2007.
13. H. İmrek, "Performance improvement method for Nylon 6 spur gears," Tribology International, vol. 42, pp. 503-510, 3// 2009.
14. H. Düzcükoğlu, "Study on development of polyamide gears for improvement of load-carrying capacity," Tribology International, vol. 42, pp. 1146-1153, 8// 2009.
15. S. Senthilvelan and R. Gnanamoorthy, "Selective Carbon Fiber Reinforced Nylon 66 Spur Gears: Development and Performance," Applied Composite Materials, vol. 13, pp. 43-56, 2006.
16. A. R. Breeds, S. N. Kukureka, K. Mao, D. Walton, and C. J. Hooke, "Wear behaviour of acetal gear pairs," Wear, vol. 166, pp. 85-91, 1993/06/15 1993.
17. H. Düzcükoğlu, R. Yakut, and E. Uysal, "The Use of Cooling Holes to Decrease the Amount of Thermal Damage on a Plastic Gear Tooth," Journal of Failure Analysis and Prevention, vol. 10, pp. 545-555, 2010.
18. K. D. Dearn, T. J. Hoskins, D. G. Petrov, S. C. Reynolds, and R. Banks, "Applications of dry film lubricants for polymer gears," Wear, vol. 298–299, pp. 99-108, 2/15/ 2013.
19. N. A. Wright and S. N. Kukureka, "Wear testing and measurement techniques for polymer composite gears," Wear, vol. 251, pp. 1567-1578, 10// 2001.

20. C. H. Kim, "Durability improvement method for plastic spur gears," Tribology International, vol. 39, pp. 1454-1461, 11// 2006.
21. S. Yousef, T. A. Osman, A. Abdalla, and G. Zohdy, "Wear Characterization of Carbon Nanotubes Reinforced Acetal Spur, Helical, Bevel and Worm Gears Using a TS Universal Test Rig," JOM, pp. 1-8, 2014/12/23 2014.
22. S. Yousef, A. Khattab, M. Zaki, and T. A. Osman, "Wear Characterization of Carbon Nanotubes Reinforced Polymer Gears," Nanotechnology, IEEE Transactions on, vol. 12, pp. 616-620, 2013.
23. A. Pogačnik and J. Tavčar, "An accelerated multilevel test and design procedure for polymer gears," Materials & Design, vol. 65, pp. 961-973, 1// 2015.
24 A. J. Mertens and S. Senthilvelan, "Effect of Mating Metal Gear Surface Texture on the Polymer Gear Surface Temperature," Materials Today: Proceedings, vol. 2, pp. 1763-1769, // 2015.
25. A. J. Mertens and S. Senthilvelan, "Effect of mating metal gear surface texture on the polymer gear surface temperature," Materials Today-Proceedings, vol. 2, pp. 1763-1769, 2015.

## APPENDIX A

DRAWING