Performance Evaluation of 3D-Printed ABS and Carbon Fiber-reinforced ABS Polymeric Spur Gears

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Acrylonitrile butadiene styrene (ABS) polymer and carbon fiber reinforced acrylonitrile butadiene styrene (CF/ABS) spur gears were 3D-printed using fusion deposition modeling (FDM) with different fillet radii of 0.25, 0.50, and 0.75 mm. The performance of the fabricated gears was studied with the effect of fillet radius on varying load and speed conditions. The thermal properties of the gears were also investigated. The results indicated that 3D-printed CF/ABS spur gear exhibited better performance than the pure ABS. The 3D-printed CF/ABS gear with fillet radius of 0.25 mm recorded the highest wear and thermal stresses. However, the optimum performance was exhibited by the gear sample with highest fillet radius of 0.75 mm. Repeated gear tooth loading during service caused an increase in gear temperature due to the hysteresis and friction. Using optical microscopy, the tooth structures of both 3D-printed ABS and CF/ABS spur gears were analyzed before and after loading conditions to establish their failure mechanism. Evidently, various applications of the FDM 3D-printed spur gears depend on their different performances under loads and operating speeds. The methods and findings of this work can be regarded as helpful for future related work related to cellulosic reinforcing particles in a polymer matrix.

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INTRODUCTION

Gears are essential components of mechanical power transmission systems. They range in size to be suitable for small wristwatches to large rotatory machines. They are typically made of a variety of metallic and non-metallic materials. Polymer-based materials are increasingly being used for structural parts. Polymer composites can be designed to meet the stringent requirements of a wide range of load-bearing applications. Polymer gears have unique advantages over metal gears, considering their light weight, low cost, noiseless operation, low friction, ability to function without external lubrication, internal damping capacity, low density, and high resilience. Gears are widely used in aerospace, automobile, food, and textile machineries, to mention but a few industries (Monfared *et al*. 2021).

Polymer components are produced frequently using additive manufacturing, which is also known as three-dimensional (3D) printing. The fundamental concept behind additive manufacturing is that a computer-aided design system can directly manufacture a model. With this technology, material waste can be avoided during production, which is quite different from conventional techniques. Due to the nature of 3D printing, each 3D printing technology is compatible with a specific set of materials. This implies that the process is inextricably linked to the materials used. Polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polycarbonate (PC), nylon, and other materials can be used for fused deposition modeling (FDM). Because of the growing interest in 3D printing, the direct mechanical and thermal properties of 3D-printed materials as well as their modification are the subject of an increasing number of studies (Ikram *et al*. 2022).

Multiple design features and performance characteristics of polymer and polymer composite gears were summarized by Singh *et al*. (2017). It was reported that polymeric materials that can be used in the gearing phenomenon have not been extensively studied, with exception of nylon and polyoxymethylene. Injection molding is the only method of producing polymer gear that has received significant attention. Additionally, there has been no research into optimizing the operating settings of polymer gears to reduce wear and the rise in surface temperature of the gear teeth. Selvaraj and Ramamoorthy (2006a) analyzed the effect of gear tooth fillet radii of 0.25 and 0.75 mm on the performance of injected molded nylon 6/6 spur gear. The gear performance was evaluated, using a power absorption gear test rig. It was reported that at low applied loads, gears with small fillet radii failed by micro cracking the pitch region, whereas gears with wide fillet radii failed by crack initiation at the root region, due to higher stress concentration.

Karupaiah and Narayana (2022) examined the quasi-static and dynamic mechanical properties of ABS and carbon fiber reinforced composites. The analysis was carried out by altering these process variables: infill density, infill pattern, and layer thickness on mechanical properties. The outcomes demonstrated that the mechanical properties of ABS improved with the addition of carbon fiber. Dynamic properties were investigated over the temperature range of 30 to 200 °C at various frequencies of 0.2, 0.5, 1.0, 2.0 and 5.0 Hz. It was shown that when the frequency increased, the molecular mobility of the polymer diminished, stabilizing the composite behavior and lowering the loss factor. Ahmed *et al*. (2020) investigated the effect of printing parameters on the interfacial bond strength of an ABS/CF-PLA laminar composite. It was reported that a medium printing speed, a high infill density, and a low layer height were responsible for the high strength quality. Similarly, ABS, high-density polyethylene and polyoxymethylene injected polymer spur gear performance were analyzed by Singh *et al*. (2020) by varying the speeds of 600, 900 and 1200 rpm and torque values of 0.8, 1.2 and 1.6 Nm. Polyoxymethylene gear operating at the torque and speed settings of 0.8 Nm and 900 rpm, respectively, recorded the best performance values.

Selvaraj and Ramamoorthy (2008) carried out metrological examinations of nylon 6/6 spur gears with and without reinforcement of glass fiber. The gear manufacturing mold flow simulation results were compared with the actual fiber orientation. The actual orientations of the fibers close to the tooth profile, weld line region, and injection locations of molded gears were observed, using an optical microscope. Fiber misalignment across the gear tooth section increased variations from design values in tooth thickness, tooth-to-tooth spacing, and radial run out. The wear parameters of sintered steel gears incorporating MoS_2 were examined by Sekar *et al*. (2008). The addition of MoS_2 enhanced density, hardness, strength, and wear resistance of the component. The outcome was discussed, showing that wear projections and observed point to the dedendum and addendum regions experienced the most wear. Zhang *et al*. (2019) examined the lifespan of 3D-spur gear teeth printed with onyx, mark forged nylon proprietary materials, nylon 618, nylon 645 and alloy 910 filaments. When low to medium torques were applied, the performance results showed that gears printed with nylon 618 performed better than the gears fabricated with injection molded nylon 66. Scanning electron microscopy (SEM) analysis of the 3D-printed gears showed that wear only occurred along the pitch, and that parts of the gear tooth surface melted, but no materials were scraped off the tooth for the printed nylon 618 gears. Conversely, material peeling from the gear tooth was visible for the other four printed materials. The material effect on the functionality of 3D-printed spur gears was investigated by Dimić *et al*. (2018). Utilizing polymer materials ABS and PLA, spur gears were produced. The results of the trials showed that 3D-printed spur gears made of PLA plastic exhibited superior operational qualities to those made of ABS plastic. The maximum temperature on contact surface of the ABS gear was 125 °C with an increase in rotational speed from 400 to 600 rpm, but the maximum temperature of a PLA gear was almost 80 °C.

Furthermore, Yousef *et al*. (2015) developed a universal test rig to assess the wear properties of polymer acetal gears. The gear test rig was intended to evaluate the performance of spur, helical, bevel, and worm gears. The experiment was performed with a constant torque of 4 Nm and a duration of 200 x 10^3 cycles on all the gears. The results showed that helical, bevel and worm gear wear rates increased by 56, 60 and 68% respectively, when compared with spur gear. Similarly, a gear test rig was designed and built by Lijesh (2015) to assess the vibrational properties of spur gears. A range of 600 to 24,000 rpm was used for the gear test set-up. As pitting increased, the gear vibration response increased with increments in sidebands around this frequency. The increase in the amplitude of spectrum signals indicated the failure in the gear. Kurokawa *et al*. (2003) studied the performance of carbon fiber reinforced polyamide gear, developed through injection molding process. Among all the polyamides, the result showed that carbon fiber polyamide-12 composite gears recorded the highest load capability, extremely good noiseless property and lowest water absorption properties. The molecular weight of PA12 increased with the improvement of the load-bearing property.

Mohamed *et al*. (2021) investigated the effect of various process parameters, including nozzle, bed temperature, printing speed, and layer thickness on the tensile properties of 3D-printed polyether ether ketone. Tensile properties were improved by increasing the nozzle temperature, print speed, and bed temperatures to high levels and decreasing the layer thickness and radiant temperature to low levels. Vigneshwaran *et al*. (2022) evaluated the interlaminar bonding capabilities of the printed ABS composite with carbon fiber reinforcement. The experimental tests showed that the ABS specimens reinforced with carbon fiber exhibited good layer adhesive and interlaminar shear strengths. Similarly, it was observed that specimens with layer height of 0.20 mm, hexagonal patterns, and infill density of 50% recorded greater interlaminar shear strength than other printed specimens. Ferreira *et al*. (2021) examined the mechanical properties of ABS specimens fabricated by 3D printing under cyclic and static torsional loads. It was observed that the zigzag infill pattern recorded improved or better mechanical qualities under torsion stress, when compared to a circular pattern. Majid *et al*. (2020) studied the mechanical characteristics of ABS specimens printed with different infill densities. The study established that both density and filling rate had a significant impact on tensile characteristics and rupture propagation. Selvaraj and Ramamoorthy (2006b) reported the characteristics of carbon fiber incorporated nylon 66 spur gear, fabricated through injection molding process. Hubs with circular and spline-shaped geometries were used to create reinforced gears. The hub region utilized low-cost unreinforced nylon 66, while the high stress tooth region employed high performance and high cost short carbon fiber reinforced nylon 66. Yoon *et al*. (2007) analyzed the behavior of poly acetal gear, fabricated through injection molding process. A better gear accuracy was achieved when plastic gear was produced using microcellular processing and a pressurized mold. As a result of the plasticizing effect of flowing gas in a state, the result showed that the microcellular process can reduce the viscosity of the molten plastic.

Based on the aforementioned relevant and previous studies, it is evident that the manufacturing of polymer and polymer composite gear has not been well explored, except for the injection molding process. The performance analysis of polymer-polymer gear pair has not been adequately investigated. The optimization of the gear operating parameters, including load and operating speed, for minimizing wear and increase in surface temperature of gear teeth has not been reported. Several gears have been developed using polymer material only, but fiber reinforcement has not been well addressed for polymer composite gear. In addition, polymer materials that can be used in the gearing phenomenon have received little attention, with exception of nylon and polyoxymethylene. Therefore, various spur gears were developed using FDM process in this innovative research. ABSand carbon fiber reinforced acrylonitrile butadiene styrene (CF/ABS) were used as filaments for the 3D printing of gears. In the future it is possible that related 3D printed composite gears could be prepared with cellulosic fibers or nanofibers as the reinforcement, together with a suitable plastic matrix. The ABS and CF/ABS spur gears were printed with optimized FDM process parameters, including layer height, infill density and infill pattern. Finally, the performance characteristics of gears were evaluated under different fillet radii, loads and operating speeds, using a developed gear test rig. The thermal properties of the gear teeth were analyzed. The failure behaviors of the 3D-printed spur gear teeth were also studied, using optical microscopy.

EXPERIMENTAL

Materials

ABS and CF/ABS filaments with a diameter of 1.75 mm were used (Nanovia Smart Chemical, France). The melting point of ABS, an oil-based filament, is higher than that of PLA. Both impact resistance and toughness are significant mechanical characteristics of ABS (Vinoth Babu *et al*. 2020).

Table 1. Properties of the Filaments Used, as Provided by the Manufacturer

Material Properties	ABS	CF/ABS
Density (g/cm^3)	1.04	1.08
Tensile strength (MPa) (ASTM D638)	42	48
Elongation at break (%) (ASTM D638)	40	42
Flexural modulus(MPa) (ASTM D790)	2255	2700
Print bed temperature (ºC)	90-120	90-110
Nozzle temperature (ºC)	240	240

ABS is a well-suited 3D printing material for a moving part, high mechanical stress and/or high-stress functionality component. Carbon fiber reinforcement in the ABS was expected to improve the mechanical strength, dimensional stability, and reduce the coefficient of thermal expansion of filament. The mechanical properties of the materials are listed in Table 1.

Fabrication of Gears

ABS and CF/ABS filaments were used to 3D printing a set of spur gears, employing FDM process through machine vision system (Fig. 1). FDM has a great ability to construct intricate geometrical parts in a timely manner. With a computer-aided design software (Dassault Systems Solid Works Corp., USA), a 3D model of test equipment was created and saved as a Stereolithography file format. The Standard Tessellation Language (STL) file was then included in a software package for operations, and parts were cut and printed in accordance with the process parameters. The dimensions for the testing and mating gear are presented in Table 2.

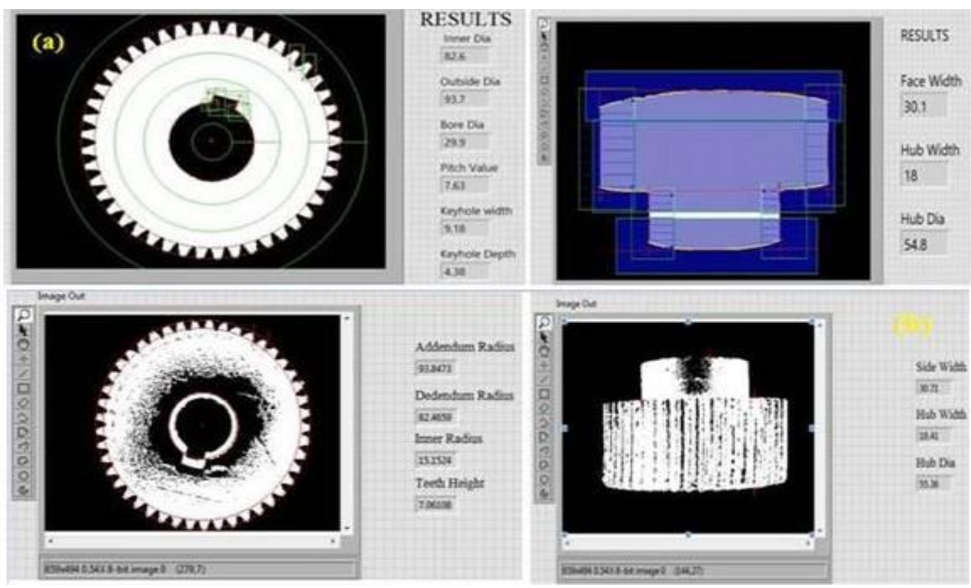

Fig. 1. 3D-printed (a) ABS and (b) CF/ABS spur gears and their machine visions

Table 2. Dimensions of the 3D-printed Gear

Gear Parameters	Value
Module (mm)	3
Number of teeth	45
Pressure angle (°)	20
Face width (mm)	30
Outside diameter (mm)	95
Bore diameter (mm)	30
Teeth height (mm)	7

Four different 3D-printed spur gears were additively manufactured and tested, using a gear test rig. The gears were printed, using ABS filament with a fillet radius of 0.50 mm and CF/ABS filaments with fillet radii of 0.25, 0.50 and 0.75 mm. All the 3D printing parameters were set as default and printing took place at recommended temperature of 210 °C and speed of 30 mm/sec. The printing parameters for the gear were infill density of

50%, layer height of 0.20 mm, and hexagon pattern at a nozzle diameter of 0.4 mm (Miller *et al*. 2021).

Gear Test Rig or Testing Apparatus

The gear test rig was intended to measure the performance of the gear when meshing and running. The fabricated gear test rig was a back-to-back configuration in which the gears were loaded to a specified limit. Gear tests were performed on a pair of the 3D-printed gears with the same geometry and printing parameters. Both driven and driver gears were made up of the same material. Afterwards, a speed-controllable DC motor with a power of 1.0 hp was connected to the pair of the polymer gears. The units were linked by a main driver shaft mounted on a pair of polymer spur gears. Power was transferred to the driver polymer gear when a driven polymer gear was operating at various levels of loads. Gears were driven by a motor, using an externally applied torque, and the reaction force between the gear teeth was equal to the force acting on the bearing block and loading arm (Kimiaei and Akbarzadeh 2019). Figure 2 shows the photographic images of the gear test rig and its loading mechanism.

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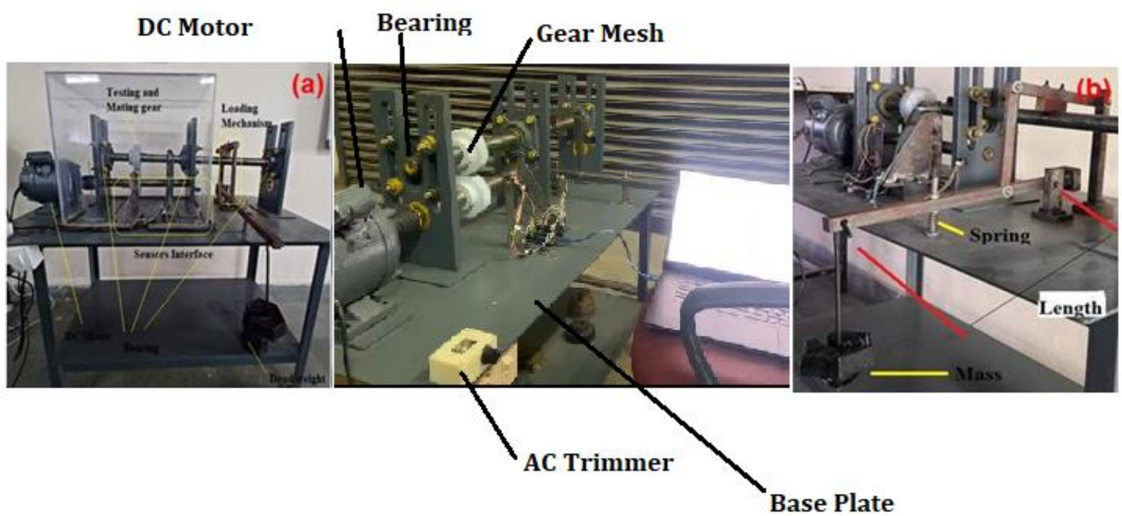

Fig. 2. (a) Gear test rig set-up and (b) its loading mechanism

Automation Process

Industrial automation increases efficiency, reliability, and safety. The automation of the gear test rig was carried out, using Raspberry Pi, embedded web server technology and regional networking norms. Python was used in the proposed system to assess the performance of the testing apparatus, and Raspberry pi was used as the controller and server. The embedded web server and the Raspberry Pi communicated with each other. The web server stored and provided information at the appropriate time when the information was linked to it. Arduino Uno was powered, using a power adapter and connected to the computer via interfacing cables. Sensors were soldered to connect jumper cables. The sensors, including the infrared temperature sensor and rpm sensor were connected to the respective pins via jumper cables. AC dimmer was connected to the motor terminals to control the speed of the motor with a regulator. The Arduino program for the sensors was coded, using Arduino software and similarly uploaded to the microcontroller. A python program was developed for data acquisition. The python program created a file when the test rig started and plotted data at a periodic rate.

RESULTS AND DISCUSSION

Stress Concentration at Fillet Region

Variation in gear tooth geometry affects tooth deflection for a given gear material and loading condition. Increased sliding velocity and contact point displacement due to deflection in the gear tooth caused an increased heat generation from friction and hysteresis effects (Ambaye 2021). It was observed that the surface area increased as the fillet radius increased, resulting in an increase in the amount of heat dissipation. Repeatedly loading and unloading the gear tooth caused severe deflection, and the internal friction generated a huge quantity of heat. The contact area and surface interaction were both increased by deflection of the gear tooth. An increase in the gear temperature was also caused by an increase in the surface interaction (Gibson *et al*. 2015). Under all applied loads, gears with a fillet radius of 0.25 mm deflected more than gears with a fillet radius of 0.75 mm. Gears with smaller fillet regions caused a greater deflection on the gear tooth. Hence, the root regions of the gears with a fillet radius of 0.25 mm experienced localized compressive stresses. In case of gears with a fillet radius of 0.75 mm, such localized compressive stress region was not observed. Figure 3 depicts the gear teeth with fillet radii of 0.75 and 0.25 mm.

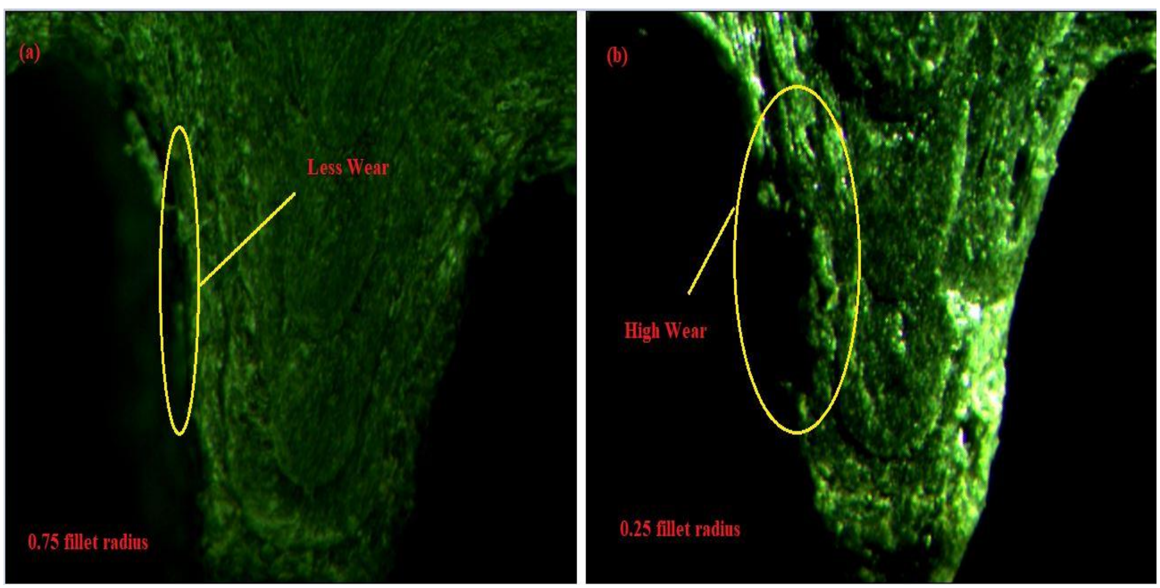

Fig. 3. Micrographic analysis of gear fillet radii of(a) 0.75 and (b) 0.25 mm

Gear Tooth Temperature

Four different sets of polymer gears were printed through FDM process, and their characteristics were assessed using the gear test set-up. Lubricants dissipate a majority of the heat produced when using metal gears under lubricated conditions. Polymer gears are typically utilized in lubricant-free environments, and they also have a lower thermal conductivity than metals (Gibson *et al*. 2015). Therefore, polymer gears heat up faster than metallic gears during operation. Temperature affects the mechanical properties of the gear material, since polymer properties are temperature-sensitive. A polymer material loses strength and modulus as the temperature increases, which causes the gear teeth to deflect more. In polymer gear, a significant tooth deflection affected conjugate meshing, which increases dynamic loads and amplified gear noise (Maitra 2000).

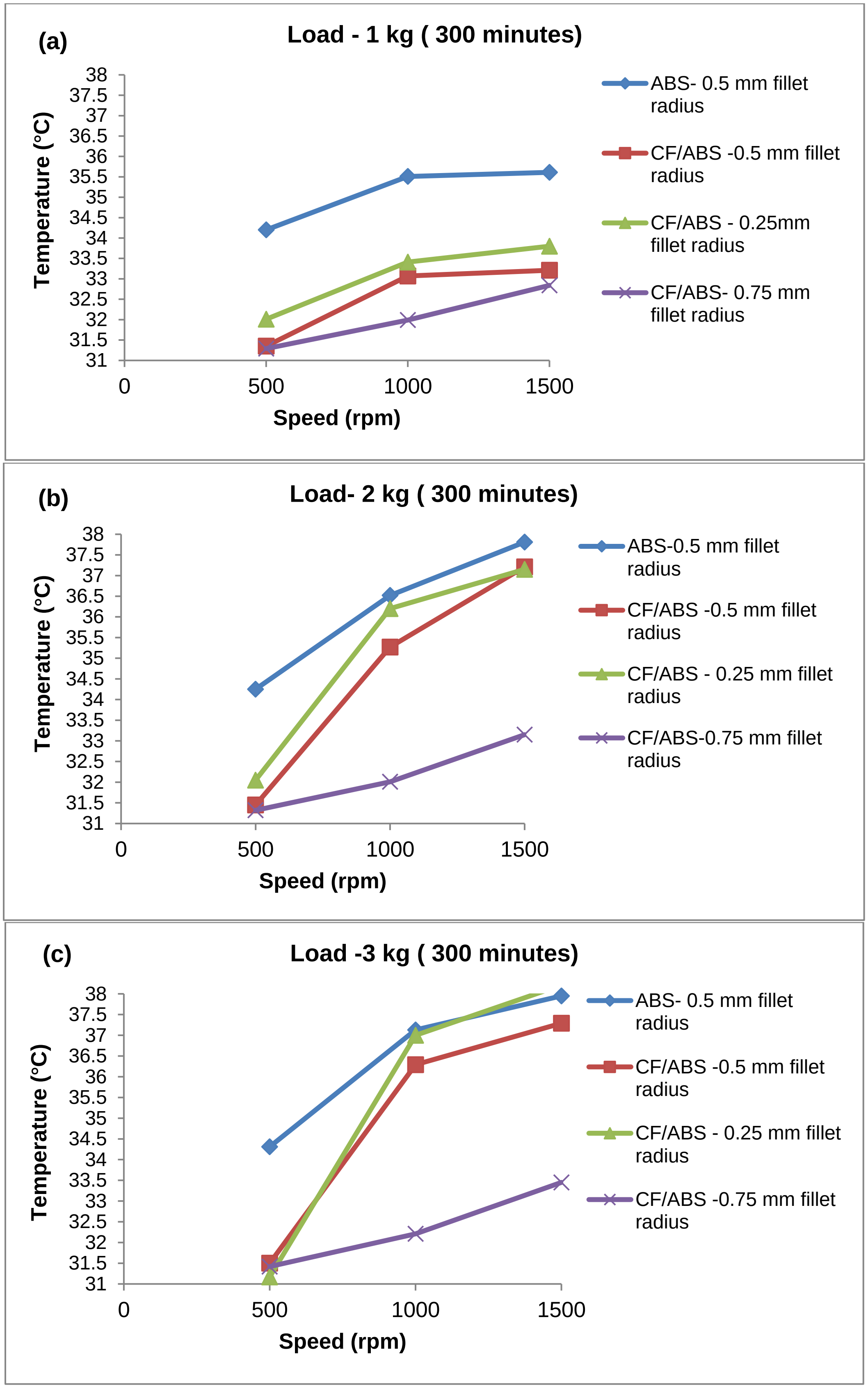

Fig. 4. Variation of loads and speeds *versus* temperatures of ABS and CF/ABS gear under (a) 1, (b) 2. and (c) 3 kg loads for 300 min

Figure 4 shows the measured surface temperature of 3D-printed spur gears during testing under applied loads of 1, 2, and 3 kg with a varying speeds of 500, 1000 and 1500 rpm for 300 min. Also, Fig. 4 depicts that as the load was increased, the heat generation in the gear increased with varying speeds. CF/ABS spur gear with a fillet radius of 0.50 mm exhibited a smaller amount of heat, due to carbon fiber reinforcement in the polymer material. Comparing Figs 4 (a) through (c), the heat generated in CF/ABS was 2 to 4% lower than that of ABS counterpart with the same fillet radius of 0.50 mm. It can be reported that heat dissipation was increased by adding 5% of carbon fiber to the polymer, and a large amount of load was absorbed by the fiber and stress developed in the gear was reduced. All the 3D-printed ABS and CF/ABS gears experienced an initial increase in temperature with increased load and speed (Cheng *et al*. 2023).

Moving forward, the gear test rig was used to test the CF/ABS spur gears printed with fillet radii 0.25 and 0.75 mm. Gears with a fillet radius of 0.25 mm generated higher heat than the counterparts with a fillet radius of 0.75 mm at all loading conditions and speeds during testing, which caused higher deflection of the polymer gear tooth. Heat dissipation was lower in gears with a fillet radius of 0.25 mm, due to the limited surface area at the root. In other words, inadequate heat dissipation caused a greater built-up of heat in the gears with smaller fillet radii. A sudden increase in gear temperature was recorded at high loading conditions, indicating increased heat generation. Therefore, the gears exhibited a severe plastic deformation that resulted in tooth shape distortion. A significant amount of heat was lost with a fillet radius of 0.75 mm. The stresses at the gear root region and tooth deflection were decreased by increasing the tooth root area. Polymer gears can be overheated when in use, due to friction and hysteresis effects. The hysteresis effect was manifested as a slowdown of strain when the gear was loaded. This incomplete recovery of strain in the gear during its unloading cycle was due to the energy consumption, which was converted into frictional energy. The viscoelastic properties and mechanical deformation of the gear resulted in a significant amount of internal friction (Malakhov *et al*. 2022).

Effects of Gear Tooth Fillet Radii on 3D-printed Polymer Composite Gears

Figure 5 depicts the measured surface temperature of the gears when tested under applied loads of 1, 2, and 3 kg. The average value of measured surface temperature with a deviation of $\pm$2.5% is shown in the figure. Figure 5(a) shows an initial increase in temperature and a steady state after a certain period of running in gears with fillet radii of 0.25, 0.50, and 0.75 mm tested under a load of 1 kg. During testing, the heat generated in gears with fillet radius of 0.25 mm was higher when compared with that of fillet radius of 0.75 mm at all the loading conditions. This can be attributed to the higher deflection of polymer gear tooth, which supported more heat generation, due to surface interaction and hysteresis effects. The heat dissipation was low in gears with fillet radius of 0.25 mm, due to the less available surface area at the root region. Poor heat dissipation resulted in an increased heat built-up in gears with a smaller fillet radius. Figures 5(b) and (c) depict the measured surface temperature of the gears under higher loads of 2 and 3 kg. A sudden increase in gear temperature was observed, indicating increased heat generation with a severe plastic deformation, leading to tooth shape distortion. Increasing the tooth root area reduced the stresses at the gear root region and tooth deflection. Excess amount of heat generation caused a severe plastic deformation of the gear tooth.

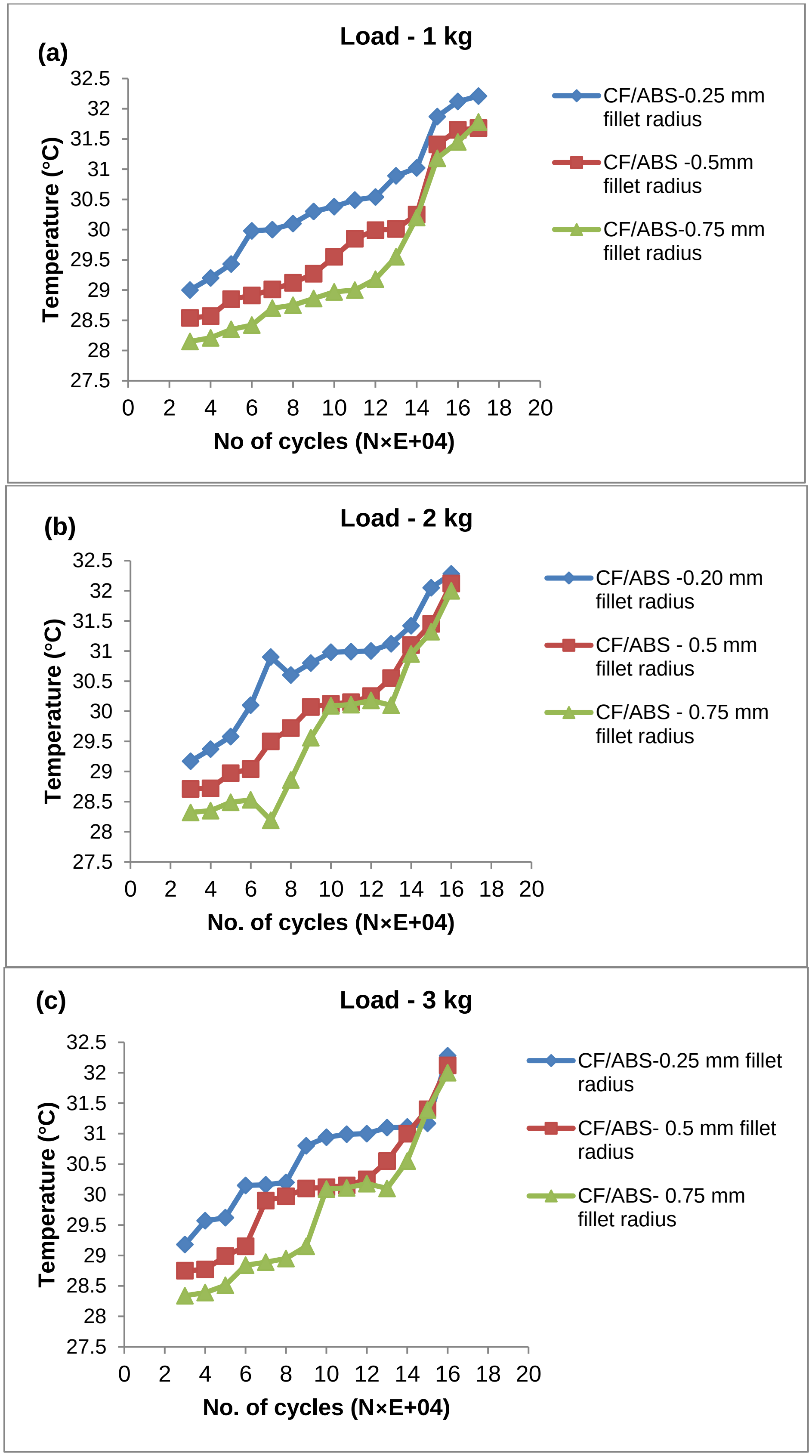

Fig. 5. Temperatures of CF/ABS gears with different fillet radii at life cycle runs under (a) 1, (b) 2 and (c) 3 kg loads

Micrographic Analysis

The micrographs of the spur gear teeth before and after loading conditions are shown in Figs. 6 through 9. Figure 6 shows the micrographic analysis of the 3D-printed ABS spur gear with a fillet radius of 0.50 mm. The gear tooth broke down after loading, due to higher heat generated by the ABS polymer material. After the tooth breakage occurred, the area was reduced in Fig. 6(b) when compared with Fig. 6(a).

Fig. 6. ABS with fillet radius of 0.50 mm(a) before and (b) after running

Figure 7 depicts the micrographic analysis of CF/ABS spur gear teeth. There was no tooth breakage, but wear occurred in the meshing region. Comparing the 3D-printed ABS with the CF/ABS spur gears, the addition of carbon fiber to ABS polymer material improved its strength and heat dissipation capability.

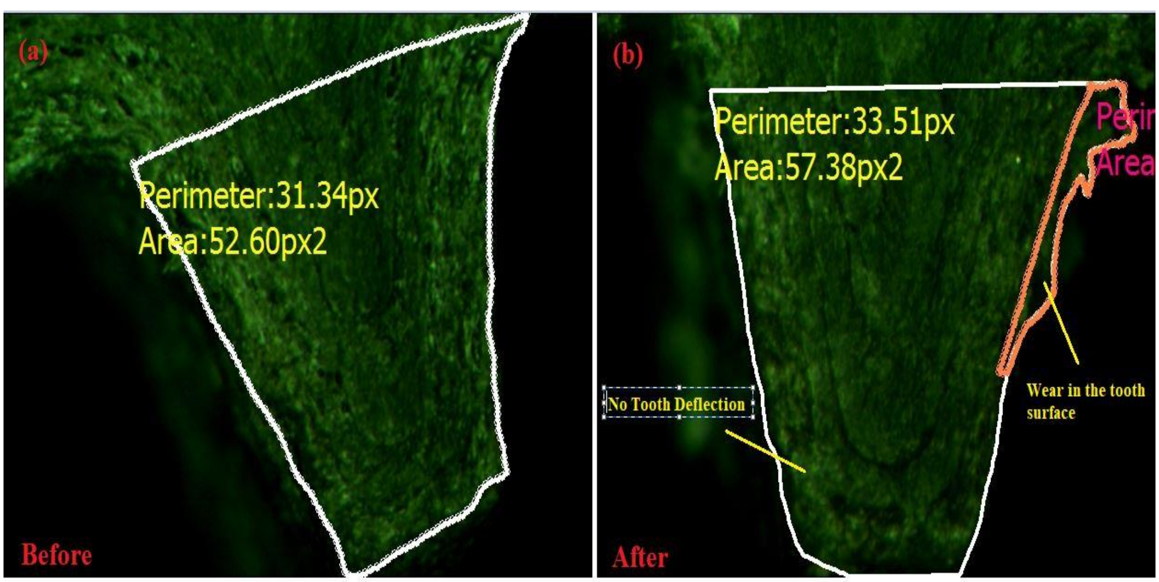

Fig. 7. CF/ABS with fillet radius of 0.50 mm (a) before and (b) after running

Figures 8 and 9 show the microscopic images of the 3D-printed CF/ABS spur gears with fillet radii of 0.25 and 0.75 mm, respectively. Figure 8 depicts that greater amount of material was removed in the meshing region and tooth breakage occurred, due to a smaller fillet radius. A high stress was generated and a large amount of material was removed from the surface of the gear tooth. Conversely, it was evident from Fig. 9 that there was no occurrence of tooth breakage and a very small amount of material was removed, due to the large dissipation of heat. The strength of the gear teeth increased with a larger fillet radius.

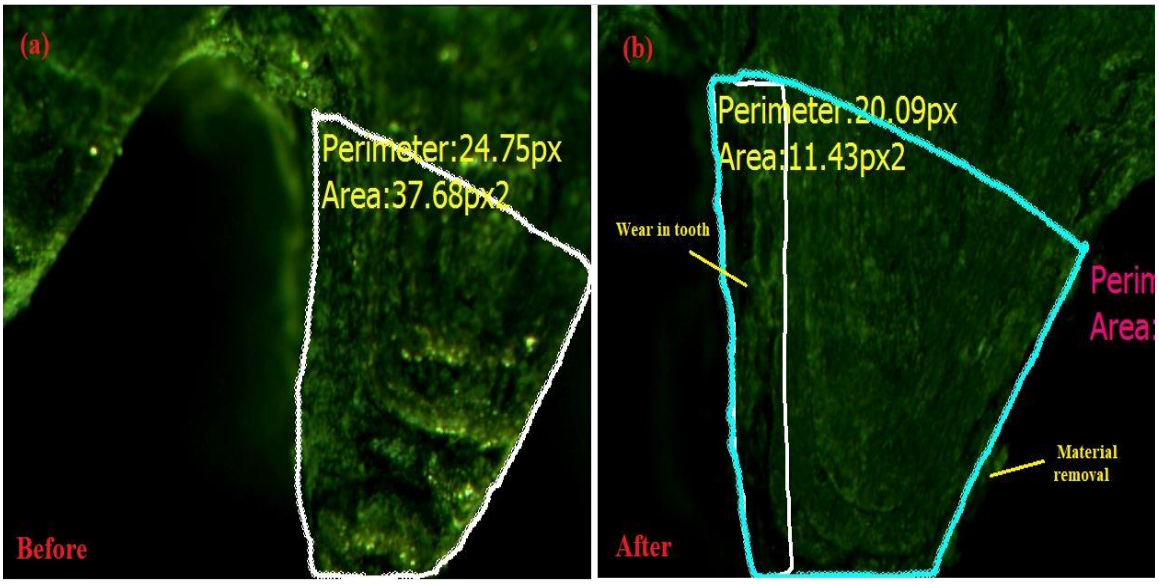

Fig. 8. CF/ABS with fillet radius of 0.25 mm(a) before and (b) after running

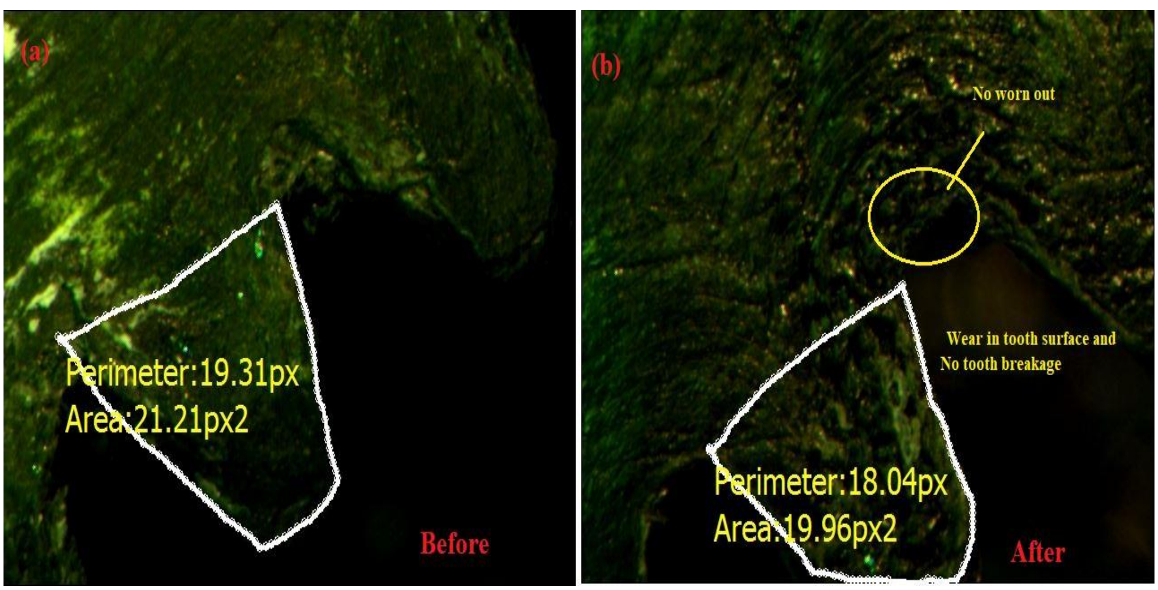

Fig. 9. CF/ABS with fillet radius of 0.75 mm(a) before and (b) after running

Within the scope of this study, 3D-printed spur gears were additively manufactured, using ABS and CF/ABS filaments with optimized FDM process parameters and different fillet radii. The performance characteristics of the samples were evaluated, using a gear test rig. From the experimental results and microscopic characteristics obtained, the following concluding remarks can be deduced. Therefore, practical applications of the various additively manufactured spur gears should depend on their different properties and performances. The optimum 3D-printed CF/ABS spur gear with a fillet radius of 0.75 could be a better choice for engineering applications or power transmission, considering its efficient working environments. These conditions include, but are not limited to, certain temperature, load and operating speed.

CONCLUSIONS

1. The heat generated in the 3D-printed gears prepared with carbon fiber / acrylonitrile butadiene styrene (CF/ABS) decreased, due to the presence of carbon reinforcement in the ABS polymer. The carbon fiber withstood a large amount of load and supported the dissipation of the heat.
2. After using 3D-printing to prepare spur gears with different fillet radii of 0.25, 0.50, and 0.75 mm, it was observed that the dissipation of generated heat was significantly higher in the 3D-printed spur gear with fillet radius of 0.75 mm. This can be attributed to the wider area, which withstood a large stress when compared with its counterparts with smaller fillet radii of 0.25 and 0.50 mm. The load increased with the quantity of heat generation in the gear teeth under different operating speeds.
3. Analysis of the failure mechanism in the 3D-printed spur gears through optical microscopy showed the material worn-out areas in both additively manufactured ABS and CF/ABS spur gear teeth. Comparatively, 3D-printed CF/ABS with a fillet radius of 0.75 mm exhibited the optimum properties and performance.

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