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INVESTIGATION OF THE DURABILITY AND PERFORMANCE OF GEARS MADE OF GLASS FIBER, CARBON AND BRONZE-REINFORCED POLYTETRAFLUOROETHYLENE MATRIX COMPOSITE MATERIAL

Polymer gears are often used in power transmission due to their numerous advantages. Heat accumulates on polymer gears during operation. Over time, this accumulated heat leads to damage; and shortens the service life of the gears. To prevent this, various fillers are added to the polymer materials. These fillers help to dissipate the heat generated on the gears. In this study, 25% glass fibers, 35% carbon powder, and 60% bronze particles were added to the polytetrafluoroethylene (PTFE) matrix to determine the wear behavior of gears. The properties of the matrix and the filler mainly influence the wear behavior of PTFE composites. The study showed that all composite gears with filler have better wear resistance than pure PTFE gears due to their better thermal stability. After the tests, it was found that the gears made of PTFE + 35% carbon additive had about 12 times better wear rates than those made of pure PTFE. Based on the average temperature values of the experiment, it was found that the mass temperature of gears made of 35% carbon-doped PTFE is about 38-39% lower than that of pure PTFE. This study contributes to the standard studies on heat build-up, thermal damage, and wear of gears made of polymers with different fillers and ratios.

Keywords: Composite; Wear; Polytetrafluoroethylene (PTFE); Glass fiber; Spur gear

1. Introduction

In recent decades, more and more polymer materials have been used for gears. These materials are widely used due to their excellent mechanical properties, such as high height-to-weight ratio, good tribological properties, low coefficient of friction, self-lubrication, and high resistance against shock loads. Despite many advantages, there are some disadvantages of polymer gears. The limitations of these materials include low load capacity, lower operating temperatures compared to steel and poor thermal conductivity [1-3]. Many polymeric materials can be combined in different pairs to make gears. Fillers, which have a positive effect, can be added to these polymers in suitable proportions to improve the mechanical properties of the materials [4]. To use plastic gears in practice and testing them under real operating conditions are of great importance. Researchers use accelerated tests on pairs of gears where stepwise torque loads are applied, since conducting tests under real operating conditions can be time-consuming and costly. These tests are conducted to determine the maximum load capacity at which the gear pair will fail, evaluate the effectiveness of additives, and determine the appropriate ratio of these additives. Polymer-based gears have a lower heat transfer coefficient, which means that heat can accumulate in the contact areas during operation. This can lead to a reduction in their load capacity. There are efforts to improve some of the mechanical properties of these materials by adding suitable combinations such as Polyoxymethylene (POM), PTFE, polyamide (PA66), polyamide (PA12), and polyether ether ketone (PEEK) in certain proportions, such as glass, carbon, and bronze materials [5].

PTFE is a polymer that has a semi-crystalline structure and offers numerous advantages. PTFE has a variety of industrial applications due to its low friction coefficient, high thermal stability, good electrical insulation properties, hydrophobicity and biocompatibility. Lin et al. investigated how addition of bronze into PTFE affects the density of particle dispersion on the surface of PTFE/bronze composites when they are subjected to abrasion with different particle sizes in an abrasion tester at different loads and speeds. Their results showed that peeling occurred when the abrasive grid's grain size is large [6]. In their study, Conte et al. examined how adding different materials – pure PTFE, PTFE with 25% carbon, PTFE with 60% bronze, and PTFE with 25% glass fiber – had an effect on the way surface temperature affected friction. According to the authors, the tribological properties of PTFE composites are influenced by their thermal properties and

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structures. According to their findings, adding fillers improved both abrasion resistance and stability. Increasing the thermal conductivity and dispersion improved the adhesion resistance of the material. When used under dry working conditions, bronze and glass fiber fillers can greatly reduce the mass loss of PTFE due to wear. However, they found that large grain sizes lead to the formation of the opposite effect on the surface and transfer film, increasing the film thickness. The thermal properties and wear performance of carbon-reinforced materials were quite good, thanks to the small size of the carbon particles [7]. PTFE is a material used for tribological applications. Carbon, bronze, glass fiber, graphite, and molybdenum disulfide fillers are the most commonly used ones in varying proportions to improve wear resistance and friction coefficient [8,9]. These additives, in certain ratios, also influence other important properties of materials such as abrasion, thermal conductivity, electrical conductivity, and chemical inertness. In general, fillers can increase the wear resistance of a material by 10 to 500 times and its thermal conductivity by 2 to 3 times [10].

Another study investigated the influence of filler content, sliding time, test speed, and load on PTFE. When it comes to improving the anti-wear properties of PTFE, the structure of the filler has more influence than the shape of the material [11]. Polymers are strongly influenced by temperature in tribological contacts due to their widely recognized thermal properties. Friction between materials generates heat. A small increase in temperature at the contact points leads to significant degradation of the mechanical and tribological properties of the material [12-13]. Gears are among the most commonly used machine components. They are essential for mechanical power transmission in many applications [14]. The objective of this research is to enhance the wear characteristics of PTFE gears through incorporation of three distinct fillers in varying proportions, aiming to assess their performance. Specifically, this study seeks to advance our understanding of thermal damage and wear properties in plastic gears. It involves a comparative analysis of the impact of additives such as glass fiber, carbon, and bronze fillers on the thermal damage and wear of plastic gears compared to pure PTFE. Using PTFE fillers in gear manufacturing aims to contribute valuable insights into the behavior of wear and thermal damage through experimental tests. The research evaluates the efficacy of employing carbon, bronze, and glass fiber-filled PTFE as composite materials for gears and investigates the effects of these composites on gear performance.

2. Gear tooth contact and temperature generation

The most common types of tooth damage in plastic-based gears are wear and thermal damage. Under the influence of the load applied during the operation of a plastic-based gear, heat builds up on the tooth surface due to the rolling and sliding motion. Fig. 1 shows the plastic gear wheel as a representation of the heat accumulation in the tooth profile during contact. In addition to the rolling movement of the tooth profile, one of the teeth shifts relative to the other. In the meantime, a frictional force is generated at the contact point. The displacement of the frictional force with the contact point reveals the frictional force, which causes the heating of the teeth. While the temperature is highest at the outermost surface, it decreases further away from the tooth surface. Due to the low heat transfer coefficient and the high Hertzian surface pressure from the single tooth grip around the pitch circle, the heat accumulates in the first region and increases the T1 temperature. It attempts to dissipate this heat to the external environment via co-gear or its mass. If this temperature rise exceeds the critical glass transition temperature of the plastic, thermal damage is inevitable. Therefore, Heat build-up on the surface of the plastic gearbox should not be permitted. The heat transfer coefficient the material must be improved in order to dissipate the accumulated heat without damaging the material. During operation, plastic gears accumulate more heat than metal gears. Therefore, plastic gears are operated together with steel gears to eliminate this heat build-up. Due to the different thermal properties of the interacting gears, the damage can look different. In this way, thermal damage occurs due to excessive wear, tooth root breakage, and heat build-up of the plastic gear [2].

3. Material and methods

3.1. Materials

This study investigated the gear performance of PTFE material reinforced by adding various proportions of glass fibers, carbon, and bronze into pure PTFE. The experimental samples were custom-manufactured by APAMEYA Industrial Products Industry and Trade Limited Company in Turkey. We determined the necessary mixture ratios and filling materi-

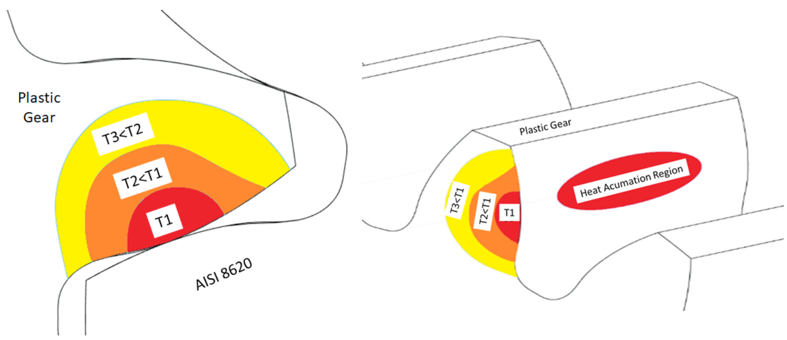


Fig. 1. Heat accumulation zones of plastic gear [2,20]

als, resulting in samples with a diameter of 110 mm. TABLE 1 shows the added amounts, specific gravity, thermal conductivity, and hardness values of four samples prepared for the gear test. The Shore D hardness values are given according to ASTM D224 standard.

TABLE 1

Properties of test gears

	PTFE composites	Specific weight (gr/cm^3)	Thermal Conductivity (W/m K)	Sh D Hardness
1	Pure PTFE (Ref.)	2.16±0.02	0.24	55
2	PTFE+25 Wt.% Glass Fibre	2.24±0.02	0.44	59
3	PTFE+35 Wt.% Carbon Coke	2.06±0.03	0.47	68
4	PTFE+ 60 wt% Bronze	3.9±0.01	0.46	66
5	Counter Gear (AISI 8620)	7.8	46.6	—

The PTFE and filler powders were mixed and stirred to create the material until they were evenly distributed. The mixture was then pressed into a mold and sent to a commercial company for sintering. The PTFE mixture contained particles that averaged 0.3 µm in size. The carbon particles were 15-25 µm in diameter, and the bronze particles averaged 25 µm in size. The samples containing PTFE and bronze powders also contained copper, tin, and zinc in a 90% Cu, 8% Sn, and 2% Zn ratios, respectively. The glass fibers had a diameter of about 10 µm and a length of 80-100 µm.

3.2. Test details of gears

We used Fellows Method to make gears, and the co-gear was made from AISI 8620 steel. The dimensions of the gears can be seen in TABLE 2. The steel used for the drive gear was carburized, quenched and annealed in oil. The hardness was measured by means of a Rockwell hardness tester under a load of 150 daN. The surface of the spur gear had a hardness of 56 HRc. The PTFE gears were produced using the same cooling system (90% water and 10% boron oil) throughout the manufacturing process to avoid excessive heating from the hot chisel tip of the CNC machine and the poor thermal conductivity of the PTFE material. The hobbing machine was used to produce the gears.

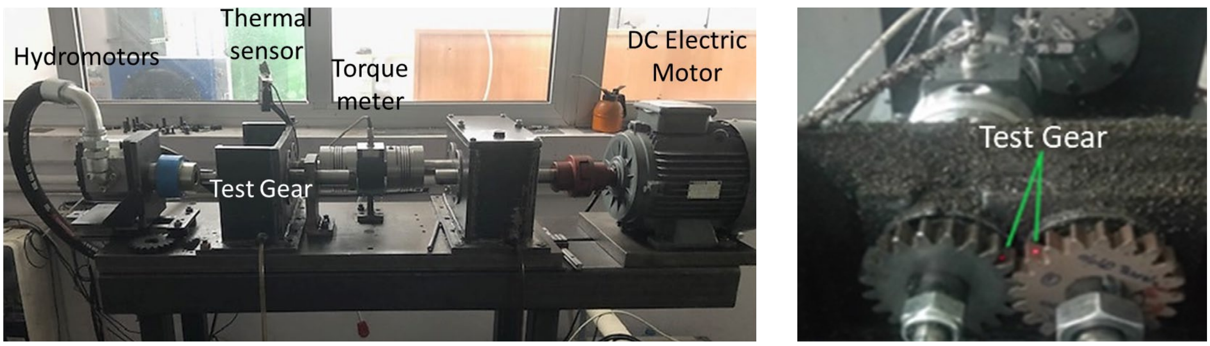
TABLE 2

Specification of the test gears

	PTFE Gear	Driver Gears (AISI 8620)
Modulus	4.5	
Number of teeth (z)	20	
Gear ratio (u)	1	
Profile shift factor (x)	0.177	
Pressure angle (deg.) α	20	
Operating pressure angle (deg) ($\alpha_{Wt.}$)	22.44	
Helix angle at the base circle (β_b)	0	
Diameter of pitch cir. (mm) (d_o)	90	
Addendum circle diameters (d_a)	100.593	
Base circle diameters (d_b)	84.564	
Centre distance (mm)	91.5	
Tooth width (mm)	20	21
Contact ratio	1.49	

The crystallinity of semi-crystalline materials in PTFE-based composites was evaluated using differential scanning calorimetry (DSC). The test samples were heated from 30 to 350°C at 10°C/min in an inert atmosphere containing N2 and then cooled. To determine the weight of the samples, a balance with an accuracy of 0.1 mg was used before and after the test, and a photo of the worn zone was taken. Scanning electron microscopy (SEM) was used to examine the worn surfaces of the tooth root, tooth pitch, and tooth tip in the worn contact areas of the pure PTFE and composite PTFE gear materials. In this way, the effects of fillers on the changing tribological properties of samples were investigated. The FZG test apparatus, on which the experiments were carried out, are shown in Fig. 2.

During the test, we used two devices to measure temperature. The Keyence FT-H30 Intelligent Series Thermo Sensor 510 infrared thermometer was used to measure the air mass temperature in the immediate contact area from a distance (Fig. 2b) [2,15-19]. We also used a calibrated thermal imaging camera (FLIR Systems Thermal-CAMTM P65) to measure temperature changes in the wear zone during the wear tests. The thermal



(a) (b)

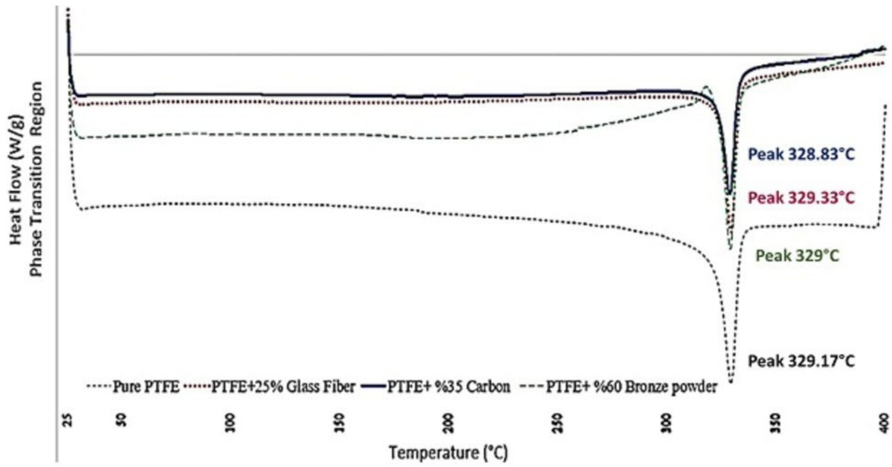
Fig. 2. Gear tester, a) test device, b) non-contact temperature measuring device

camera was placed directly above the gear tester, and it recorded the temperature changes at one-minute intervals. The thermal imaging camera had a temperature range of –40°C to +2000°C with an accuracy of ±2% or 2°C, and a frame rate of 60 Hz. It had a thermal sensitivity of 0.08°C at 30°C and a spectral range of 7.5-13 µm at a resolution of 320 × 240 pixels. The emissivity of the camera was set to 0.91-0.94.

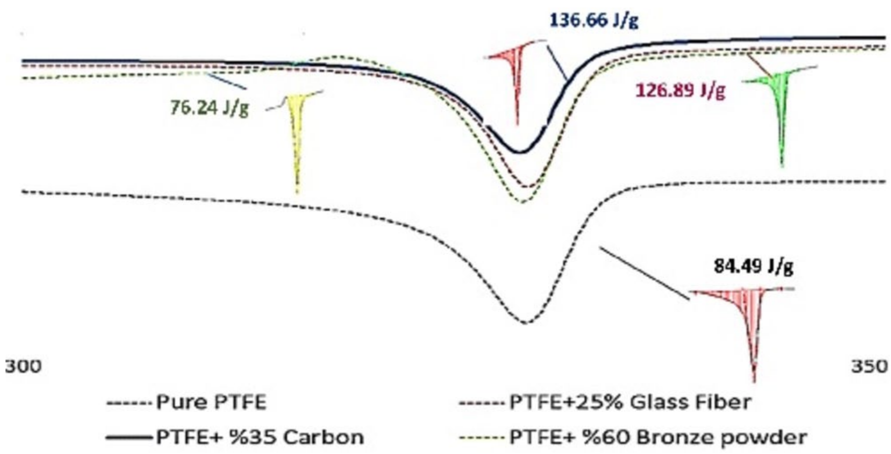
4. Results and discussion

4.1. DSC analysis

Fig. 3 shows the DSC analysis of the PTFE composites. The graph shows the relationship between the total heat input and the mass of the sample. The heat of fusion is the amount of heat absorbed as per unit mass of the matrix during melting and is equal to the area of the melting peak divided by the mass of the sample. The size of the crystals depends on the mobility of the polymer chains, which are more accessible at higher temperatures and are influenced by the content and type of fillers. From the thermal traces in Fig. 3a, it was found that the PTFE did not react differently from the glass fiber, carbon, and bronze fillers; and the temperature of the melting peak remained the same. The data obtained in this study were similar to those reported in previous studies [7,20]. The pure PTFE material had almost identical melting peaks. While the slopes of almost all samples in Fig. 3 looked the same, the pure sample had a more pronounced downward slope, indicating a higher thermal stability of the pure polymer when the heat flux decreased with time. The results showed that the glass fiber and carbon-filled PTFE composites had higher fusion heat values than the neat and bronze powder-added PTFE polymer composites. This can be attributed to the fillers in the PTFE matrix, which improve stability and increase crystallinity. Among the composites, PTFE with 35% carbon exhibited the highest stability and fusion heat value (136.66 J/g), followed by PTFE with 25% glass fiber (126.89 J/g). However, the addition of 60% bronze powder resulted in a lower fusion heat value (76.24 J/g) than pure PTFE. It is worth noting that pure PTFE is a semi-crystalline material with amorphous regions between the crystalline regions. When it slides, the amorphous phase wears away, leaving deposits rich in the crystalline phase. Friction can cause the fibers or fragments to align in a particular direction, increasing the crystallinity due to local heating [21]. As mentioned earlier, the bronze particles are assumed to act as a heat source as the temperature rises,



(a)



(b)

Fig. 3. Thermal traces of PTFE and PTFE composites, determined with DSC, a) heat of fusion and melting peak, b) heat of fusion in the range of 300-350°C

contributing to the melting of the matrix. The heat melting values of PTFE combined with glass fiber and carbon additives were found to be much higher than those of the pure and bronze-added samples, indicating better thermal stability of these reinforced composites than pure PTFE.

In the temperature range used for operation, the slope of the DSC curve indicated that small crystals formed during the cooling phase. This was because these crystals required less energy to break. Polymers have high mobility after the glass transition, increasing their temperature and releasing heat to form stable dispersions known as crystals. However, PTFE composites, containing glass fibers and carbon, limit the size and weight of the bronze particles, making them more stable. The bronze material is absorbed by bronze particles mainly between 230°C and 310°C (Fig. 3a). Above these temperatures, these particles also act as a heat source for PTFE matrix. This process can cause the bonds between the bronze particles and PTFE matrix to loosen more easily, as they cannot be completely bound. A higher proportion of bronze particles in the PTFE composite prevents the formation of larger and more stable crystals. As a result, the wear profile, formed in the gear profile of the PTFE + 60% bronze reinforced gear, would be more affected. This means that the contact temperature of the PTFE composites reinforced with glass fiber, carbon and bronze powder in the contact area of the gears was better than that of the pure PTFE material in terms of dispersion.

Based on the data shown in Fig. 4, the gear made of pure PTFE had the highest mass loss, while the gear made of PTFE with 35% carbon reinforcement had the lowest mass loss. All composite gears used in this study showed better wear resistance than the pure PTFE gear. In particular, the PTFE + 35% carbon gear showed almost 12 times better wear performance than the pure PTFE gear in weight loss.

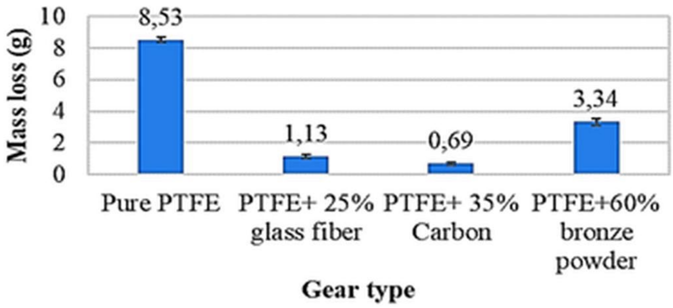
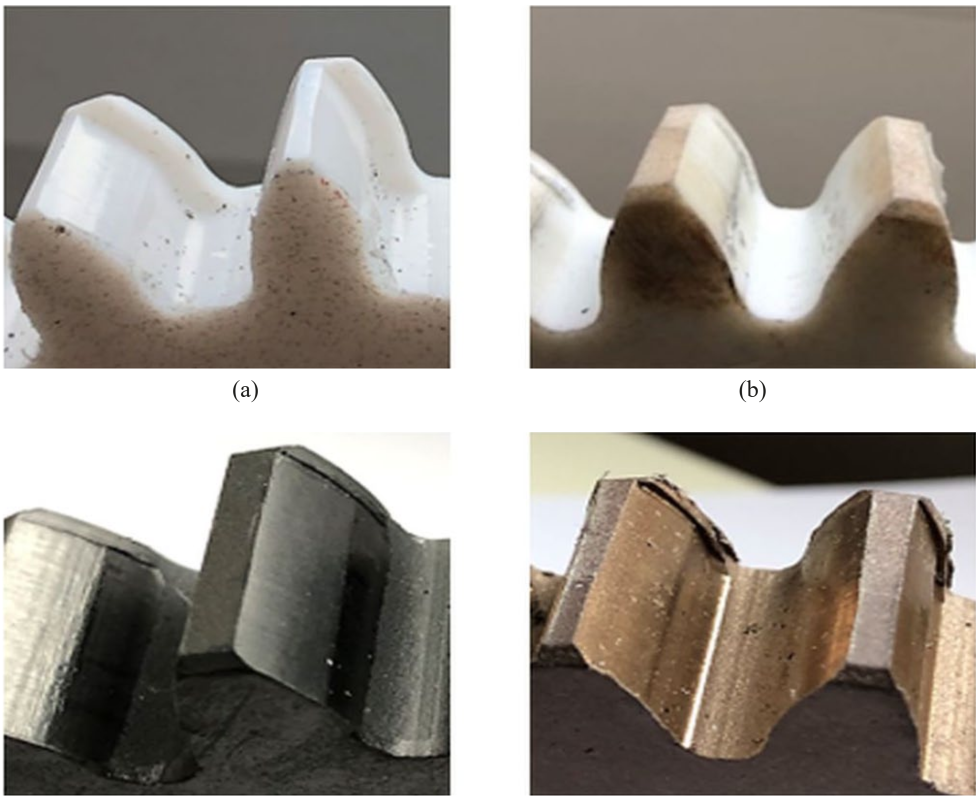


Fig. 4. Test gear wheels, mass losses after testing

Polymers are viscoelastic materials, which means their deformations under pressure are also viscoelastic. When the frictional force generated by a load of pure PTFE gear material reaches certain values, the critical surface energy of the PTFE increases. This causes large particles to flake off the surface, increasing wear (Fig. 5a).

Fig. 3 shows that small crystals were formed during the cooling phase, which required less energy to break. This resulted in surface abrasion of the pure PTFE gear material due to the frictional force in the gear contact area. In contrast, the tooth



(a) (b)

(c) (d)

Fig. 5. Wear in the tooth contact areas of PTFE composite gears, a) pure PTFE, b) PTFE+25% glass fiber, c) PTFE+35% carbon, d) PTFE+60% bronze powder gears

contact surface of the composite material made of PTFE and 35% carbon had a smooth appearance with minimal wear depth (Fig. 5c). This composite had the highest wear resistance among all test samples, which can be attributed to the self-lubricating properties of the black carbon particles scattered on PTFE material (Fig. 4). In Fig. 5b, it was found that the PTFE + 25% glass fiber reinforced gear material had the second highest abrasion resistance. This is because the carbon and fibers in the material act as barriers that prevent large-scale degradation of PTFE, resulting in a low amount of wear debris. The hard carbon particles also help embed the glass fibers into the matrix, making the material thermally more conductive. Graphite, a solid lubricant, also improves the tribological behavior of the material. Although the glass fiber-reinforced PTFE material is more abrasive than the carbon-reinforced gear material, it showed excellent abrasion resistance compared to pure PTFE and bronze-reinforced PTFE materials. The abrasion depths on the tooth profiles of the tested gears are shown in Fig. 5. The tooth load on the PTFE + 60% bronze powder material could not be effectively transferred from the matrix to the filler particles. This resulted in the bronze powder and matrix not being fully impregnated in some areas, making it easier for them to detach from the surface in layers on contact. This resulted in the bronze-reinforced PTFE experiencing severe wear due to the displacement of the bronze particles in the main matrix. Sliding between layers was easy, as the bronze particles did not form a strong bond with PTFE matrix. Since the PTFE material is filled with bronze particles that prevent the formation of large crystals, as the relative crystallinity of bronze-reinforced PTFE is low [21].

Wear is known to be one of the main damage mechanisms in the testing of polymeric and doped gears, resulting in the formation of a 2D wear depth in the tooth profile, as shown in Fig. 6. Accordingly, it is important to note that there can be deviations from the expected values due to tooth wear, which can increase the temperature. The wear distribution is highest in the upper and lower areas of the tooth profile (Figs. 5-6), while the section circle region displays less wear. The reason for this is that the steel gear caused deformation of the pure PTFE gear during operation, resulting in higher friction and a temperature rise of about 105°C (Fig. 8). When the wear of the gear profile reached a certain level, the temperature partially decreased.

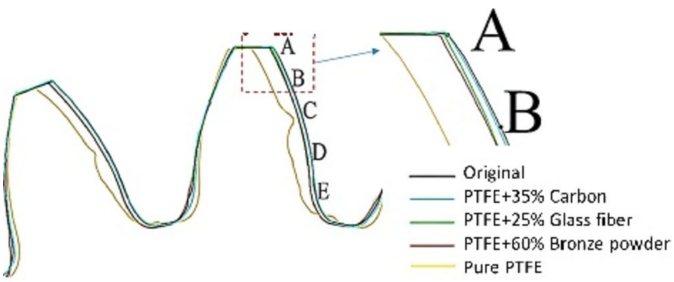


Fig. 6. 2D wear depth in the tooth profile

After a sudden temperature rise, the glass fiber and carbon-reinforced PTFE gears experienced a slight temperature rise. The temperature values then remained almost balanced throughout the rest of the test, as shown in Fig. 7. The thermal conductivity value of the carbon-reinforced PTFE gear material was higher than the other test samples, resulting in a more linear trend towards thermal equilibrium. The maximum temperature was 62.2°C, and the mean temperature was 59.6°C. The glass-fiber-reinforced PTFE gear material had a maximum mass temperature of 70.1°C and a mean temperature of 64.4°C. The carbon-reinforced PTFE composite had the highest thermal conductivity and hardness values among the tested materials, resulting in better heat dissipation. During the test period, the thermal conductivity of the bronze-reinforced PTFE gear material was similar to that of the carbon-reinforced PTFE material. However, a downward trend was observed in the middle of the test period, although the temperature of the mass continued to increase after reaching equilibrium. This is thought to be due to the bronze addition causing rapid heat transfer to the external environment and increased wear in the contact zone of the tooth material. This reduced the temperature in the contact zone due to the worn particles. The average temperature values during the test showed that the mass temperature of 35% carbon-reinforced PTFE gear material was about 38-39% lower than that of the pure PTFE material. For 25% glass fiber reinforced, 33%, and bronze-reinforced PTFE materials, the temperatures were about 23% lower than the pure PTFE material. The temperature values measured during the test were similar to the wear of the gears.

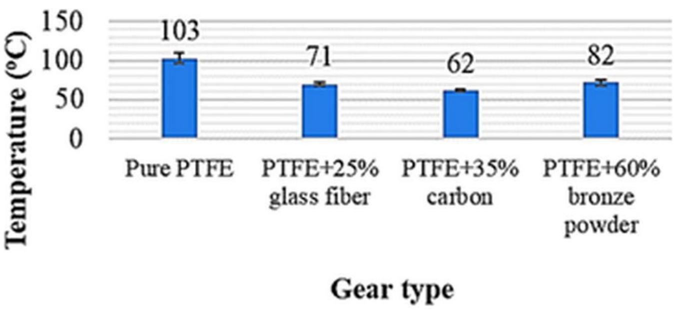


Fig. 7. Highest temperature values measured during the test

During the experimental tests shown in Fig. 8, temperatures rose rapidly due to tooth forces and friction, reaching about 0.3×105 within 35-45 minutes. This increase was observed in almost all samples and resulted in a partial transition of the material from a hexagonal phase to an irregular phase. The temperature values of the pure PTFE sample ranged from 93-103°C, those of the PTFE + 25% glass fiber composite from 55-69°C and those of the PTFE + 35% carbon composite from 55-64°C. The PTFE + 60% bronze powder composite had temperatures around 63-80°C. The heat that accumulated on the surface of the PTFE composite gear tended to be distributed to the cooperating AISI 8620 gear, which had a higher thermal conductivity and which was colder. The PTFE composite material and AISI 8620 gear reached thermal equilibrium during the test, resulting in a stable temperature. The pure PTFE gear material initially caused

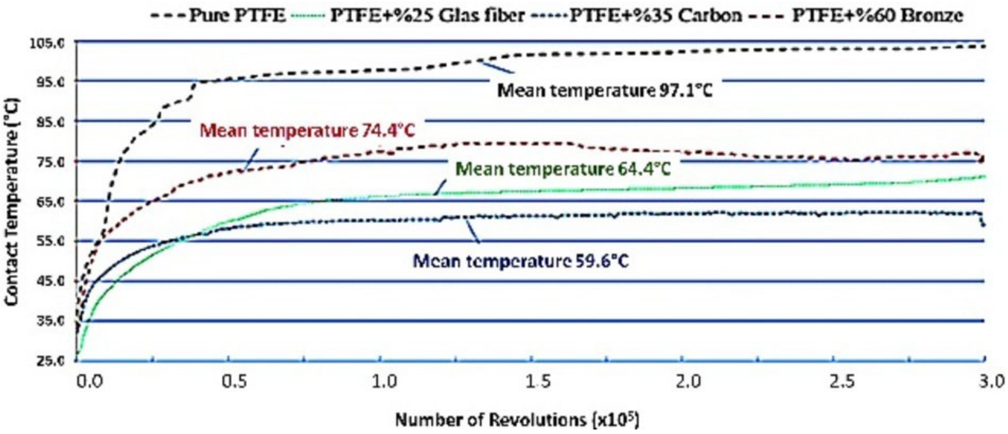


Fig. 8. Change in tooth temperature in the contact zone of the gear during the test

significant wear due to its high contact temperature. However, once the equilibrium temperature was reached, it rose again and peaked at 103.7°C, close to the glass transition temperature for PTFE materials. The average temperature of the pure PTFE gear material was 97.1°C throughout the test. This information is shown in Fig. 8.

4.2. SEM analysis

Fig. 9a-d shows SEM images of the root, pitch region, tip, and the worn particles. It can be seen that the carbon and glass fibers, incorporated into the PTFE matrix, acted as barriers that prevent the PTFE from breaking, as can be seen in Fig. 9a-b,

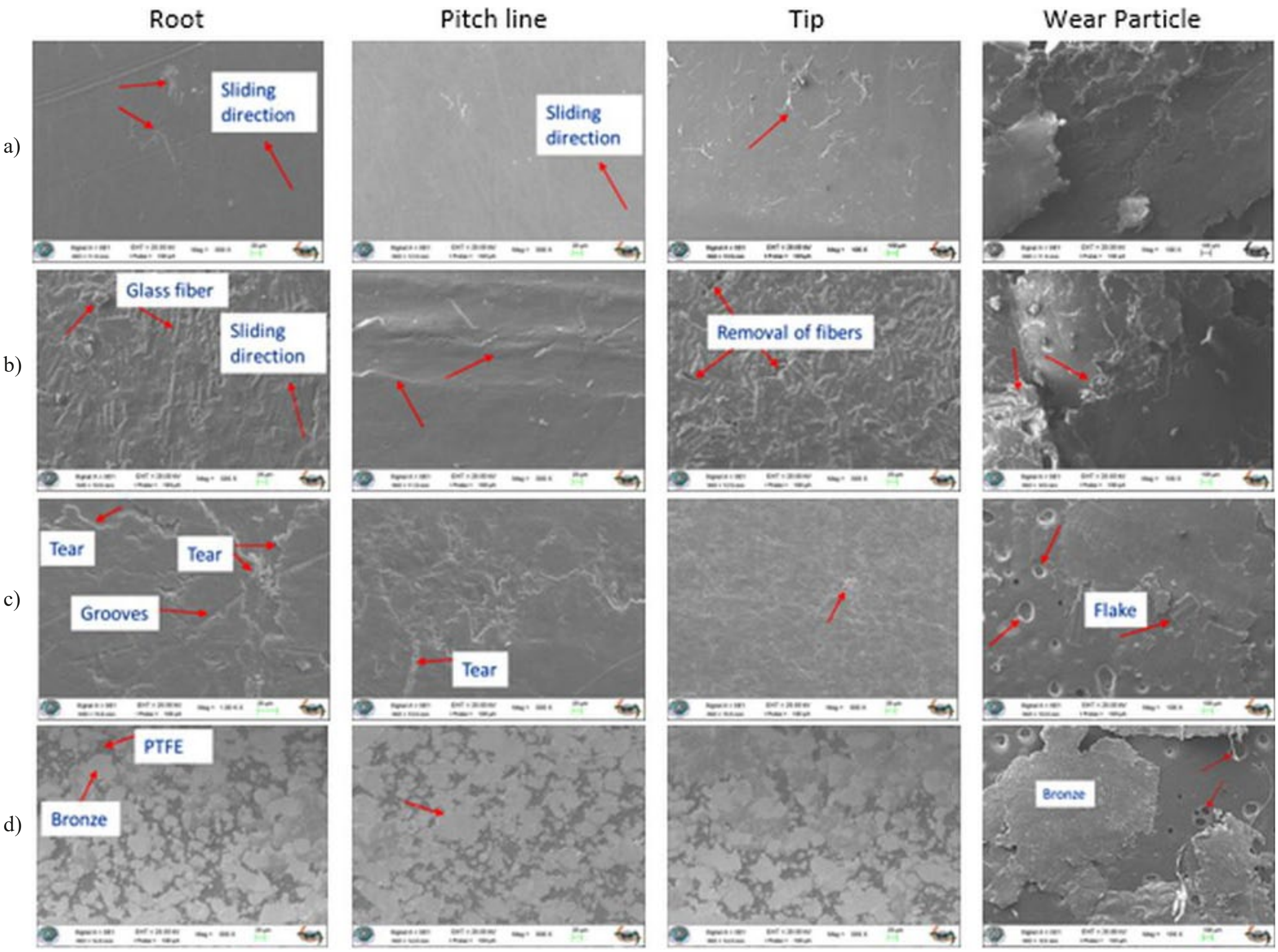


Fig. 9. SEM images of the root, pitch region, tip, and wear particles after the test, a) pure PTFE, b) PTFE+25% glass fiber, c) PTFE+ 35% carbon, d) PTFE+60% bronze powder

glass fibers and black carbon particles and their contribution to increasing the hardness values acted as effective dispersion reinforcing elements. In addition, graphite acted as a solid lubricant and thus improved the tribological behavior of PTFE. The contribution of the matrix and fibers to the wear behavior varied depending on the type of filler. As seen in Fig. 9c, due to the hardness of the carbon-reinforced PTFE sample compared to the other samples, a groove was formed by the micro-flow-like movement of the sharp abrasive particles. Along the surface topography of the glass fiber-reinforced PTFE composite, more fiber dusting, less fiber breakage, and less separation of the fiber-matrix bond were observed. As a result, the material's mechanical properties were improved by glass fibers and carbon particles and the wear rate of the material was reduced. Due to the small size of the carbon particles, the composite exhibited a good combination of thermal properties and structure. The presence of bronze in PTFE matrix prevented the formation of larger (more stable) crystals, significantly affecting the wear resistance results. Although the bronze-reinforced PTFE sample significantly improved the thermal conductivity and hardness, the wear resistance was quite low compared to other composites. Although the bronze particles were homogeneously dispersed in the matrix, they did not show good adhesion due to poor bonding. It can be seen that the worn particles are divided into layers of large particles (Fig. 9d). Fig. 9a shows a smooth, fracture-free PTFE gear surface with layers on the tooth surface. Due to the reinforcement, detachment of particles from the surface was difficult for the tooth profiles of the PTFE+25% glass fiber and PTFE+35% carbon reinforced gears shown in Fig. 9b and c, respectively. The wear surface of PTFE+60% bronze powder in Fig. 9d was smooth, but the wear was more pronounced than the other additive gears and less pronounced than on the pure PTFE gears due to heat build-up from the bronze powder in PTFE. Heat build-up on these particles at high temperatures also had a negative effect on wear to some extent. However, these bronze powders released the heat to the external environment.

5. Conclusion

This study investigated the wear performance of glass-fiber, carbon, and bronze-reinforced PTFE composites at certain transmission ratios as gear material. The thermal transition of PTFE composites was investigated by DSC analyses for all test samples. A better understanding of the wear behavior of materials can make an important contribution to the experimental testing of components and the integration of information into laboratory test results. Accordingly, the following conclusions were drawn in this study:

- It was found that the reinforcing materials showed no differential response at the additive-matrix interface and did not change the melting peak temperature.
- The glass fiber and carbon-reinforced PTFE composites showed higher heat values than pure and bronze powder-reinforced PTFE materials. This indicates that the glass fiber and carbon-reinforced composites are thermally more stable than pure and bronze powder-reinforced polymers.
- The composite material of PTFE and 35% carbon exhibited higher stability and had the highest thermal melting value of 136.66 J/g. The composite material of PTFE and 25% glass fibers followed closely in second place with a value of 126.89 J/g. The addition of carbon and glass fibers to the composites increased their heat absorption capacity.
- The composite PTFE + 60% bronze powder had a lower heat melting value of 76.24 J/g than pure PTFE material. When the temperature rose, the bronze particles became a heat source and melted the matrix. It was found that the heat melting values of PTFE materials with glass fiber and carbon additives are significantly higher than those of the pure and bronze-reinforced samples.
- Based on the test results, it was found that composites with a high heat absorption capacity had better wear resistance.
- In particular, the bronze material was absorbed by the matrix between about 230°C and 310°C, and above these temperatures, these particles also appeared to provide a heat source for the PTFE matrix. This result is thought to be due to the fact that the bonds between the bronze particles and the PTFE matrix were easily separated as they could not be fully bound.
- While the highest mass loss occurred in the pure PTFE gear, it was lowest in the PTFE + 35% carbon-reinforced gear. All composite gears used in this study showed better wear resistance than the pure PTFE gear. The PTFE + 35% carbon reinforced gear had almost 12 times better wear performance than the pure PTFE gear in terms of weight loss.
- Thanks to the self-lubricating properties of the black carbon particles dispersed in the PTFE matrix material, this composite had the highest wear resistance among all test samples.
- The tooth load formed on the PTFE material reinforced with 60% bronze powder could not be effectively transferred from the matrix to the filler particles. Since the bronze powder and the matrix were not fully integrated in some areas, they could more easily detach from the surface through layers upon contact.

The study employed a temperature-based step-loading approach to assess the failure modes and determine the load-carrying capacity of polyoxymethylene (POM) gears reinforced with carbon black (CB) and various concentrations of $CaCO_3$. The failure analysis of the gears indicated that incorporating CB and $CaCO_3$ had a suppressive effect on tooth fracture and thermal bending, attributed to the synergetic reinforcing effects of these additives. Currently, the aspiration is to mitigate thermal damage formation by incorporating nano additives and materials with enhanced heat conduction characteristics in granular form into the composition of gear materials [22-23].

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