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*Research Article*

# Study on performance of multiwall carbon nanotubes and functionalized multiwall carbon nanotubes/ poly aryl ether ketone polymer composite gears

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**Abstract**

This study investigates the thermal and wears resistance performance of polymer gears made of pristine poly aryl ether ketone (PAEK) and PAEK polymer matrix incorporating both pristine multi walled carbon nanotube (MWCNT) and functionalized MWCNT polymer composites under different operating conditions. The investigation involves the thermal behavior, wear performance and surface roughness of gears at different torques (0 Nm, 6 Nm, 8 Nm, and 10 Nm) and at rotational speeds such as 1000 rpm and 1500 rpm. The polymer composite materials are prepared by using a twin-screw extruder and the gears of these materials are manufactured by using an injection molding machine. The gears are examined using a gear test rig. The surface temperature, specific wear rate and surface roughness are the parameters that are measured at different torques and rotational speeds using a gear test rig, before and after the running operations of these gears. The gears made of PAEK and amine functionalized MWCNT composite materials exhibits improved performance in terms of wear resistance and thermal behavior.



## 1. Introduction

Gears are the major element in various mechanical systems used for power transmission. The transformation of power and motion using gears is better than other transmission systems such as belt, rope and chain drive due to less slippage between two mating gears [1]. The polymer gears have gained significant attention due to unique set of inherent properties such as light weight, low noise, and self-lubrication, ability to resist shock and impact load, ease of manufacturing [2]. These properties have driven polymer gears adoption for metal gears replacement in industrial applications such as automotive, aerospace, textile, robotics, industrial machinery, and consumer products.eg. Lightweight gearboxes [3]. The load, temperature, surface roughness, wear and rotational speed are the major analyzing parameters to investigate the performance of polymer gears [4][5]. The teeth of polymer gears experience fatigue loads while operating conditions. It produces heat internally and, on the surface, due to contact stress when the gear pairs are in motion under loading conditions [6].

Several studies have indicated that polymer composite gears showed improved results than pristine polymer gears in terms of overall performance improvement [7-9]. In recent

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years, there has been extensive research conducted on polymer composite gears reinforced with glass and carbon fibers in polymer matrix materials. These studies have consistently demonstrated enhanced performance of wear resistance, durability under specific loads, and other relevant properties and the results showed improvements in overall performance of gears [10, 11].Thermoplastic materials, such as nylon, acetal, polycarbonate etc. find extensive use in industrial applications, including the manufacturing of gears and seals etc.[12].The study of gears made of these thermoplastics and its composites were widely explored [13, 14].The graphene reinforcement in nylon and acetal polymer composites gears exhibited superior performance in terms of wear resistance[7, 15].The investigation of gears made with incorporation of different fillers such as multilayer graphene nanoplatelets, clay, graphite in polyamide (PA6) matrix, showed enhancement in mechanical, thermal and tribological properties [16-18]. The gears manufactured by high performance polymer composites i.e. poly ether ketone (PEEK) and carbon fiber exhibits enhanced results for load capabilities and wear performance [19]. The relative performance of PEEK and steel gears are also investigated and it showed superior performance [20, 21]. PAEK gears have been studied under dry, greased, and lubricated conditions, demonstrated superior performance at elevated temperatures and lubricated conditions [22]. MWCNTs are considered the most suitable nanofiller for polymer composites due to their exceptional properties. These properties include high mechanical strength, excellent electrical conductivity, and superior thermal stability, which significantly enhance the performance and durability of the polymer composites in which they are incorporated. Additionally, MWCNTs exhibit a large surface area and strong interfacial interaction with polymer matrices, leading to improved load transfer and dispersion within the composite material. This makes MWCNTs an ideal choice for applications requiring enhanced material properties [23-25]. The behavior of commodity and engineering polymer gears considering different performance parameters are widely explored to achieve better power transmission.

This study specifically focuses on the performance of gears manufactured using high temperature polymer such as poly aryl ether ketone (PAEK) and PAEK based nanocomposite reinforced with multiwalled carbon nanotube (MWCNT) and functionalized MWCNT. The investigation encompasses the examination of wear and thermal properties of these gears under different loading conditions.

## 2. Materials and Methods

### 2.1 Materials

The semi-crystalline granular polymer material PAEK 1200G, utilized for the injection molding process, was sourced from Gharda Chemicals Ltd., Panoli, Gujarat, India. This PAEK material exhibits a density of 1.3 g/cc, a melting temperature of 152°C, and a glass transition temperature of 372°C.The nanomaterials employed in this study include MWCNT and amine-functionalized MWCNT were procured from Adnano Technologies Pvt. Ltd., Shimoga, Karnataka, India. These powdered nanomaterials possess a surface area ranging from 110 to 350nm, with outer diameters falling within the range of 10-30nm, inner diameters between 5-10nm, 99% purity level and a length of 10 µm.

### 2.2 Preparation of Composites

The uniform mixtures at concentrations of 0.5% weight of MWCNT and functionalized MWCNT nanofillers were carefully mixed and dispersed in PAEK matrix using a high-speed mechanical mixer for duration of 15 minutes to achieve a homogeneous mixture. As an additional measure, Tris Nonyl phenyl phosphite (TNPP) at a concentration of 0.02% by weight was incorporated as an antioxidant.

Table 1. Temperatures at different zones

| Zones | Zone 1 | Zone 2 | Zone 3 | Zone 4 |
|---|---|---|---|---|
| Temperature | 380°C | 385°C | 390°C | 400°C |

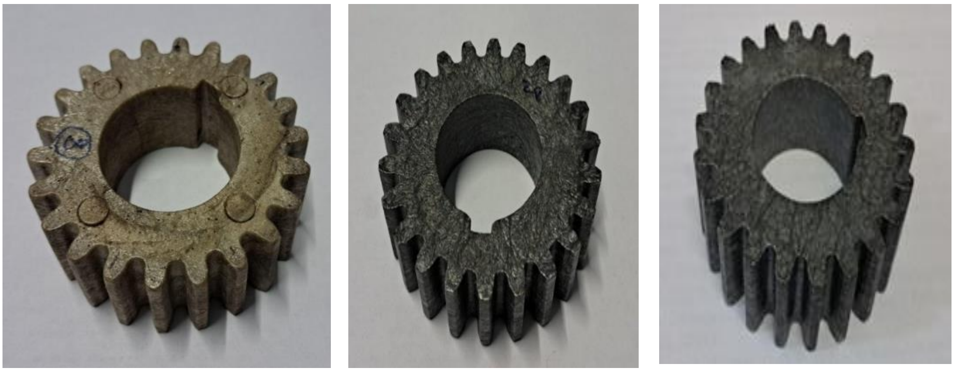
The compounding process was carried out by utilizing a twin-screw extruder, featuring a screw diameter of 26mm and a length to diameter ratio of 40:1. The temperatures at different zones within the twin-screw extruder are shown in table 1. The screw speed was maintained at 300 rpm. Following compounding, the resulting strands were prepared through extrusion and subsequently chopped by a cutter to produce samples of composites in granular form [26].

### 2.3 Manufacturing of Gears

The gears are manufactured using injection moulding machines with PAEK based polymer composite materials. Prior to the injection moulding process, the materials underwent a preheating process at a temperature of 220°C for 3 hours. This preheating served the purpose of eliminating moisture content and drying of the mixture. The gears are manufactured by injection molding process at A.K. Engineers, Mumbai, using an injection molding machine of 40-tonnage capacity manufactured by R.K.Techniques, Mumbai, India. During the injection molding process, specific parameters were carefully controlled to ensure optimal results. The injection time was set at 22 seconds and holding time of 8 seconds. The temperature settings for different zones in the injection moulding machine were adjusted as follows: 380°C for temperature zone 1, 385°C for zone 2, 390°C for zone 3, and 400°C for zone 4. These temperature zones spanned from the feed zone to the nozzle, playing a critical role in the moulding process. In addition to the machine temperature settings, the mould temperature was maintained at 220°C. This temperature control was essential for ensuring the proper moulding of the materials and achieving the desired properties in the final product of gears. The controlled operating temperatures of extruder and mould contributed to the successful fabrication of the injection-moulded gears. The detailed information about materials, parameters and manufacturing method of test gears are given in table 2 and manufactured gears are shown in fig. 1.

Table 2. Detail information of test gears

| Parameters | Specifications |
|---|---|
| 1. Materials | 1. PAEK<br>2. PAEK+ 0.5 weight % MWCNT<br>3. PAEK + 0.5 weight % Amine functionalized MWCNT |
| 2. Module | 2.5 |
| 3. Pitch circle diameter (mm) | 60 |
| 4. Number of teeth (No's) | 22 |
| 5. Addendum circle diameter (mm) | 60 |
| 6. Dedendum circle diameter (mm) | 52 |
| 7. Pressure angle (Degree) | $20^0$ |
| 8. Face width (mm) | 20 |
| 9. Manufacturing process | Injection moulding |

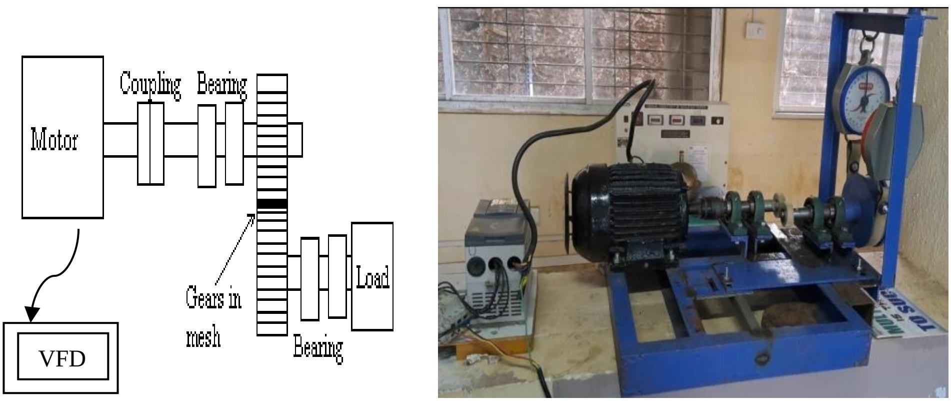


(a) (b) (c)

Fig. 1 Gear images (a) PAEK gear, (b) PAEK+ MWCNT gear, (c) PAEK +Amine functionalized MWCNT gear

### 2.4 Testing of the Gears

The gears were tested using a gear test rig shown in fig. 2 Each gear underwent testing for a duration of 1 hour and 40 minutes including different speeds (1000 rpm and 1500 rpm) and at different torque conditions (0 Nm, 6 Nm, 8 Nm and 10 Nm). The test gears are run for 1*105 and 1.5*105 revolutions for comparative analysis of these gears. The speed of motor was controlled by using variable frequency drive (VFD). The surface temperature of gears was monitored using an infrared thermometer throughout the testing process. Additionally, the weight of each gear was measured using a digital weighing machine before and after the running operations.




(a) (b)

Fig. 2 Gear test rig (a) Schematic diagram of gear test rig, (b) Photograph of gear test rig

To assess surface conditions of the major affected area such as the face surface of gear teeth, a surface roughness tester (Mitutoyo, resolution - 0.01μm) was used for both prior to and following the operation. By comparing the pre and post operation gear surface temperature, weights and roughness, the assessment provides insights into factors such as thermal behavior, wear rate and roughness that may have occurred during the testing period. Specific wear rate (Ws) of polymer gears is calculated using the following equation.

$$W_S = W_V / (2zmbN_T) \quad (1)$$

Where, $W_V$ is the wear volume ($mm^3$), z is the number of gear teeth, m is the module (mm), b is the tooth face width (mm), $N_T$ is the number of revolutions.

## 3. Results and Discussion

The performance of gears is significantly influenced by the surface temperature, wear and roughness as the mechanical properties of polymer materials are closely tied to it. All these three types of gears made of three different materials exhibit distinct behaviors attributed to their physical and chemical properties. These gears are tested for 0 Nm, 6Nm, 8 Nm and 10Nm torques and rotational speeds of 1000 rpm and 1500 rpm. These gears are operated for $1*10^5$ and $1.5*10^5$ revolutions.

### 3.1 Surface Temperature of Polymer Gears

The surface temperature of gears produced with PAEK, PAEK reinforced with MWCNT nanofiller and PAEK reinforced with amine functionalized MWCNT nanofiller materials is shown in fig. 3, 4 and 5. Figures indicated that, temperature of gear surface increases with rise in torques. Additionally, it reveals that the temperature of the gear surface rises with an increase in rotational speeds. This pattern was observed in all three types of gears. The increase in gear surface temperature was comparatively low in amine-functionalized MWCNT-reinforced PAEK composite gears than PAEK and PAEK reinforced with MWCNT composite gears, under the same operating conditions, including torques and rotational speeds. Furthermore, it was noted that the surface temperature of the driver gear was consistently higher than that of the driven gear for all three types of gears at these different torques and speeds.

The elevation in temperature weakens the hydrogen bonds between polymer chains, leading to the degradation of mechanical properties. While in operation, the interaction of gears during meshing induces heat at both the tooth surface and within the bulk material. This heat generation stems from several factors, including friction, hysteresis, fatigue load, and higher contact stresses resulting from the sliding and rolling actions of the gears [7, 27].

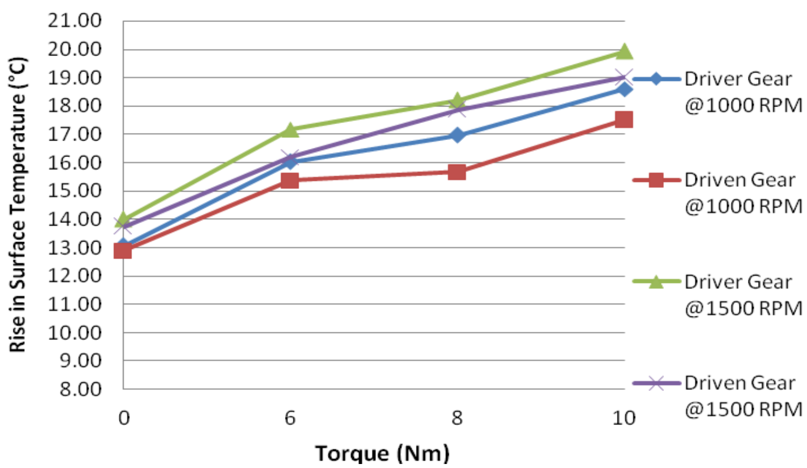



Fig. 3. Surface temperature of PAEK driver and driven gears at 1000 rpm and 1500 rpm

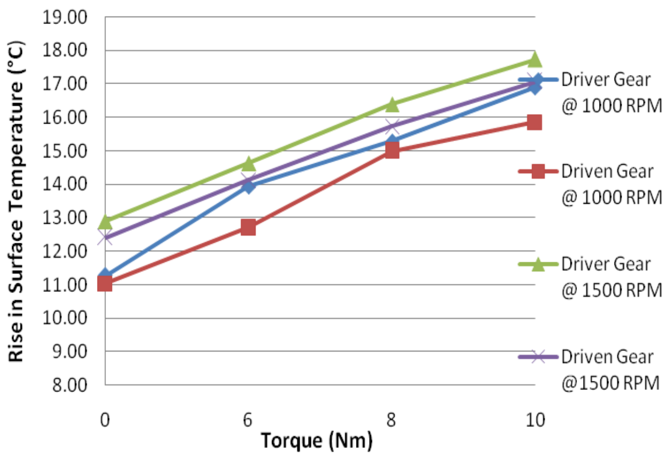



Fig. 4. Surface temperature of PAEK reinforced with MWCNT driver and driven gears at 1000 rpm and 1500 rpm

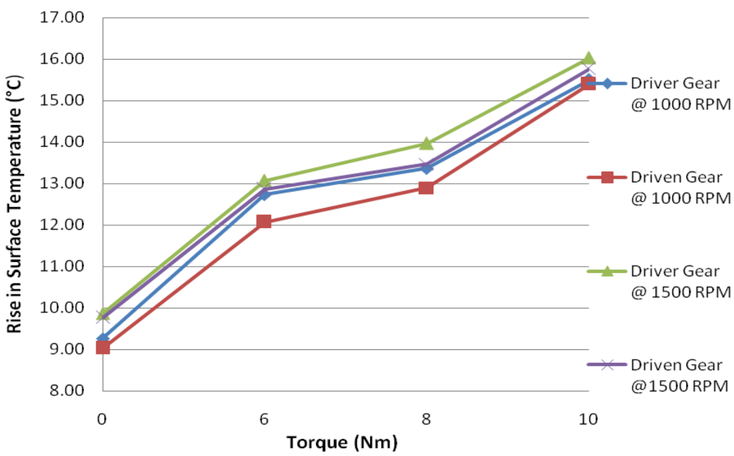



Fig. 5. Surface temperature of PAEK reinforced with an amine functionalized MWCNT driver and driven gears at 1000 rpm and 1500 rpm

The substantial increase in rotational speed leads to a considerable rise in loading frequency due to repetition of contacts and concurrently rises the surface temperature of gears. The surface temperature increases with higher surface roughness and contact area [28][29]. Hence, at low torque levels and at 1000 rpm rotational speed, there was minimal frictional heating of gear teeth, while at high torque levels and 1500 rpm speed, there was an increase in frictional heating resulting in a rise in temperature of gears teeth at high torque and at higher rotational speed. This observed phenomenon is a result of the proportional increase in heat generation driven by the factors such as slightly higher friction, high contact stresses, higher fatigue load and hysteresis loss, coinciding with an increase in both the rotational speeds and torques of the gears [13].

The heat generation in reinforced composite gears than unreinforced gears [13]. The enhancement in thermal properties is attributed to the reinforcing effect of MWCNT in the polymer composites, owing to their tensile modulus, stiffness, and thermal properties [30][31]. The improved mechanical performance of PAEK composites was achieved by incorporating functionalized MWCNTs compared to PAEK composites with non-functionalized MWCNTs. This enhancement is attributed to the improved interfacial interaction and better heat dissipation resulting from the surface treatment of MWCNTs [32].The functionalized MWCNTs enhance thermal conductivity and mechanical stability, reducing the temperature rise in polymer composites under operational conditions [33]. Similarly, those amine-functionalized MWCNTs significantly improve the dispersion within the polymer matrix, leading to better load transfer and thermal management [34]. Hence, gears made of PAEK materials incorporated with amine-functionalized MWCNTs demonstrated a lesser temperature rise in comparison to gears made from standard PAEK and PAEK reinforced with MWCNTs, across varying torque levels.

The driver gear drives the driven gear during running the meshing gears. Therefore, there are higher active and reactive forces exerted on the driver gears compared to driven gears when gears are in motion. As a result, the temperature rise in driver gears is comparatively higher than the driven gear.

### 3.2 Wear Performance

Fig. 6 and 7 illustrates the wear performance of gears manufactured from PAEK, PAEK reinforced with MWCNT nanofiller and PAEK reinforced with amine-functionalized MWCNT nanofiller materials at 1000rpm and 1500 rpm respectively. Figures indicated that the rise in specific wear rate of gears with rise in torques and rotational speeds of gears. This trend was observed in all three varieties of gears. Notably, amine-functionalized MWCNT gears exhibit a lower specific wear rate compared to PAEK and MWCNT-reinforced PAEK gears under identical operating conditions, including torques and rotational speeds. Moreover, it was observed that, across various torques and speeds, the specific wear rate of the driver gear remained higher than that of the driven gear for all three gear types.

The wear rate of these meshed gears was slightly higher at higher rotational speeds compared to lower rotational speeds, primarily due to increased friction resulting from repeated contact between the surfaces within a minimal time period. Additionally, a higher wear rate was observed at higher torque levels, due to the elevated stresses experienced in comparison to lower torque conditions. Hence, the higher wear rate is observed for higher rotational speed i.e. 1500 rpm and higher torque such as 10 Nm.

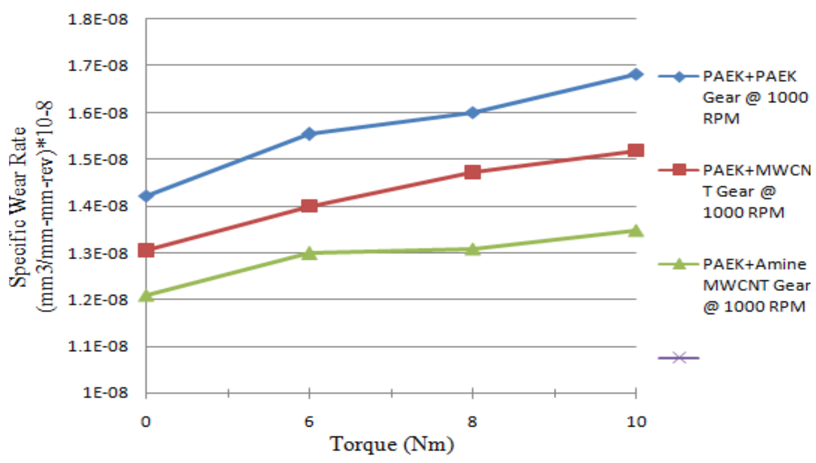



Fig. 6. Wear performance of PAEK and its composites with MWCNT and amine-functionalized MWCNT gears at 1000 rpm

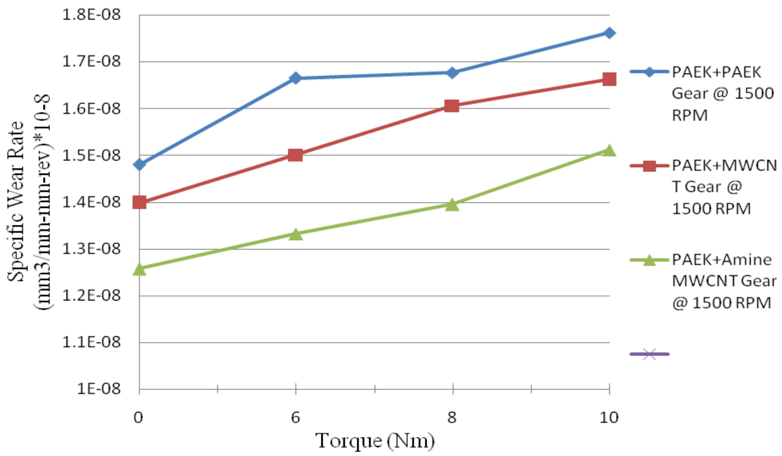



Fig. 7 .Wear performance of PAEK and its composites with MWCNT and amine-functionalized MWCNT gears at 1500 rpm

The aspect ratio, smaller in size and excellent mechanical properties of MWCNTs improves the mechanical properties such as stiffness, hardness, rigidity, tensile modulus, fatigue properties and the strengths of MWCNTs reinforced polymer composites [35, 36]. But, functionalized MWCNT improves the cross-link density, dispersion and interfacial interaction by increasing dispersibility and surface polarity resulting in the enhancement in the strength of composites, fatigue properties and reduces asperity deformation than MWCNT reinforced composites [6, 37]. Hence, the mechanical strengths of amine functionalized MWCNT incorporated PAEK composites are higher than MWCNT reinforced PAEK composites and pristine PAEK polymer [26]. Therefore, the wear performance of gears made of PAEK/amine functionalized MWCNT composites is superior to gears made of PAEK and PAEK/MWCNT composites.

During meshing, the gear tooth slides, and the direction reverses at the pitch point. The driver gear rotates towards the pitch point, while the driven gear consistently slides away from the pitch point. The relative direction of sliding and rolling actions plays a significant role for wear of gears [38][39]. Therefore, the driver gear experiences a higher rate of wear compared to the driven gear, caused by the more active and reactive forces experienced by the driver gear as compared to the driven gear. Wear was noticed on the gear tooth faces rather than the flanks, primarily due to the larger contacting surface area while gears are in motion. The melting temperature and glass transition temperature of PAEK and PAEK based composites is high as these materials are high temperature and high performance in category [40]. Therefore, these studied materials do not undergo softening at these temperature rises. Hence, there was no failure of teeth or no more wear rate of these gears due to the excellent mechanical and thermal properties of all these three types of gear materials.

### 3.3 Surface Roughness of Gears

Fig. 8 and 9 depicts the surface roughness of gears made from PAEK, PAEK reinforced with MWCNT nanofiller, and PAEK reinforced with amine-functionalized MWCNT nanofiller materials at 1000 rpm and 1500 rpm respectively. These figures reveal an increase in surface roughness (Ra) value with the elevation of torques and rotational speeds of the gears. This trend was consistent across all three gear types. This phenomenon can be attributed to the intensified friction, contact stresses, and sliding actions experienced by the gear teeth under higher torque and rotational speed conditions [41]. Notably, amine-functionalized MWCNT gears exhibit a lower surface roughness value compared to PAEK and MWCNT-reinforced PAEK gears under identical operating conditions, including torques and rotational speeds. Furthermore, it was observed that, across various torques and speeds, the surface roughness value of the driver gear was consistently higher than that of the driven gear for all three gear types. The excellent properties such as hardness, lower asperity deformation, improved adhesion and reduced friction of the MWCNT and amine functionalized MWCNT incorporated PAEK composites gears exhibited lower roughness (Ra value) than PAEK gears after the running operation [42].

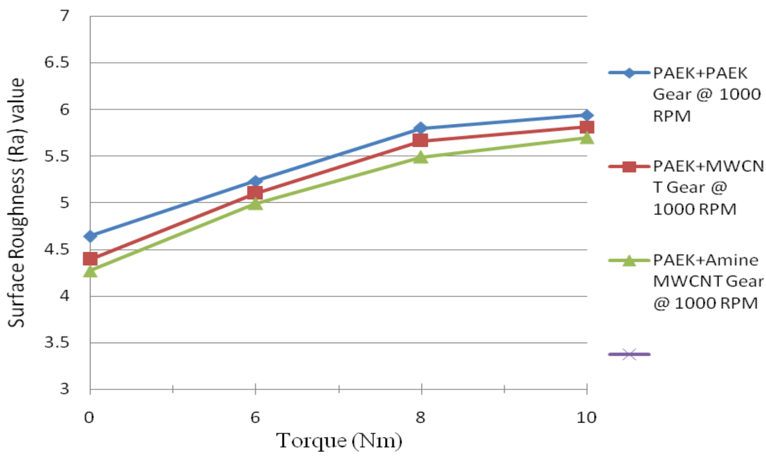



Fig. 8. Surface roughness of PAEK and its composites with MWCNT and amine-functionalized MWCNT gears at 1000 rpm

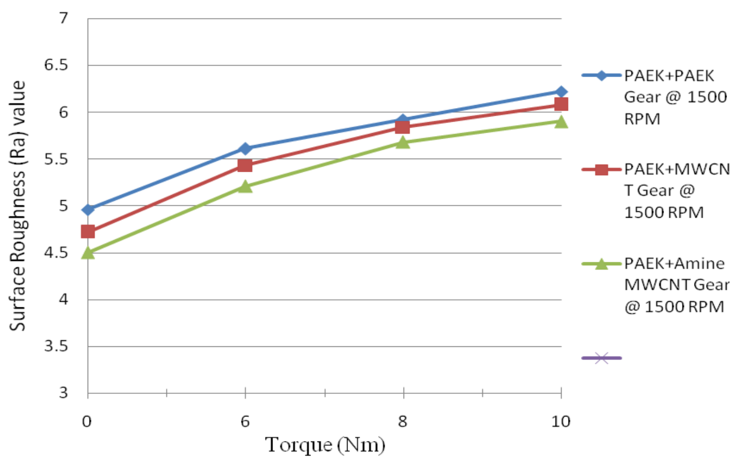



Fig. 9. Surface roughness of PAEK and its composites with MWCNT and amine-functionalized MWCNT gears at 1500 rpm

In the driving gear, the frictional force consistently acts away from the pitch point, whereas in the driven gear, it acts towards the pitch point. As a result, the frictional forces in the driving gear tend to separate the surfaces, leading to increased roughness on the teeth surface of the driver gear [6]. The surface roughness of gears was influenced by factors such as material composition, operational conditions, and the presence of additives like MWCNTs. Gears incorporating amine-functionalized MWCNTs demonstrate reduced

## 4. Conclusions

The investigation conducted on running meshed gears made of PAEK, MWCNT reinforced PAEK and amine-functionalized MWCNT reinforced PAEK materials under various operating conditions has led to several key conclusions are as follows:

- With increasing speed and torque, there is a concurrent increase in the surface temperature and wear rate of all these three types of gears. Notably, the contribution of torque to the rise in surface temperature is proportionally higher than that of rotational speed.
- Gears composed of amine-functionalized MWCNT reinforced PAEK materials exhibit slightly superior performance compared to those made from PAEK and MWCNT reinforced PAEK. This advantage can be attributed to the comparatively higher mechanical and thermal properties of amine-functionalized MWCNTs, enhancing the overall durability and reliability of these gears.
- The surface temperature and wear rate of driver gears are slightly higher than those of the driven gears. This discrepancy can be attributed to the differential distribution of frictional forces and contact stresses experienced by the gears during operation.
- No instances of tooth failure or abnormal wear rates were observed in any of the gears tested. This can be attributed to the high inherent strengths of PAEK and MWCNTs nanofiller, ensuring the structural integrity and longevity of the gears under the specified operating conditions.
- Post-operation analysis revealed that the surface roughness of gears composed of amine-functionalized MWCNT reinforced PAEK materials was lower than that of gears made from PAEK and MWCNT reinforced PAEK. This indicates a good surface finish and potentially improved performance in terms of friction and wear characteristics. These gears can be useful at the high temperature and loading working conditions.
- The investigation highlights the significant influence of operating conditions and material composition on the performance of meshed gears. The superior properties of amine-functionalized MWCNT reinforced PAEK materials suggest their potential for applications requiring high durability and reliability in dynamic mechanical systems.

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