Comparison of wear behaviour of polymer spur gears using FDM process

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Abstract. The goal of this study is to explore the potential of three different thermoplastic materials used in plastic gearing applications, such as ABS(Acrylonitrile butadiene styrene), PLA (Polylactic acid) and NYLON. The gears are created by the process of 3D printing.

In order to find the torque at various speeds, experimental investigations are conducted using a gear test rig.

Key words: Polymer-based gear, Injection moulding process, Acrylonitrile Butadiene Styrene (ABS), High Density Polyethylene (HDPE) and Polyoxymethylene (POM).

INTRODUCTION

Due to its lower weight and low manufacturing cost, part weight and quiet performance compared to metal gears, polymer composite gears are finding growing applications. However, compared with metals, polymeric materials suffer from low mechanical strength and thermal resistance. Reinforced polymers are ideal for structural/load bearing and have high mechanical strength and thermal resistance and are suitable for structural/load bearing applications.

Short fiber-reinforced polymers allow complex formed products to be manufactured economically using the injection-molding process. Many studies have been done on the performance problems of polymer and polymer composite gears. In these papers, the effect of reinforcement on polymer gears’ fatigue efficiency and wear resistance is well discussed.

Because many polymer-based gear designs are derived from the method of designing metal gears, polymer-based gears require complex heat build-up considerations and their related effects that occur in operation.

Prashant et al. Investigated on the potential of three different thermoplastic materials used for plastic gearing applications are Acrylonitrile Butadiene Styrene (ABS), High Density Polyethylene (HDPE) and Polyoxymethylene (POM). The gears are manufactured by injection moulding process.

Akant et al. studied the performance and durability of the polymer gears is an important aspect about their application. This paper investigates the various techniques employed for the enhancement of the performance of polymer gears.

As suggested the significance of polymer gears to transmit power and motion is increasing continuously due to their inherent characteristics. Polymer gears have established themselves as attractive alternatives to traditional metal gears in plethora applications. They are light in weight, have lower inertia, and run noiseless than their metal counterparts.

W. Li et al. Performed the experiment on polymer gear (acetal and nylon) friction and wear behaviour. First, a unique test method for polymer gear wear will be described in brief and later used in the extensive investigation of acetal and nylon gear wear. Initial tests were performed using acetal pinions with acetal gears, and nylon pinions with nylon gears, with further investigation carried out using dissimilar polymer gears.
P. Langlois et al. Examined on machine cut acetal gear wear and thermal mechanical contact behaviour. The results for machine cut acetal gears will be compared to previously published results obtained for polymer gears manufactured through injection moulding.

K. Mao. Employed a new design method for polymer composite gear has been proposed in the current paper. This design method is based on the link between polymer gear wear rate and its surface temperature. It has been found from the tests that the polymer (acetal) gear wear rate will be increased dramatically when the load reaches a critical value for a specific geometry.

S. Senthilvelan et al. Experimented on polymer based gears replace metal gears in many light duty power and/or motion transmission applications due to their noiseless operation even under unlubricated conditions. Visco elastic behaviour of the polymer, which is mainly responsible for the sound absorption, is altered by the addition of short fibers.

S.M. Evans et al. Investigated a new methodology to predict the transient operational temperature of a polymer–steel gear pair under loaded running is presented.

R. Gnanamoorthy et al. Studied unreinforced nylon 6/6 and 20 per cent carbon-fibre-reinforced nylon 6/6 gears were injection moulded in the laboratory and tested for transmission efficiency using an in-house developed power absorption test rig.

K D Dearn et al. Observed the role of materials in the generation of noise made by plastic gears.

T.J. Hoskins et al. Suggested the sound frequency spectrum is influenced by the various polymeric gear materials and operating conditions.

POLYMER SPUR GEAR

A great deal of modern technology depends on more conventional equipment to get the job done, considering the proliferation of electronic devices. For instance, in many important machines, from wind farms to heart pumps, gears still play a large role. Several gears are made of plastic to save cost and weight.

Gears made of plastic tend to be lighter in weight than similar gears made out of metal. Plastic gears are, in general, less expensive to produce than those made of metal. Plastic gears can have their teeth worn down from repeated use. While this is true of any gear, plastic as a material isn't as durable as metals, though manufacturers can add coatings for the teeth.
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MATERIALS AND METHODS

The materials used to manufacture the polymer spur gear are ABS (Acrylonitrile butadiene styrene), NYLON, and PLA (Polylactic Acid).

| Tensile Strength (MPa) | 40.96 |
|------------------------|-------|
| Flexural Strength (MPa) | 45.44 |
| Impact Strength (MPa)  | 22.11 |
| Melting Temperature °C  | 220 – 260 |
| Density g/cm³           | 1.07  |

Table 1: ABS material properties

| Tensile Strength (MPa) | 62.63 |
|------------------------|-------|
| Flexural Strength (MPa) | 65.02 |
| Impact Strength (MPa)  | 4.28  |
| Melting Temperature °C  | 190 – 220 |
| Density g/cm³           | 1.25  |

Table 2: PLA material properties
Tensile Strength (MPa) | 50 – 55  
Flexural Strength (MPa) | 85 – 90  
Impact Strength (MPa) | 354  
Melting Temperature (°c) | 220 – 260  
Density g/cm³ | 1.15  

Table 3: NYLON material properties

FUSED DEPOSITION MODELING PROCESS:

Fused deposition modeling (FDM) is a method of additive manufacturing that belongs to the extrusion class of materials. An object is constructed in FDM by selectively depositing melted material into a layer-by-layer pre-determined path.

The production was performed in think-3D, Visakhapatnam,

These materials take the form of plastic threads, or filaments, during printing, which are unwound from a coil and fed through an extrusion nozzle. The nozzle melts and extrudes the filaments onto a foundation, often referred to as a building platform or table. A computer controls both the nozzle and the foundation, which transforms an object's dimensions into X, Y and Z nozzle coordinates and base to follow during printing.

In a standard FDM device, the extrusion nozzle travels horizontally and vertically across the building platform, drawing a cross section of an object onto the platform. This thin plastic layer cools and hardens, binding to the layer underneath it instantly. The base is lowered after a layer is finished, normally by approximately one-sixteenth of an inch, to make room for the next layer of plastic.
Printing time is dependent on the size of the produced item. Small objects, only a few cubic inches, and tall, thin objects print easily, while printing takes longer for larger, more geometrically complex objects.

Once an object is removed from the FDM printer, the support materials are either removed by soaking the object in a solution of water and detergent or snapping the support material off by hand in the case of thermoplastic supports. In order to enhance their function and appearance, objects can often be sanded, milled, painted or plated.

Once an object is removed from the FDM printer, in the case of thermoplastic supports, the support materials are either removed by soaking the object in a water and detergent solution or snapping the support material off by hand. Objects may frequently be sanded, milled, painted or plated to improve their function and appearance.

FABRICATION OF POLYMER SPUR GEARS

3D PRINTING PROCESS

In the production of a three-dimensional object through additive manufacturing, a variety of processes, equipment and materials are used.

Some techniques melt or soften the layer content, such as fused deposition modeling (FDM), selective laser melting (SLM), selective laser sintering (SLS), fused filament manufacturing (FFF), etc. Thin layers are cut to form and joined together (e.g., paper, polymer, metal).

Each process has its own advantages and disadvantages, which is why some businesses have the material used to create the object with a choice between powder and polymer. In order to create a robust prototype, others often use regular, off-the-shelf business paper as the construction material.

Speed, costs of the 3D printer, the printed prototype, choice and cost of the materials, and color capabilities are usually the key considerations in selecting a computer.
Fig 4. ABS gear

MODELING OF THE SPUR GEAR IN POLYMER:

Polymer gears give engineers more versatility and different cad software such as CATIA, PRO-E and solid-works etc. can design the gear and the part can be drawn in a specific dimension where the part can be drawn.

A gear component built by CATIA V5 R21.

You must save this part in the form of the STL format. This file is used for the process of fabrication.

Figure 5: Polymer Spur gear using catia V5
POLYMER GEAR DIMENSIONS:

| Material       | Test Gear          | Mating Gear        |
|----------------|--------------------|--------------------|
| Manufacturing Process | 3D Printing Process | Gear hobbing       |
| Tooth profile  | Involute           | Involute           |
| Type           | Spur Gear          | Spur Gear          |
| Pressure angle | 20°                | 20°                |
| Module         | 2                  | 2                  |
| Diameter of Pitch circle (mm) | 34              | 34              |
| Diameter of Tip circle (mm)    | 38              | 38              |
| Diameter of Root circle (mm)   | 29              | 29              |
| No. of teeth   | 17                 | 17                 |
| Face width (mm) | 6               | 6                  |
| Diameter of Hub (mm)            | 18              | 18              |
| Diameter of Bore (mm)           | 12              | 12              |

Table 4: Dimensions of polymer spur gear and mating metal gear

RESULTS AND DISCUSSION:

Polymer gear test rig: The test rig is a system used on the components or assemblies to carry out such tests. It's a way of exploring and obtaining results from an experimental test. Polymer gears are built of polymers such as nylon etc. These gears are to be checked on a test rig to provide further design approval based on the results of the tests.

These rigs typically include components such as structural frame, engines, gear mount fixtures, data output sensors such as rpm, acceleration, temperature, Show of user interfaces etc. A motor, generator and a rheostat are part of the RAMSON polymer gear test rig. The speed of the motor and generator can be changed.

The DC motor starts spinning once the speed is determined, which gives rotational motion to the mild steel gear that meshes with the polymer spur gear attached to the DC generator. A rheostat is mounted between the engine and the generator, which provides the DC generator with a load of 1 kW at intervals of 250W, 250W and 500W.

The corresponding values are given by the temperature sensor and the speed sensors present in the apparatus. From the user interface display, all these will be noted.
Experimentation is carried out for three different materials at different speeds (600rpm, 800rpm, 1100rpm) and specific wear rate is calculated using standard formula.

\[ W_s = \frac{W_v}{2zmbNT} \quad [1] \]

- \( W_s \): specific wear rate
- \( W_v \): wear volume (mm³)
- \( z \): number of gear teeth
- \( m \): module (mm)
- \( b \): tooth face width (mm)
- \( NT \): total number of revolution (rev)

\[ W = \frac{W_v}{2zmbN} \quad [1] \]

- \( W \): wear volume (mm³)
- \( z = 17 \)
- \( m = 2 \) mm
- \( b = 6 \) mm
- \( N = 371579 \)
| S.no | Days | Speed (rpm) | Motor | Generator | Torque (N-m) | No. of rotations per day |
|------|------|-------------|-------|-----------|--------------|------------------------|
|      |      | N           | Voltage (V) | Current (amp) | Voltage (V) | Current (amp) |
| 1    | 1st  | 600         | 101      | 0.99       | 33          | 0.40      | 1.364      | 123912     |
| 2    | 2nd  | 600         | 101      | 0.99       | 33          | 0.40      | 1.364      | 123882     |
| 3    | 3rd  | 600         | 101      | 0.99       | 33          | 0.40      | 1.364      | 123785     |
| 4    | 1st  | 800         | 147      | 0.97       | 15          | 0.36      | 1.371      | 123581     |
| 5    | 2nd  | 800         | 147      | 0.97       | 15          | 0.36      | 1.371      | 123423     |
| 6    | 3rd  | 800         | 147      | 0.97       | 15          | 0.36      | 1.371      | 123350     |
| 7    | 1st  | 110         | 175      | 0.98       | 60          | 1.03      | 1.388      | 123682     |
| 8    | 2nd  | 110         | 175      | 0.98       | 60          | 1.03      | 1.388      | 123211     |
| 9    | 3rd  | 110         | 175      | 0.98       | 60          | 1.03      | 1.388      | 123146     |

**Table 5:** Experimental values of Nylon Gear at different speeds.

Fig 7. Nylon gear at 600 rpm  
Fig 8. Nylon gear at 800 rpm  
Fig 9. Nylon gear at 1100 rpm
| S.no | Days  | Speed (rpm) | Motor | Generator | Torque (N-m) | No. of rotations per day |
|------|-------|-------------|-------|-----------|--------------|-------------------------|
|      |       | N           | Voltage (V) | Current (amp) | Voltage (V) | Current (amp) |                     |
| 1    | 1<sup>st</sup> | 600         | 101   | 0.99      | 33           | 0.40        | 1.364      | 123756             |
| 2    | 2<sup>nd</sup> | 800         | 147   | 0.97      | 15           | 0.36        | 1.371      | 123621             |
| 3    | 3<sup>rd</sup> | 110         | 175   | 0.98      | 60           | 1.03        | 1.388      | 123512             |

Table 6: Experimental values of ABS Gear at different speeds
| S. no | Days | Speed (rpm) | Motor | Generator | Torque (N-m) | No. of rotations per day |
|------|------|-------------|-------|-----------|-------------|-------------------------|
| 1    | 1<sup>st</sup> | 60          | 101  | 33        | 1.364       | 123692                 |
| 2    | 2<sup>nd</sup> | 0           | 0.99 | 0.40      |             | 123522                 |
| 3    | 3<sup>rd</sup> |             |      |           |             | 123348                 |
| 4    | 1<sup>st</sup> | 80          | 147  | 15        | 1.371       | 123458                 |
| 5    | 2<sup>nd</sup> | 0           | 0.97 | 0.36      |             | 123231                 |
| 6    | 3<sup>rd</sup> |             |      |           |             | 123123                 |
| 7    | 1<sup>st</sup> | 1100        | 175  | 60        | 1.388       | 123021                 |
| 8    | 2<sup>nd</sup> | 0           | 0.98 | 1.03      |             | 122983                 |
| 9    | 3<sup>rd</sup> |             |      |           |             | 120341-Break           |

Table 7: Experimental values of PLA Gear at different speeds
### Table 8: Experimental values of specific wear rate for Nylon gear.

| Speed  | Weight loss. (g) | Density (g/cm³) | Weight volume (mm³) | No of rotations,(N) | Specific Wear ×10⁶ mm³/mm-mm-rev |
|--------|------------------|-----------------|---------------------|---------------------|----------------------------------|
| 600 rpm | 0.040            | 1.15            | 34.783              | 371579              | 0.229                            |
| 800 rpm | 0.092            |                 | 80.000              | 370354              | 0.529                            |
| 1100 rpm| 0.140            |                 | 121.739             | 370039              | 0.806                            |

### Table 9: Experimental values of Specific wear rate for ABS gear.

| Speed  | Weight loss. (g) | Density (g/cm³) | Weight volume (mm³) | No of rotations,(N) | Specific Wear ×10⁶ mm³/mm-mm-rev |
|--------|------------------|-----------------|---------------------|---------------------|----------------------------------|
| 600 rpm | 0.08             | 1.07            | 74.766              | 370889              | 0.494                            |
| 800 rpm | 0.14             |                 | 130.841             | 369858              | 0.867                            |
| 1100 rpm| 0.22             |                 | 205.607             | 369635              | 1.363                            |

### Table 10: Experimental values of Specific wear rate for PLA gear. PLA gear breaks at 1100 rpm.

| Speed  | Weight loss. (g) | Density (g/cm³) | Weight volume (mm³) | No of rotations,(N) | Specific Wear ×10⁶ mm³/mm-rev |
|--------|------------------|-----------------|---------------------|---------------------|--------------------------------|
| 600 rpm | 0.05             | 1.25            | 40                  | 370562              | 0.264                            |
| 800 rpm | 0.14             |                 | 112                 | 367011              | 0.748                            |
Fig 16. Plot between Specific wear rate and No. of Rotations for Nylon gear.

Fig 17. Plot between Specific wear rate and No. of Rotations for ABS gear.

Fig 18. Plot between Specific wear rate and No. of Rotations for PLA gear.
CONCLUSIONS

- For plastic gearing applications, the potential of three different polymeric gears (Nylon, ABS and PLA) created by the FDM process (3D printing) is examined.

- With increasing rotation speed, the real wear rate for polymer equipment increases.

- The results show that ABS gear has the maximum specific wear rate (at 600 rpm 0.494, at 800 rpm 0.867 and at 1100 rpm 1.363), while nylon has the minimum specific wear rate (at 600 rpm 0.229, at 800 rpm 0.529 and at 1100 rpm 0.806).

- It is clear that the nylon gear shows the best results while compared to other material gears.

- Polymer gear failure is investigated at a torque of 1.388Nm and a speed of 1200 rpm. PLA gear has an unacceptable wear rate and breaks after ABS and Nylon gears have completed 3L rotations at various speeds.

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