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Research Paper / Makale

Investigation of Thermal and Wear Behaviour of 3D Printed PA-12 Nylon Polymer Spur Gears

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Abstract: The study investigates the potential of 3D-printed gears of PA-12 Nylon material which are intended for use in polymer gearing. The gears are made through an additive manufacturing process known as SLS (Selective Laser Sintering). Thermal and wear characteristics of this set of gears are investigated at varying torque values of 1.6, 2.0, and 2.4 Nm in combination with varying rpm of 800, 1000, 1200 and 1400. The gears are subjected to 1 x 10^5 load cycles. The gear failed due to a rise in contact surface at 1400 rpm and 2.4 Nm torque. At high torque, there is a decrease in the durability of the gear. The specific wear rate is more at low rotational speed in comparison to high speed. At low torque and low rotational speed, there is not any significant sign of failure and gears operate smoothly.

Keywords: 3-D printing, polymer gears, failure behaviour, wear characteristics, PA-12 nylon

3D Baskılı PA-12 Naylon Polimer Düz Dişlilerin Termal ve Aşınma Davranışlarının İncelenmesi

Öz: Çalışma, polimer dişlilerde kullanılması amaçlanan PA-12 Naylon malzemeden 3D baskılı dişlilerin potansiyelini araştırmaktadır. Dişliler, SLS (Seçici Lazer Sinterleme) olarak bilinen bir eklemeli üretim süreci ile yapılır. Bu dişli takımının termal ve aşınma özellikleri, değişen 800, 1000, 1200 ve 1400 devir sayısı ile kombinasyon halinde 1,6, 2,0 ve 2,4 Nm'lik değişen tork değerlerinde incelenmiştir. Dişliler 1 x 10^5 yük çevrimine tabi tutulur. 1400 rpm'de ve 2,4 Nm torkta temas yüzeyindeki artış nedeniyle dişli başarısız oldu. Yüksek torkta, dişlinin dayanıklılığında bir azalma vardır. Spesifik aşınma oranı, yüksek hıza kıyasla düşük devirde daha fazladır. Düşük tork ve düşük dönüş hızında önemli bir arıza belirtisi yoktur ve dişliler sorunsuz çalışır.

Anahtar Kelimeler: 3-D baskı, Polimer dişliler, başarısızlık davranışı, aşınma özellikleri, PA-12 naylon

1. Introduction

The gear wheel, which has at least two gear teeth, is the most extensively employed mechanism among power- and rotation-conveying elements. Parallel to technological progress, gear wheels have become rather ubiquitous in practically every sphere of life [1].

Polymer gears are much better in comparison to metal gears in the context of cost and weight, efficiency, quiet operation, and are capable of working without lubricant. The wear and thermal

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performance of the gears manufactured by the injection moulding process have been previously investigated [2,3].

3D printing technique known as additive manufacturing has gained a lot of popularity for manufacturing polymer parts due to their ability to develop intricate components. When compared to plastic injection moulding, 3D printing is usually believed to be more cost-effective provided manufacturing quantities are less than 1000 units [4]. The 3D printing technology is being applied in numerous industries i.e automotive, aviation, medical science, and construction. The 3D printing methodology is directly linked with the material to be used for component development. SLS (Selective Laser Sintering) process uses powder material like Nylon. The component is developed layer-wise by sintering the material by heating it with a laser [5]. PA-12 Nylon polymer components are used and tested for various applications in automotive [6]. Because of the growing popularity of 3D printing, more research is being carried out to know the physical and temperature-dependent properties of 3D printed components, as well as how to modify them.

According to Kalin et al., thermal properties can affect gear performance and durability and concluded that the life cycle of the gear is reduced as the operating temperature rises [7].

Much of the research done for polymer gears has revealed that gear performance is affected by material, torque, and rotational speed. Polymer gears are most typically made from thermoplastic materials like Nylon PA-6, Nylon PA-66, Acetal, Polycarbonate, and others. Polyurethane and Polyester are two thermosetting materials that are employed [8].

Senthilvelan and Gnanamoorthy [9] researched regarding effects of rotational speed on gear’s performance only under extreme stress. As the rpm of the gear increases, the contact period of the two teeth decreases which results in less wear [10]. Mao et. al. [11-15] discovered a significant wear rate increment as the transmitted torque hits a definite value for a given gear configuration. This occurs due to the surface temperature of the gear material reaching its melting point due to the torque which reaches its perilous level. As a result, the elevated surface temperature of polymer gear is a significant restriction. When two bodies rub together, the true contact region achieves the highest temperature, called flash temperature.

Blok [16] recognised the significance of the flash temperature for component design and offer methods for calculating flash temperatures in polymer gears. Evans et. al. [17] developed a device with a steel rod rubbing with a polymer disc which can anticipate the polymer disc's thermal behaviour. The anticipated temperature values have a 9% correlation with the experimental readings. Transmission efficiency, noise, and vibration damping are the other output properties of polymer gears, in addition, to the rate of wear and temperature of the surface. As the gear tooth deteriorates with increased cycle time, the transmission efficiency of polymer gear decreases [18].

PA 12 (also known as Nylon 12) is a strong, tensile, impact, and flex-without-fracture plastic with a wide range of additive uses. Injection moulders have traditionally utilised PA 12 because of its mechanical characteristics [19]. PA 12 has lately been a popular material for making functional components and prototypes in additive manufacturing procedures. Polyamide (Nylon) is a synthetic polymer utilised in many industrial applications and has excellent mechanical qualities, chemical resistance, and acid resistance [20].

Ye Zhang et. al. investigated the wear and thermal characteristics of 3D printed gear manufactured with a fused deposition modelling process. The gears were manufactured from Nylon 618, Nylon 645, and alloy 910 filaments, together with Onyx and Markforged nylon proprietary material. The result showed at Nylon 618 has better wear properties in comparison to other materials. Nylon 66 and Nylon 618 exhibited better thermal behaviour compared to other materials. Finally, it was concluded that the thermal and wear behaviour is highly dependent on the level of sintering effect between the layers in the FDM Process [21].

A K Pandian et.al. compared the bending fatigue behaviour of the polymer gear manufactured by selective laser sintered (SLS) gears Nylon 12 and injection moulded Nylon 66 spur gears. The cyclic pulsating load was applied on a single tooth for fatigue test in a custom-built test rig. The load was applied by pulsating steel gear. They concluded that selective laser sintered Nylon 12 gears have superior bending fatigue life in comparison to injection moulded gears. They also determined that SLS spur gears have low fatigue strength at a low cycle fatigue regime as the temperature of the gear is high in this region, but at a high cycle fatigue regime, SLS Nylon 12 gears have very well performed in comparison to injection moulded Nylon 66 gears. The crack developed in SLS Nylon gears has a rough surface in comparison to a smooth surface in injection moulding. The rough surface of the crack in SLS gears is due to the sintering of powder of Nylon 12 [22].

Harsha et. al. probed the wear behaviour of polymer gears manufactured by fused deposition modelling 3D printing process. The gears were developed from Acrylonitrile Butadiene Styrene (ABS), Nylon and Polylactic Acid (PLA). The wear behaviour was tested for 03 RPM levels i.e. 600,800 & 1100 at a torque level of 1.3. The specific wear rate of Nylon was less in comparison to ABS and PLA with 0.229 at 600 rpm; 0.529 at 8000 & 0.806 at 1100 rpm compared to ABS having 0.494 at 600 rpm; 0.867 at 800 rpm & 1.363 at 1100 rpm. Further testing of gears for 1.3 Nm torque and 1200 rpm, PLA gear failed earlier than ABS and Nylon gears which operated till 3 Lakh cycles [23].

Pisula et.al. analysed the polymer spur gears with Melted and Extruded modelling (FDM) & Fused Filament Fabrication (FFF) additive manufacturing techniques. The materials used for gears were ABS M-30 (Acrylonitrile Butadiene Styrene), ULTEM 9085 (PEI Polyetherimide) and PEEK (Polyetheretherketone). The customised test rig was designed to determine the fatigue life of polymer gears. The polymer gears were subjected to a constant 400 rpm but the torque was kept incremental w.r.t time (min). The torque was increased from 1.7 Nm to 3.0 Nm within the period of 0 to 70 min. The analysis and experiment suggested that PEEK gears are more resistant to wear, ABS has ranked second and then Ultem gears which have maximum wear. The major wear which was observed was in the flank area of the gear resulting in the concavity of the flank [24].

Polymer gears manufactured by injection moulding are investigated in the above studies. Surprisingly, there are fewer studies available on the study of mechanical behaviour of 3D printed polymer gears made from the SLS technique to date; this could be due to uncertainty or preconceived notions about their potential mechanical performance. In this paper, the performance of PA-12 Nylon polymer gears under different loading conditions investigated, which are manufactured using SLS 3D printing technology.

2. Specimen Preparation

The spur gears are additively manufactured with PA-12 Nylon material. The properties of this PA-12 Nylon polymer material are listed in Table 1. The polymer spur gears are manufactured by the Selective Laser Sintering (SLS) rapid prototyping method. The dimensional parameters of the mating spur gears are given in Table 2. The 3D Printed specimen of the spur gear is shown in Figure 1.

3. Testing of Gears

The testing of polymer gears has been carried out on a power absorbing test rig of polymer gear manufactured by DUCOM Instruments, India. The picture of the test rig is shown in Figure 2. The polymer gear test rig is connected to a DC motor of 1 kW and meshes with a matching metal gear of material AISI 1040. The metal gear driven by an AC motor (SEIMENS) of 1.5 kW has a maximum capacity of 1500 rpm. The gears rotate in a clockwise direction so as the right flank of the polymer gear comes in contact with the opposite gear.

Table 1. Gear Material Properties

Material Property	**NYLON PA-12**
Density (g/cm^3)	0.95
Tensile Strength Yield (Mpa)	50
Elongation yield (%)	14
Thermal Conductivity (W/m K)	0.21
Heat Deflection Temperature (º C)	86
Surface Roughness (µm) (Face, flank & along pitch line)	4.628
Coefficient of Friction [25] (AISI 1040 & PA-12)	0.28
Hardness (Shore D)	82

Figure 1. 3D Printed Spur Gear

Table 2. Spur gear parameters

	Driver Gear	**Driven Gear**
Material	AISI 1040	NYLON PA-12
Module – mm		2
Teeth		20
Pressure Angle		20
Face width - mm	10	8
Pitch diameter - mm		40
Addendum Diameter - mm		44
Contact Ratio	1.557	

Table 3. Design of Experiments

Sr. No.	RPM	Torque Driver Gear Nm (T)
1	800	1.6
2	800	2
3	800	2.4
4	1000	1.6
5	1000	2
6	1000	2.4
7	1200	1.6
8	1200	2
9	1200	2.4
10	1400	1.6
11	1400	2
12	1400	2.4

The gears to be tested are loaded by a DC motor via a rheostat. Torque sensors with an accuracy of 0.2% are being used to quantify torque from both, the driver and driven sides. A non-contact infrared temperature sensor (OMEGA, OS 100EV2) with a 1% accuracy measures the surface temperature of the running gears. As shown in Figure 3, the sensor is located just directly above the polymer gear contact location in the acrylic chamber along with gears so that temperature can be measured in steady air condition. The test rig is connected to the computer where continuous data is logged regarding mating temperature, input torque and output torque.

The design of the experiment for testing nylon PA-12 gears (RPM and Torque - Nm)is carried out as shown in Table 3, for 10^5 load cycles.

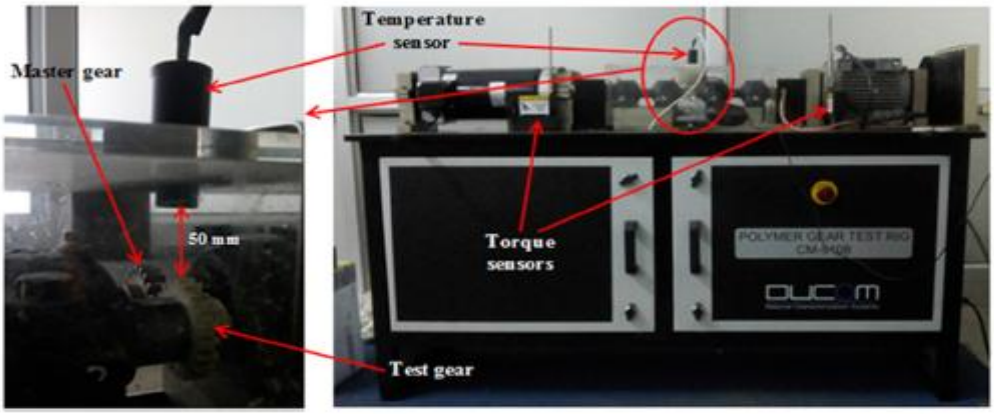


Figure 2. Polymer gear test rig

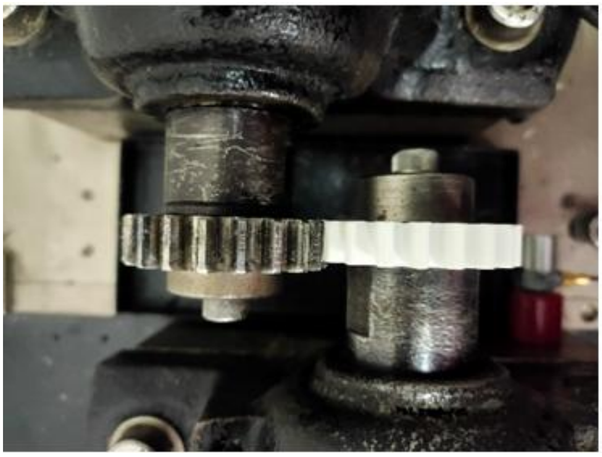


Figure 3. Mating gear

4. Thermal Behaviour of PA-12 Polymer Gears

The thermal behaviour of Nylon gears operating at different rpm and torque levels are shown in Figures 4, 5, 6 & 7. Initially, the gear's surface temperature increases rapidly and then it stables after completion of some load cycles. The increase in the surface temperature is due to friction between the two gears. Initially, up to approx.10000 to 15000 load cycles, there is a significant rise in temperature, which is much higher than ambient temperature (30°C), at this moment the conduction process is started by the metal gear. The metal gear initiates to reject heat from the surroundings until the thermal equilibrium is not established resulting in steady thermal behaviour.

Figure 8 shows there is a substantial rise in temperature from the ambient temperature (30°C) at the 2.4 Nm torque level in comparison to the 1.6 & 2.0 Nm torque for all RPM. The temperature rises at 1.6 Nm torque at all rpm i.e. 800, 1000, 1200 & 1400 is almost steady with a change of 5.104 ºC only. If torque is increased to 2.0 Nm, the temperature rise is more at 1400 rpm in comparison to

800, 1000 & 1200. At high torque i.e. at 2.4Nm, there is a substantial increase in temperature difference at all rpm levels. At 1400 rpm and torque of 2.4 Nm the gear fails in 14100 load cycles.

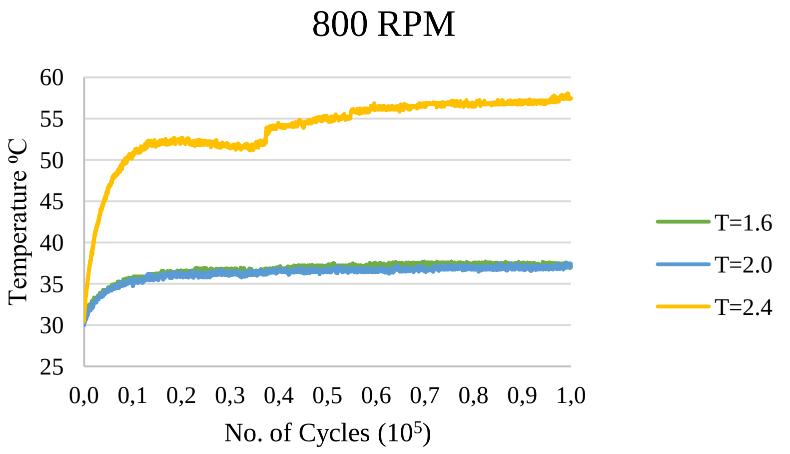


Figure 4. Thermal Behaviour of spur gear at 800 rpm at different Torque (T)

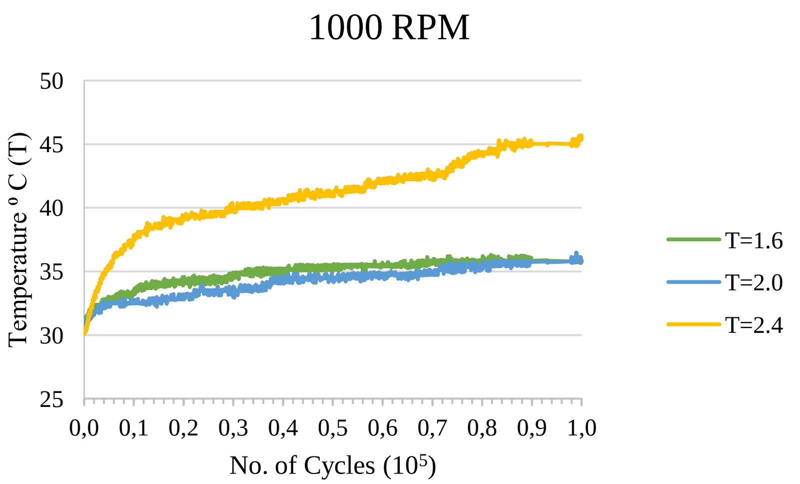


Figure 5. Thermal Behaviour of spur gear at 1000 rpm at different Torque (T)

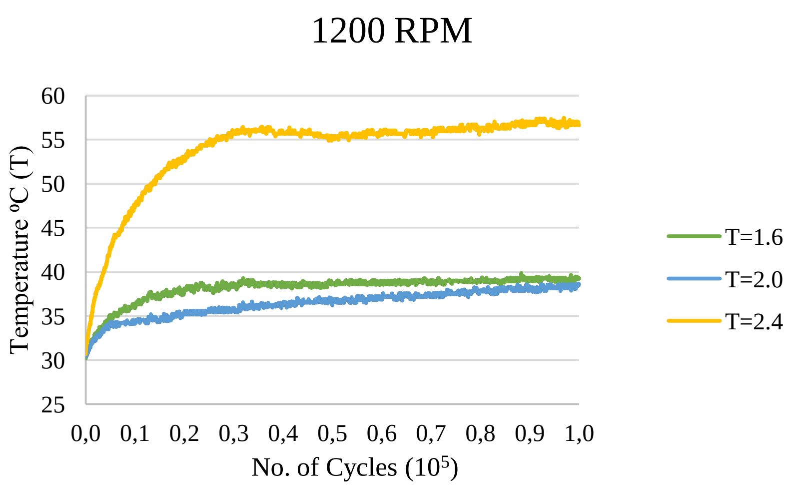


Figure 6. Thermal Behaviour of spur gear at 1200 rpm at different Torque (T)

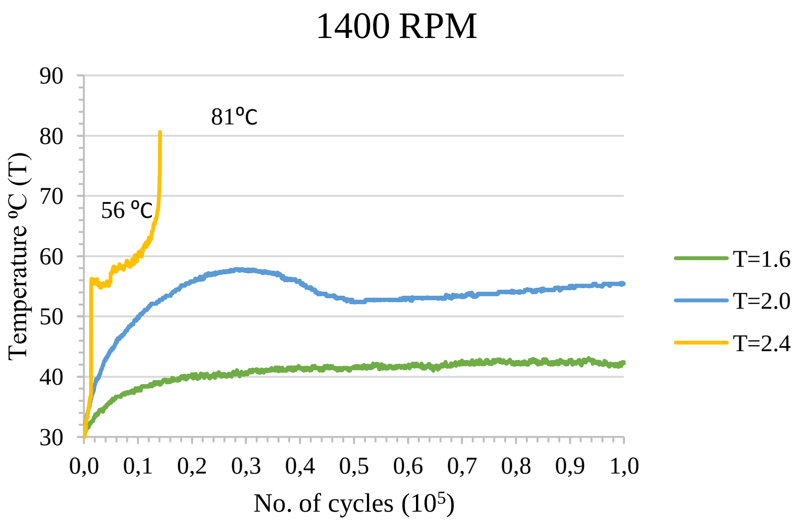


Figure 7. Thermal Behaviour of spur gear at 1400 rpm at different Torque (T)

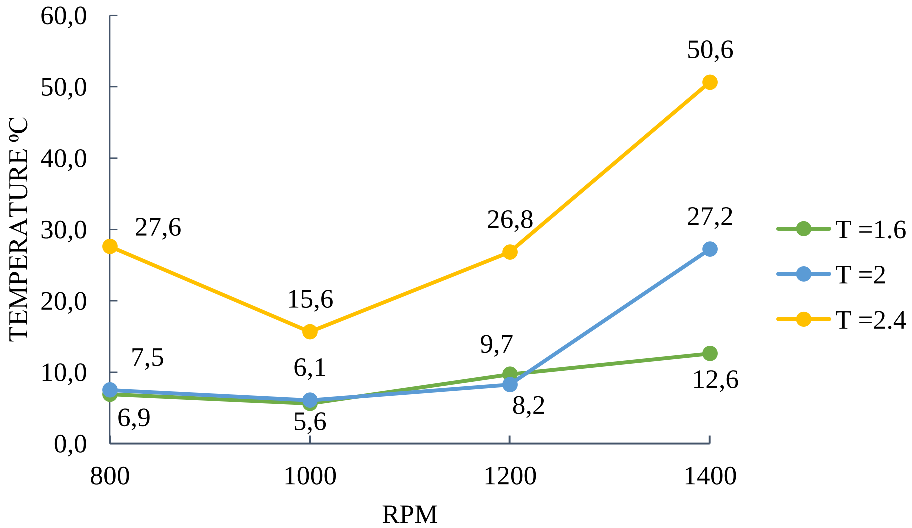


Figure 8. The temperature rise of spur gears at different Torque (T)

The gear fails due to a rise in functional temperature to 81ºC, which is more than the deformation temperature of PA – 12 materials (86ºC) as shown in Figure 7. At 2.2 Nm torque and 1400 RPM, the gear has thermal failure resulting in melting of gear tooth as shown in Figure 9.

Figure 9. Failure of spur gear

5. Estimation of Temperature of Gear Surface by Mao Model

The experimental value of rising in surface temperature is matched to the Mao model's estimated surface temperature rise value. The value of temperature generated on the test rig is the difference between the equilibrium temperature and the initial surface temperature. By the Mao model [15], the θ_b temperature rise of gear is calculated as:

$$\theta_b = \frac{0.625\mu T}{c\rho Zb(r_a^2 - r^2)} \qquad (1)$$

Where,
μ – Coefficient of Friction of gear material,
T - Torque - Nm,
c – The Specific heat of the PA12 polymer material - J/Kg K,
ρ – The Sp. gravity of the polymer material,
Z – Number of teeth,
b - Gear face width - m,
r_a - Outer circle radius - m
r - Pitch circle radius - m

Table 4 & Figure 10 exhibit a comparison of the calculated and experimental values of surface temperature rises at different levels of torque 1.6, 2.0 & 2.4 Nm and rpm 800, 1000, 1200 & 1400.

Table 4. Calculated and experimental values of surface temperature rises

Torque Nm (T)	Mao Model	800 (RPM)	1000 (RPM)	1200 (RPM)	1400 (RPM)
1.6	7.25	6.87	5.59	9.69	12.59
2	9.06	7.85	6.05	8.23	27.22
2.4	10.87	27.59	15.63	26.80	50.60

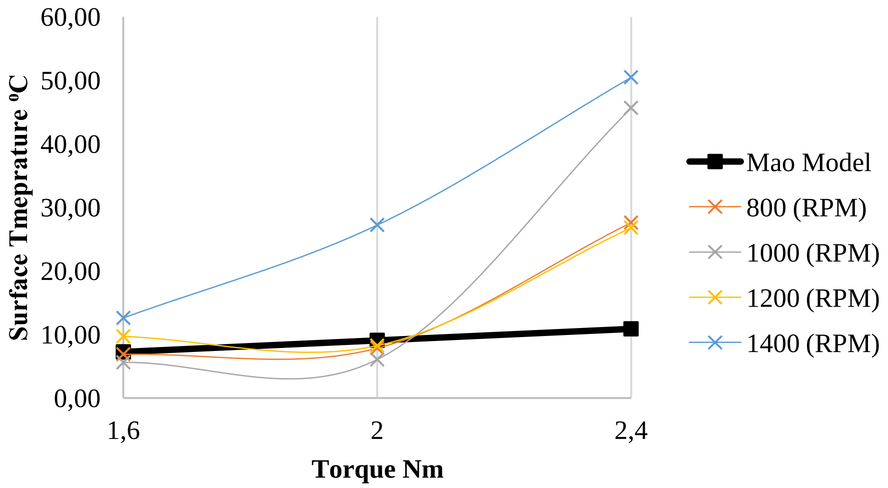


Figure 10. Comparison of the measured and predicted rise in gear temperature

The Mao model is in best agreement with experimental results at torque 1.6 Nm for all RPM (i.e 800, 1000, 1200 & 1400). At 2.0 Nm torque, the experimental and estimated surface temperatures differ significantly. At 2.4 Nm torque, there is a vast deviation between the surface temperature of gear obtained through experiment and calculated by the Mao model. At low torque, the Mao model is well in agreement with the experimental data but as the RPM and torque increase, there is a significant difference between the data, especially at 1400 RPM.

6. Quantitative Comparison of Thermal Behaviour

The quantitatively compared thermal behaviour of the polymer gears concerning torque 1.6 Nm, 2.0 Nm & 2.4 Nm and to rpm 800, 1000, 1200 & 1400 is shown in Figure 11 & 12.

The surface temperature rises to 28% with a change in rpm from 800 to 1400 at a torque level of 1.6 Nm, while there is a 51% rise in surface temperature as the torque rises from 1.6 to 2.4 Nm at 800 RPM. The torque applied, plays a major role in raising the surface temperature in comparison to the rpm at which the gears are operating. The increase in surface temperature generated by torque is 2-3 times more than the effect of rotational speed.

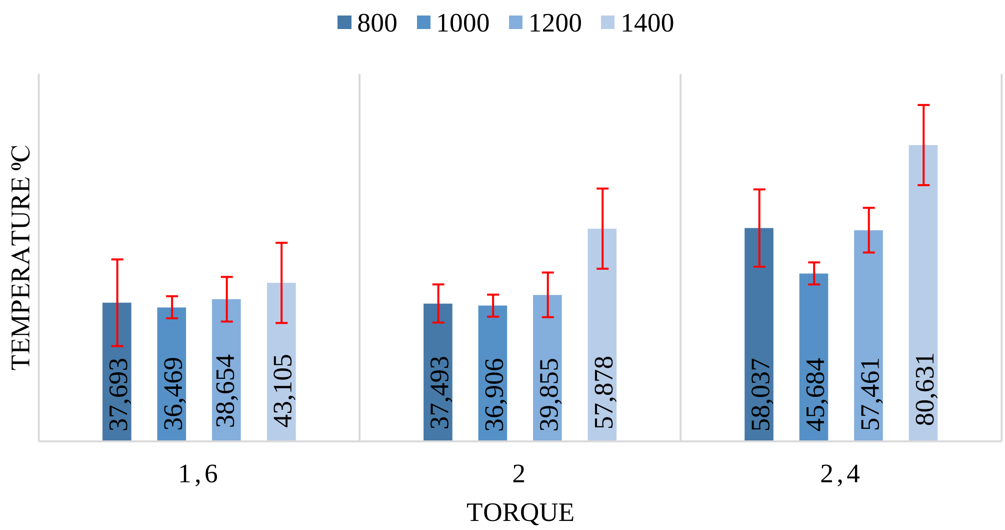


Figure 11. Quantitative Comparison of thermal behaviour w.r.t torque

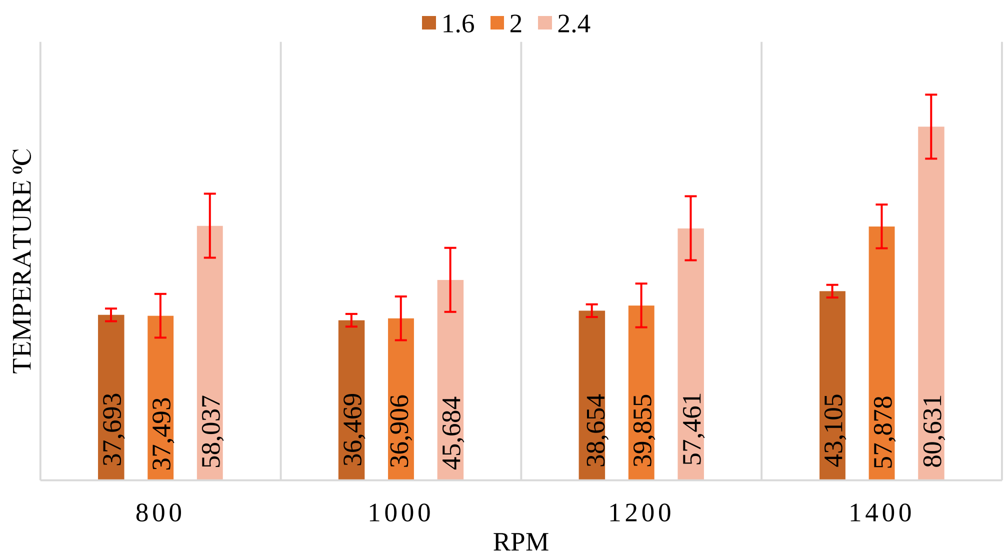


Figure 12. Quantitative Comparison of thermal behaviour w.r.t RPM

7. Wear Behaviour of PA-12 Polymer Gears

PA-12 Nylon gears wear behaviour at different levels of torque of different speeds is as shown in Figure 13. The gear's specific wear rate is calculated by [14]:

$$W_s = \frac{W_v}{2zmbN_T} \tag{2}$$

Where,
W_v - Wear volume - mm^3,
z - Gear teeth,
m - Module - mm,
b - Tooth face width - mm
N_T – RPM

Wear volume (W_v) is derived by dividing the weight loss by the material density of gear material. The loss in gear's weight is determined by weighing it before and later the test with a weighing machine manufactured by Denver instruments having an accuracy of 0.01 mg. A roughness tester with a resolution of 0.01 µm is used to measure the surface roughness of the gear teeth roughness in the pitch region.

The wear rate of the gear increases as the torque increases. The experimental results show that at low rpm specific wear is high in comparison to a consequent increase in speed. This is due to a reduction in the gear tooth's contact time. On the other side, at low torque, the specific wear rate is low but it increases as the torque is increased. It happens due to the rise in torque which increases the load on the gear tooth resulting in the generation of heat which in turn loosens the gear material. The images of wear damage of gears at different RPM and torque level is shown in Table 5.

Wear is maximum at 800 rpm but it remains constant at all torque levels. At higher speeds i.e. 1200 & 1400 rpm gears show a significant amount of wear at higher torque levels. At the 1000 rpm speed wear rate of the gear, there are minor increases in wear rate.

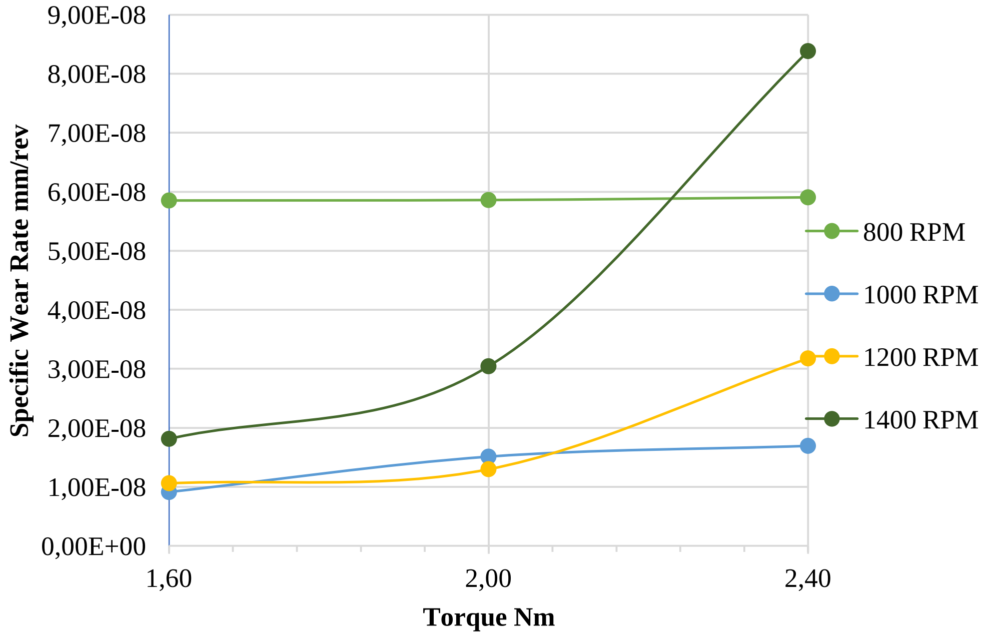
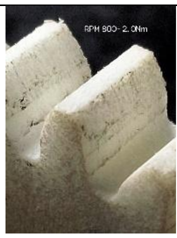
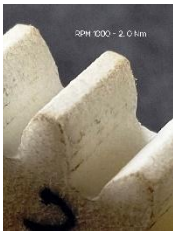
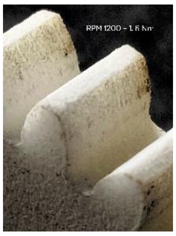
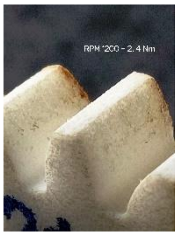
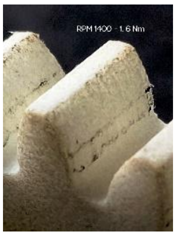
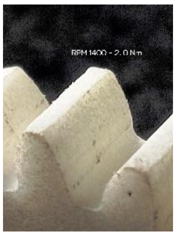


Figure 13. Wear behaviour of spur gear

Table 5 Wear damage to gears

Gear Without Wear Damage			
Gear with wear at 800 RPM and Torque of 1.6 Nm, 2.0 Nm &2.4 Nm.			
Gear with wear at 1000 RPM and Torque of 1.6 Nm, 2.0 Nm &2.4 Nm.			
Gear with wear at 1200 RPM and Torque of 1.6 Nm, 2.0 Nm &2.4 Nm.			
Gear with wear at 1400 RPM and Torque of 1.6 Nm, 2.0 Nm &2.4 Nm.			

8. Polymer Gear Failure Mode

The polymer gears were subjected to 1 x 10^5 load cycles for different speed levels and torque. As per fig: - 7, the gear failed at 1400 rpm and 2.4 Nm torque level in just 14100 load cycles. Due to high torque and speed, the contact temperature of the gear was raised to 81 ºC. The gear tooth failed as the contact temperature of gears has gone beyond the deformation temperature of PA-12 Nylon i.e. 86ºC.

9. Comparison of Thermal and Wear Behaviour

The thermal and wear behaviour of 3D printed gears is compared with gears which are injection moulded from Acrylonitrile Butadiene Styrene (ABS), High-Density Polyethylene (HDPE) and Poly-oxy-methylene (POM) material.

Prashant Kumar Singh et. al. 26] tested the polymer gears (ABS, HDPE and POM) manufactured by an injection moulding process. The gears were tested for different combination of torque-Nm (0.8, 1.2, 1.6 & 2.0) and RPM (600, 800, 1000 & 1200) for 10^5 load cycles. A comparison of common operating parameters (RPM 1200 & 1.6 – 2.0 Nm torque) is done to get insight into the performance of the injection moulded and 3D printed gears. Figure 14 shows the max surface temperature generated during operation and Figure 15 shows the specific wear rate of the gear surface.

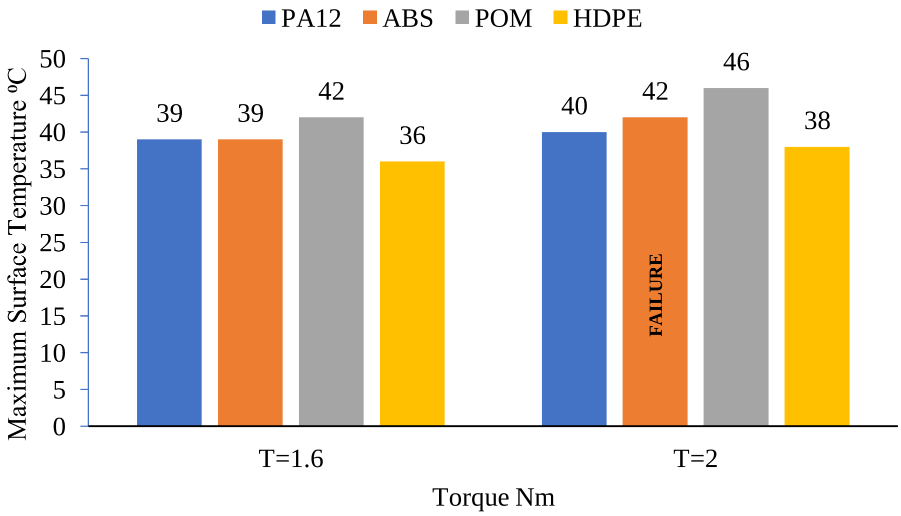


Figure 14. Comparison of Max Surface temperature at 1200 RPM

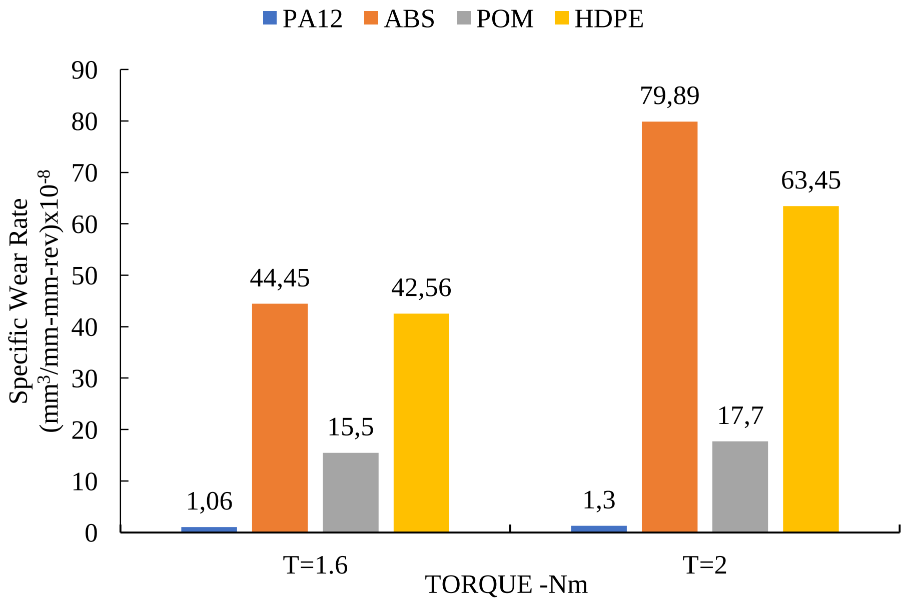


Figure 15. Comparison of Specific Wear Rate at 1200 RPM

As per Figure 14, the maximum operating surface temperature of the gear manufactured with ABS material is almost equivalent to the 3D printed gears but due to the brittleness quality of ABS material, it failed at 2.0 Nm torque and 1200 RPM at about 30000 load cycles. POM material gear has a low operating temperature in comparison to the other material, but the specific wear rate is very high in comparison to the 3D printed PA-12 nylon gears as shown in Figure 15. As shown in

Figure 16 the hardness of POM and PA12 Nylon is almost the same but nylon is more wear-resistant and has a low coefficient of friction in comparison to POM.

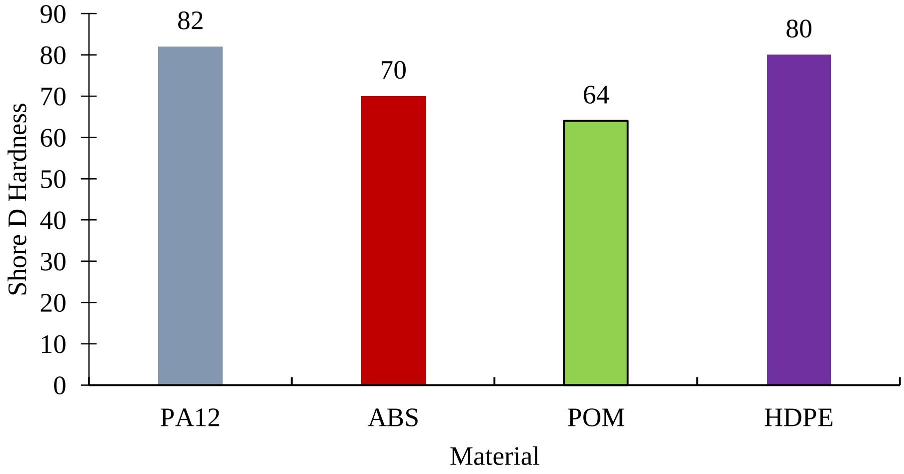


Figure 16. Shore D Hardness of Gear material

10. Conclusion and Future Scope

The 3D – printed PA-12 Nylon gears are tested to check the potentiality of their application in the field of engineering. The outcomes of the investigation are as follows:

1. The thermal and wear performance of the Nylon PA-12 gears were investigated for varying rotational speed and torque. It institutes that at high torque and high speed the gear surface temperature increases but specific wear increases at low rpm.
2. Torque contributes largely to increasing the surface temperature rather than speed. Torque is 2-3 times more significant than speed in consideration of operational conditions.
3. The wear rate of the Nylon PA-12 gear increases as the torque increases, but the wear rate decreases as the rotational speed increases. This results in less wear rate at a high speed of operation.
4. The experimental values are compared to the predicted value for the increase in the gear's surface temperature. It shows that at low torque both the data are in best agreement. There is a significant deviation at higher torque levels.
5. The gears were tested in dry condition i.e. without any lubricant which resulted in high friction between the gear teeth resulting in the rise of surface temperature. The major failure of the polymer gear is due to an increase in contact temperature of the gear tooth resulting in loosening of the polymer material and finally melting at more than the deformation temperature of the material. The gear life can be increased by operating them in a proper heat-dissipating atmosphere i.e. with lubricants.
6. The 3D printed PA-12 gears have a very low specific wear rate in comparison to POM, ABS and HDPE gears manufactured by an injection moulding process.
7. At the same operating conditions, the nylon PA-12 gears are more temperature and wear-resistant.
8. Polymer gears are more sensitive to torque and RPM applied – the higher the torque & RPM more the chances of failure.

The current investigation opens the gates for further research on 3-D printed i.e. additively manufactured Nylon PA-12 polymer gears. Some of the propositions are given below for future research:

1. The gears were additively manufactured by the SLS method. Other 3-d printing technologies can also be used for investigating the performance.
2. Gears can be made of Nylon PA-12 polymer material of different properties, which can be mixed and investigated.
3. Another type of gear i.e. helical and bevel can also be manufactured and tested.

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Author Contributions

Anand proposed and developed the overall concept of the paper and conducted the gear design and testing. Dr Rita helped write and edit the paper. Dr Jeetendra and Dr Siddhartha supervised and structured the paper.

All the authors have read and approved the final submission.

Competing Interests

The contact author has declared that neither they nor their co-authors have any competing interests.

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