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RESEARCH PAPER

Development and Performance Analysis of Polymer Composite Gears: A Comprehensive Review of Material Innovations and Key Parameters

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Abstract: *The increasing demand for lightweight, corrosion-resistant, and high-performance gear systems has driven growing interest in polymer composite gears as alternatives to conventional metallic gears. In high-speed and high-load applications, gear materials are required to withstand cyclic stresses, frictional heating, and long-term service without excessive wear or dimensional instability. This review aims to critically evaluate recent advances in high-performance polymer composites for gear applications, with a particular emphasis on Poly Aryl Ether Ketone (PAEK) based materials reinforced with Multi-walled Carbon Nanotubes (MWCNTs). The review synthesizes published literature focusing on polymer matrices, pristine and functionalized MWCNT reinforcements, processing techniques, and gear-relevant mechanical, thermal, and tribological performance parameters. The analysis shows that PAEK/MWCNT composites exhibit a favourable combination of high strength-to-weight ratio, enhanced thermal stability, improved wear resistance, and superior load-carrying capability compared to unreinforced polymers. Functionalization of MWCNTs plays a critical role in improving nanotube dispersion and interfacial bonding, leading to more consistent and reliable property enhancements. The influence of processing methods and testing approaches on gear performance and durability is also examined. Overall, the reviewed studies indicate that MWCNT-reinforced PAEK composites are strong candidates for advanced polymer gear applications. However, direct gear performance evaluations under realistic operating conditions remain limited. Future research should focus on systematic gear testing, long-term durability assessment, and optimization of processing strategies to enable reliable industrial implementation of these materials.*

Keywords: *Polymer gears, High performance polymer, Carbon nanotube reinforcement, Nanocomposites, Gear performance.*

1. INTRODUCTION\

The demand for lightweight, efficient, and reliable gears for mechanical applications has increased rapidly in a wide range of applications such as automotive, aerospace mechanisms, precision instrumentation, and industrial machinery [1–4]. Modern mechanical gear systems are expected to operate at elevated speeds while maintaining low noise levels, less energy consumption, and better resistance to severe operating environments, including chemically aggressive ones. Under such demanding conditions, mechanical systems with metal gears often face performance limitations, such as high density, susceptibility to corrosion, higher frictional losses, and a more significant requirement for lubrication, which collectively contribute to increased maintenance and operational expenditures [1–4]. In response to these challenges, polymer gears have become an attractive alternative option, providing benefits such as lighter weight, lower noise, design flexibility, resistance to corrosion, and ease of manufacturing through injection molding process [5, 6]. However, the adoption of polymer gears in maximum loading conditions and high-speed applications necessitates materials with superior mechanical strength, thermal stability, and wear-resistant properties. Within this context, high-performance polymers, including Poly Ether Ether Ketone (PEEK), Poly Ether Ketone (PEK), Poly Ether Ketone Ketone (PEKK) and the PAEK polymer family have shown potential for gear systems applications due to their properties such as mechanical strength, thermal stability, wear resistance, and chemical durability [7, 8]. Nevertheless, further improvements in load-carrying capacity, heat dissipation, and wear resistance are often required to meet industrial performance requirements. The performance of this polymer material can be improved by incorporating nanofillers such as multi-walled carbon nanotubes (MWCNTs) and functionalized MWCNTs [9-11]. Functionalized MWCNTs improve uniform dispersion and stronger bonding with the polymer chains, leading to more consistent and reliable property enhancements. The following studies have shown that the stiffness,

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load transfer, thermal conductivity, and tribological performance can be improved by incorporating MWCNTs [9-11]. However, the research on advanced PAEK/MWCNT materials developments and gear-specific performance requirements remains limited, particularly the relationship between material properties, processing methods, and standard gear-testing methods is not properly addressed in the existing literature. This gap restricts the effective translation of advanced nanocomposite materials into practical industrial gear applications. This review addresses this gap by bringing together existing studies on high-performance polymer composites for gear applications, with a particular focus on PAEK-based polymer materials reinforced with pristine and functionalized MWCNT nano-materials. This article reviews material developments, reinforcement effects, manufacturing techniques, performance evaluation parameters, and recognized gear-testing methodologies for polymer gears in a well-structured manner. The sequence of topics covered in this review is presented below: Section 2 presents Requirements and Limitations of Materials for Gear Applications; Section 3 outlines the significance of polymer composites; Sections 4 to 8 includes detailed advancements in high-performance polymers, PAEK/MWCNT composites, and their mechanical, thermal, and tribological attributes, gear testing methods, and performance parameters; and Section 9 provides concluding insights and future research directions.

2. REQUIREMENTS AND LIMITATIONS OF MATERIALS FOR GEAR APPLICATIONS

The operation of mechanical systems depends on the material's ability to sustain mechanical loading conditions, thermal stability, and tribological stresses encountered during operation. Therefore, the selection of a material is important for ensuring durability, efficiency, and stable performance in automotive, aerospace, and industrial applications (12). Gears must fulfill multiple functional demands. However, both traditional and polymer materials also possess inherent performance constraints.

A clear understanding of the requirements such as material limitations and functional requirements is essential for the effective development and wider adoption of high-performance polymers and composite materials in gear applications.

2.1. Requirements for Gear Materials

- Mechanical properties: The high contact stresses, endurance, repeated loading cycles, and continuous tooth engagement without failure are the conditions required for gear materials for industrial applications (12). Adequate strength, stiffness, and resistance to fatigue are the qualities required to maintain the dimensional stability and for efficient torque transmission. Long-term operation can be affected by surface fatigue, permanent deformation, or tooth breakage if these material properties are lacking.
- Weight reduction: Weight reduction remains a major parameter in many industrial applications such as automotive and aerospace applications (13, 14). The use of lightweight materials such as advanced polymer materials and polymer composite materials lowers inertial loads, energy efficiency, and contributes to superior performance of mechanical systems having gears. These materials have high strength-to-weight ratios properties. Because of this property, these materials present viable alternatives to conventional metallic components.
- Corrosion and chemical resistance: Metallic gears are susceptible to corrosion and material degradation in corrosive environments. In contrast, polymer composite gears exhibit superior resistance to corrosion and chemical environments, which improves durability, extends service life, and reduces maintenance requirements (1, 3, 4).
- Noise and vibration damping: The reduced noise and vibration during gear operations can be achieved due to damping characteristics of polymer composite materials, which is particularly required in many applications that require smooth and quiet operation (3, 15).
- Design and manufacturing flexibility: Polymers and polymer composites offer better design flexibility. Such capability makes manufacturing processes simple and supports the lightweight production. Also, gear designs as per applications that are well suited for large-scale manufacturing is possible due to design and manufacturing flexibility characteristics of polymer materials (10, 16).

2.2. Limitations and Challenges of Gear Materials

- Wear and friction behavior: Many polymers and their composites showed higher wear rates or friction coefficients compared to metals under certain operating conditions (17, 18). To ensure long service operating conditions,

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especially at high speeds as well as loading conditions, better tribological behavior is necessary.

- Thermal and dimensional stability: Gears frequently experience temperature rises due to frictional heating during operation. This rise in temperatures of gears can affect the dimensional stability and mechanical performance of these polymer gears (19). This issue particularly observed in polymers having low glass transition temperatures. High-performance polymers such as PEEK and PAEK partially address these issues at high operating temperatures, but it will resolve by adding nanomaterials for enhancement of thermal properties of these materials (20).
- Fatigue resistance and durability: Resistant to cyclic loading prevents the fatigue wear, crack initiation, and eventual failure. Presently, the ability of fatigue resistance compared to metallic gears remains a challenge for many polymer materials used for high operating conditions such as load and speeds (19, 21).
- Processing challenges: There is difficulty in manufacturing components with polymer composites with uniform filler dispersion, desired crystallinity, and minimal defects. These factors i.e. uniform dispersibility of fillers without defects and desired crystallinity strongly influence gear wear resistance, surface finish, and mechanical strength and stability (16, 22)."

3. SIGNIFICANCE OF POLYMER COMPOSITES FOR GEAR APPLICATIONS

The limitations and challenges discussed in Section 2.2, particularly the weight reduction, low noise, improved corrosion resistance, and material stability and strength under different operating conditions, have attracted interest towards the study of polymer materials for polymer and composite gears applications (23). Polymers and polymer composites having advantages such as low density, desirable damping properties, and compatibility with molding-based manufacturing processes make them suitable for applications requiring low noise, geometric flexibility, and high strength. However, many conventional engineering polymers, including polyamides, polypropylene, epoxy, and PMMA, showed issues related to high load or high temperature gear environments due to limitations in strength, thermal endurance, and wear behavior (24). These challenges have increased the interest in high-performance polymers such as PEEK, PEK, PEKK, and particularly the PAEK family, which has mechanical strength, excellent thermal and dimensional stability during mechanical loading operations (24). The superior wear resistance and chemical stability characteristics of these polymers make them strong candidates for gear applications where frictional heating, cyclic stresses, and environmental exposure can cause problems to lower-grade polymers with minimum strength and thermal instability. Due to their performance characteristics, such polymers are increasingly used in demanding automotive, aerospace, and industrial applications where gears are used (24). The performance of these high-performance polymers is enhanced by reinforcing different nanofillers such as MWCNTs, graphene, etc. Many existing studies have shown that incorporating MWCNTs into polymer matrices improves stiffness, tensile properties, thermal conductivity, and tribological behavior [25, 26]. The main finding from the existing literature is that functionalized MWCNTs such as carboxylate or amine functionalized nanotubes exhibit superior dispersion and stronger interfacial interactions with high-performance matrix polymer materials. As a result, polymer composites reinforced with functionalized MWCNTs are effective for load transfer and superior wear resistance [27, 28]. These enhancements directly overcome the limitations of main polymer gears such as excessive wear, less stiffness, and dimensional instability under repeated cyclic operating conditions. Based on the literature studies, PAEK-based nanocomposites reinforced with pristine and/or functionalized MWCNTs represent one of the best alternative materials for high-load, high-temperature gear applications. Their ability to have low weight with high strength, improved thermal stability, and less wear make them suitable for operational requirements of advanced gear systems. The explanation of materials in detail, including their mechanical, thermal, and tribological characteristics related to the performance requirements of polymer gears is presented in further sections."

4. STUDIES ON HIGH PERFORMANCE PAEK POLYMERS FOR GEAR APPLICATIONS

The shift from conventional polymers to high-performance polymer mechanical systems has become essential for overcoming the operational challenges faced by modern gear mechanisms. While the performance of general engineering

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polymers such as polyamides, polyoxymethylene (POM), polypropylene (PP) and epoxy used for gear applications, their performance is comparatively limited under high loads, high temperatures, and continuous meshing cycles. This has resulted in growing interest in high-performance polymers, particularly in the PAEK polymer family. This polymer family includes PEEK, PEK, and PEKK polymer materials. These materials exhibit superior performance because of their exceptional strength, thermal stability, wear, and chemical resistance. All of these properties are important for demanding gear industrial applications.

4.1. Importance of High-Performance Polymers for Gear Systems

High-performance polymers provide exceptional mechanical and thermal properties compared to other engineering polymer materials. The high-performance materials such as PEEK, PEK, and PEKK showed higher tensile strength, improved modulus, and better resistance to creep and fatigue properties, which is very important for gear teeth subjected to fluctuating loads, impact stresses, and frictional heating during meshing and continuous running operation [29]. Their semi-crystalline morphological nature exhibits excellent dimensional stability, allowing gears to maintain tooth profile and load distribution throughout the gears at high operating conditions such as high loads and speeds [19, 29]. Moreover, their elevated glass transition and melting temperatures, these high-performance polymers outperform at high-temperature operating environments where general polymers may soften, deform, or undergo excessive wear. Their resistance to chemicals, lubricants, and thermal degradation further extends their life in corrosive and humid conditions, making the high-performance polymers suitable for advanced gear applications.

4.2. PAEK as the Leading Candidate for Gear Applications

Among high-performance polymers, PAEK polymer has superior mechanical, thermal, and tribological characteristics. PAEK polymer has a rigid aromatic backbone chain with alternating ether and ketone linkages, which provides high stiffness, better high-temperature stability, and improved resistance to thermal degradation [30, 31]. These attributes make PAEK polymer material very suitable for gear systems that must endure continuous meshing, high contact stresses, and heating due to friction. The previous studies have shown that PAEK maintains excellent structural integrity even under severe loading and thermal conditions. It outperforms many other high-performance polymers in terms of fatigue strength, chemical resistance, and long-term durability [32]. The gears manufactured with PAEK-based nanocomposite materials also exhibit lower wear rates compared to unreinforced PAEK polymers, making them ideal material for power-dense, high-precision gear systems in the different areas such as aerospace, automotive transmissions, and advanced industrial machinery [23, 33].

4.3. Enhancing PAEK Performance through Reinforcements

Although PAEK already exhibits excellent mechanical, thermal, and tribological properties, additional improvements are often required to satisfy the demanding performance requirements of advanced gear applications. As a result, the research has therefore focused on reinforcement of micro and nano scale fillers, solid lubricants, and high-performance nanomaterials into PAEK polymer material. The relevant studies are discussed below.
Ceramic fillers and solid lubricants: Fillers such as hexagonal boron nitride (hBN), mica, graphite, and silica have been incorporated into PAEK. These studies showed better hardness, reduced friction, and improved wear resistance. Also, mica-filled PAEK composites exhibit increased tensile modulus and improved frictional performance, while hBN additions contribute to superior tribological performance under high-pressure sliding conditions [7, 33, 34]. Similarly, graphite and thermo graphite showed effectively reduced wear and improved lubrication characteristics of PAEK composites, especially under dry sliding conditions [33, 34, 35].
Nanofillers such as MWCNTs: The incorporation of MWCNTs has become one of the most effective reinforcement methodologies for PAEK polymer material. MWCNTs provide significant improvements in stiffness, tensile strength, and thermal conductivity due to their exceptional mechanical properties and high aspect ratio. The existing studies on PAEK/MWCNT and PAEK/functionalized-MWCNT nanocomposites have reported the significant enhancements in mechanical properties, dynamic mechanical stability in different systems, and resistance to thermal degradation [36]. Functionalized MWCNTs make superior interfacial bonding with the PAEK matrix, resulting in more effective load transfer and reduced agglomeration of fillers

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than unmodified MWCNTs [20, 26, 33]. These improvements in these polymer materials are helpful for minimize the gear failure modes such as wear, thermal softening, and deformation under loading conditions.

Hybrid reinforcement systems: Hybrid composite polymer materials including MWCNTs with fillers such as boron carbide (B_4C) showed synergistic improvements in mechanical strength, thermal stability, fatigue resistance, and even radiation resistance [37, 38]. Because of these improved properties of materials, such hybrid reinforced PAEK-based polymer materials useful for different environments, including aerospace and nuclear sectors, where gears must maintain the required performance over long service periods [39].

4.4. Relevance to Gear Applications

The existing studies indicate that PAEK-based polymer composites come out one of the best materials for advanced gear applications. The ability to withstand high load-bearing capacity, thermal stability, resistance to moisture and chemicals, and excellent wear-resistant performance meets the required operating conditions of gears such as cyclic stress, frictional heating, and long-duration service [40]. When reinforced with optimized fillers, mainly functionalized MWCNTs, PAEK polymer composite materials exhibit additional performance gains that translate into higher mechanical durability, lower wear rates, and more consistent gear operation under demanding conditions. [41, 42]. Thus, PAEKs are advantageous materials that overcome the limitations of conventional polymers and provide a strategy for developing advanced lightweight, high-performance gears capable of operating in industrial and automotive environments as per requirements.

5. ENHANCING PAEKS WITH MWCNTS

The reinforcement of Multi-walled Carbon Nanotubes (MWCNTs) into Polyaryletherketone (PAEK) matrix material is one of the best methods to produce an engineering high-performance polymer composite for gear applications in industry. PAEK polymers have exceptional mechanical strength, thermal stability, and chemical resistance. However, the operational conditions requirements of gears, such as repeated cyclic loading, frictional heating, and wear during sliding contact, require further improvement in material properties. These required high mechanical, thermal, and tribological properties can be achieved by reinforcing nanomaterials into PAEK polymer.

MWCNTs nanomaterials have remarkable tensile strength, high modulus, and superior thermal conductivity, providing improvements in stiffness, durability, heat dissipation, and wear resistance when incorporated into PAEK polymer material [43, 44]. The high aspect ratio of MWCNTs provides efficient stress transfer, while the nanotube network improves thermal conduction, reducing temperature buildup during meshing. These combined effects of MWCNT-reinforced PAEK composites make them a highly promising material for lightweight, durable, and reliable industrial applications such as gear systems [45, 46]. The reinforcement process and performance improvements are summarized conceptually in Fig. 1. It illustrates the relationships between MWCNT functionalization, dispersion quality, matrix bonding, and enhancements in mechanical, thermal, and tribological behavior.

6. MWCNT-REINFORCED PAEK NANO-COMPOSITES

6.1. The Role of MWCNTs in Polymer Composites

Multi-Wall Carbon Nanotubes (MWCNTs) contribute significant improvements to polymer composites by increasing their load-carrying capacity, stiffness, and thermal stability. Due to their extremely high tensile strength and modulus, MWCNTs enhance the rigidity of the entire polymer composite material, improving resistance to fatigue and deformation. The good thermal conductivity of MWCNTs also helps minimize heat from the gear tooth contact region, which reduces softening of gear teeth or thermal degradation of teeth and ensures stable performance during continuous gear meshing operations. Many polymer materials such as epoxy, polyamide, and phenolic resins have demonstrated considerable rises in mechanical strength, impact resistance, and dynamic mechanical properties after reinforcement with MWCNTs [10, 11, 47–51]. These reinforcing mechanisms are applicable to PAEK matrices, making MWCNTs highly suitable for the development of gears for advanced and high-performance applications where load and speeds are essential factors [52].

6.2. The Critical Need for Functionalization

To achieve effective reinforcement from MWCNTs into PAEK matrix polymer material, uniform nanotube dispersion and strong interfacial bonding between the polymer matrix and the nanotubes are essential during this process.

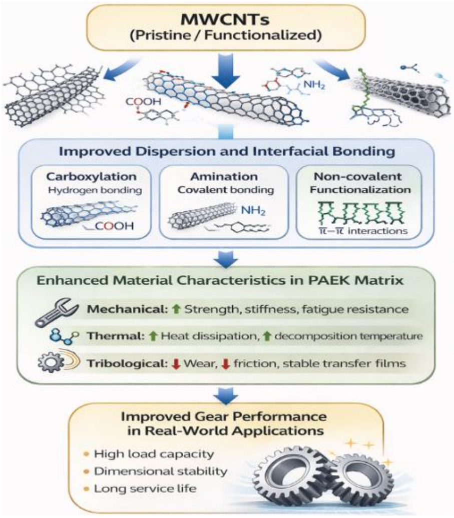

Fig. 1. Conceptual diagram illustrating reinforcement mechanisms of MWCNTs in PAEK composites for gear applications

Prristine nanotubes tend to cluster together and have poor chemical affinity with PAEK polymer chains, which reduces their reinforcing efficiency and the strengths of composite materials. The aforementioned issues are overcome by surface functionalization of MWCNTs, improving compatibility, dispersion, and interfacial interaction with the polymer matrix. There are different functionalization processes discussed below:

- Carboxyl-functionalised MWCNTs (–COOH) disperse more evenly within the polymer and enable hydrogen bonding, which improves tensile strength and thermal stability [53–55].
- Amine-functionalised MWCNTs (–NH_2) can form covalent bonds with polymer chains, resulting in notable improvements in dynamic mechanical behavior and fatigue resistance compared to carboxylic functionalization [56–58].
- Non-covalent functionalization has been shown to enhance polymer–nanotube compatibility without damaging the intrinsic structure of the nanotubes, as reported for CNT/PEEK systems [8]. Overall, nanotube functionalization plays a crucial role in producing PAEK/MWCNTs-based composites with high strength and durability.

6.3. Processing Techniques for MWCNT/PAEK Nanocomposites

The method employed for processing MWCNT/PAEK nanocomposite preparation plays a major role in deciding their final structure and performance. Because MWCNTs naturally tend to agglomerate due to strong van der Waals forces, achieving their uniform distribution in the highly viscous PAEK melt is difficult. Therefore, an effective processing methodology should provide sufficient shear to break up nanotube clusters, ensuring even dispersion throughout the polymer matrix and making strong interfacial interaction between the nanotubes and the PAEK chains.

The melt-processing methods, such as twin-screw extrusion and melt blending are generally used to disperse MWCNTs within the PAEK matrix polymer material. To break the nanotube agglomerates, improve polymer wetting, and strengthen the interaction at the polymer–nanotube interface, the strong shear forces generated during these processes [59, 60] help. Melt blending also provides a well-controlled thermal and mechanical environment, which maintains the structural integrity of the nanotubes with its uniform microstructure. In many studies, MWCNTs have been observed to act as nucleating agents, leading to increased crystallinity of PAEK. This increase in crystallinity improves the stiffness, better thermal resistance, and dimensional stability, which are important characteristics for gear-assisted mechanical systems [36].

After the melt compounding method, injection molding is widely used to shape the nanocomposite into required test samples or actual components. The shear forces applied during mould filling help to improve nanotube dispersion, while controlled cooling process reduces porosity and makes a more uniform internal structure. For polymer gear applications, injection molding is more advantageous because it produces more accurate tooth profiles,

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close dimensional control, and uniform microstructural quality. All of these parameters play an important role in improving wear behavior and long-term mechanical reliability [61].

Compression moulding and hot pressing are also used to densify the nanocomposite, minimize voids, and improve overall material compactness. The controlled application of heat and pressure during these methods can promote partial alignment of nanotubes, hence, it enhances stiffness and thermal conductivity. Such improvements are particularly useful for gear manufacturing processes, exposed to local heating and repeated contact stresses. As a result, better load-sharing capability and heat dissipation can significantly extend service life of gears [38, 43].

The processing conditions such as temperature, shear rate, and residence time are the key factors to obtain the optimum properties of composite materials. These factors directly affect nanotube integrity, dispersion, and interfacial bonding. Excessively high shear can damage or shorten nanotubes, whereas insufficient shear results in poor dispersion and agglomeration. Similarly, inadequate temperature control can cause the polymer degradation or incomplete mixing. Therefore, achieving well-balanced processing conditions is very important for producing MWCNT/PAEK nanocomposites with the mechanical, thermal, and tribological performance required for high-performance gear applications [62].

6.4. Resulting Mechanical, Thermal, and Tribological Properties

The addition of MWCNTs to PAEK matrices made improvements in the overall performance of the composite material by modifying its deformation behavior, heat transfer capability, and friction and wear performance. These improvements are mainly observed because of stronger interfacial bonding, efficient load transfer from the polymer to the nanotubes, restricted movement of polymer chains, enhanced crystallinity, and the formation of protective transfer films during sliding conditions. Collectively, these effects help effectively reduce common failure problems found in polymer gears such as progressive wear, thermal softening, tooth distortion, and cracking due to fatigue [63, 64].

Mechanical performance enhancements: The incorporation of MWCNTs showed an increase in tensile strength, elastic modulus, micro-hardness, and fatigue resistance of PAEK composites. These improvements are observed mainly due to the high aspect ratio and stiffness of the nanotubes, which allow effective load transfer when they are uniformly dispersed in the matrix. Strong interfacial bonding, especially in composites with functionalized MWCNTs, promotes more uniform stress distribution and delays the onset of crack formation. Moreover, the nanotubes restrict crack propagation by acting as physical barriers, thereby improving fracture resistance and better durability under repeated loading conditions. These enhancements in mechanical performance are important for gear teeth, which are continuously subjected to bending stresses and high contact forces during operation [8].

Thermal performance enhancements: MWCNTs possess very good thermal conductivity. Hence, their addition in PAEK considerably improves heat dissipation within the composite material. Better heat transfer helps lower build-up temperature at the gear tooth contact region, thereby reducing softening due to frictional temperature and thermo-mechanical damage. PAEK/MWCNT composites also exhibit higher thermal decomposition temperatures and better stability during repeated heating and cooling cycles. In addition, nanotubes often act as nucleating agents, leading to increased crystallinity in the polymer matrix. This increases thermal stability and helps maintain dimensional integrity at high operating temperatures [19, 20, 32, 33].

Tribological Performance Enhancements: Under sliding or rolling during operation, PAEK/MWCNTs composite material showed a noticeable reduction in friction coefficient and wear rate than the unreinforced PAEK polymer. These improvements arise due to several contributing mechanisms. During sliding operation, the presence of MWCNTs promotes the formation of a thin and stable transfer film on the contact surface, reducing direct contact between surface asperities. Also, the rigid nanotube network improves the load-carrying ability of the composite by increasing local hardness, thereby reducing surface deformation and micro-cutting or cracking. Also, stronger interfacial bonding between the polymer matrix and nanotubes reduces polymer chain pull-out, helping in reducing debris formation and adhesive wear. Finally, the enhanced thermal conductivity provided by MWCNTs minimizes frictional heat build-up at the contact surface, reducing the temperature-driven wear mechanisms.

These tribological benefits are particularly important for polymer gears, which often operate under dry, lubricated, or marginal lubrication conditions,

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where control of friction and wear parameters is important for reliable performance [19, 21, 31]. These improvements are summarized in Table 1.

Also, Table 2 summarizes key published studies on PAEK/MWCNT nanocomposites, highlighting the influence of nanotube functionalization and processing methods on property enhancements and their relevance to gear applications.

PAEK/MWCNT composites show very good structural and thermal stability under demanding service conditions, making them suitable for advanced engineering applications. The high aspect ratio and stiffness of MWCNTs create an interconnected nanoscale network within the polymer matrix material, which effectively restricts the movement of polymer chains within their structure. This restriction increases crystallinity and reduces thermal deformation, improving dimensional stability, creep resistance, and stress relaxation behavior at high temperatures. These properties are important for polymer gears to maintain accurate tooth geometry and load-carrying ability during cyclic loading and frictional heating operating conditions. Hybrid composites made of MWCNTs with ceramic micro-fillers, such as boron carbide (B_4C), have been reported to exhibit additional remarkable benefits, including improved thermal resistance, higher modulus, better oxidative stability, and in some cases enhanced radiation tolerance. As a result, the application range of these materials can be extended to demanding areas such as aerospace, nuclear technology, and industrial operations with considerable speed, load, and temperature [32, 38]. In addition, the nanotube network improves thermal conductivity, allowing more efficient removal of heat generation at the gear meshing zone. This reduces local temperature rise and helps to prevent progressive wear, softening, and material degradation in polymer components. Despite these developments, studies that directly evaluate the performance of PAEK/MWCNT composites at the gear level are still limited. Most of the existing studies are on bulk mechanical, thermal, or tribological properties rather than parameters that directly control the gear behavior [38]. Important aspects such as contact fatigue life, tooth deformation under dynamic loading, resistance to scuffing and pitting, and temperature rise at the gear meshing have not yet been examined in sufficient detail for these nanocomposite materials.

Table 1. Summary of property enhancements in MWCNT-reinforced PAEK nanocomposites

Property category	Observed improvements	Representative references
Mechanical	Increase in tensile strength, modulus, micro-hardness, fatigue resistance, and dynamic mechanical stability.	[20, 26, 60, 65]
Thermal	Increase in thermal conductivity, higher decomposition temperature, and enhanced thermal stability under cyclic loading.	[20, 22, 65]
Tribological	Reduction in friction coefficient and wear rate; improved surface durability; formation of protective transfer films.	[28, 33, 65, 66]

Table 2. Summary of key studies on PAEK/MWCNT nanocomposites relevant to gear applications

Base polymer	MWCNT type/ functionalization	Processing method	Key property improvements	Potential gear relevance	References
PAEK	Pristine MWCNT	Melt blending + compression moulding	Increased tensile strength, modulus, and thermal stability	Improved load-bearing capacity for polymer gears	[20]
PAEK	COOH-functionalized MWCNT	Twin-screw extrusion + injection moulding	Enhanced dispersion, improved fatigue resistance, reduced wear rate	High-speed gears with improved durability	[32]
PAEK	NH_2-functionalised MWCNT	Melt mixing + hot pressing	Strong interfacial bonding, higher dynamic mechanical stability	Gears under cyclic loading and vibration	[56–58]
PAEK	Pristine + functionalised MWCNT	Melt compounding	Improved thermal conductivity, reduced friction coefficient	Reduced thermal softening in gear meshing zone	[26, 33]
PAEK	MWCNT + B_4C (hybrid system)	Melt blending + compression moulding	Synergistic improvement in stiffness, wear resistance, and thermal stability	Heavy-duty gears for high-temperature environments	[37, 38]

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Furthermore, long-term tribo-mechanical studies that closely simulate real operating conditions, including varying torque, high rotational speeds, different lubrication regimes, and repeated thermal cycling, are relatively limited [67, 68]. Addressing this research gap is important to translate the promising material-level advantages of PAEK/MWCNT composites into reliable, high-performance gear components. Future investigations should therefore focus on gear-level testing, including advanced wear and fatigue modeling, to fully validate and utilize the applicability of MWCNT-reinforced PAEKs in demanding mechanical applications."

A thorough assessment of gear behavior is necessary to determine whether PAEK/MWCNT composites are suitable for practical operations. Standard mechanical, thermal, and tribological testing methods are commonly used to assess the performance of it under controlled loads and rotational speeds. Wear and friction tests using pin-on-disc experimentation, block-on-ring, and specialized gear test rigs are used for experimentation of mass loss, wear rate, changes in surface roughness, and friction behavior [28, 33, 34]. These parameters are particularly important for polymer gears that operate under dry or lubrication conditions. Infrared (IR) thermography is widely used to measure the temperature at the gear teeth contact surface. This technique provides information about the material's ability to dissipate friction-generated heat during operation [37, 38]. Dimensional stability and accuracy of the gear tooth profile are assessed by using three-dimensional profilometry and coordinate measuring systems to ensure that the required geometry for proper meshing is retained. Fatigue and durability tests simulate repeated loading cycles, enabling evaluation of crack initiation, crack growth behavior, and long-term resistance to mechanical stress. Together, these testing methods provide a detailed understanding of the mechanical reliability, thermal stability, and tribological performance of PAEK/MWCNT gears under operating conditions."

The performance results obtained from the testing methods discussed in Section 8, including wear behavior, coefficient of friction, temperature increase, deformation, and fatigue life, are closely governed by the improvements introduced through MWCNT reinforcement in the material. Clearly relating these test results to the underlying material properties helps in better understanding how enhancements at the nanoscale are reflected in the overall performance of gear systems. Wear rate and surface durability: The marked decrease in wear rate noted during tribological tests can be directly related to the increase in stiffness, micro-hardness, and stronger interfacial bonding reported for MWCNT-reinforced PAEK materials (Section 6.4). These improvements are mainly due to effective stress transfer between the matrix and the nanotubes and a reduction in surface deformation during sliding. Similar behavior has been reported in earlier studies on CNT-filled polymer systems, where lower wear and improved long-term durability were consistently observed [28, 33, 34]. Coefficient of friction: The reduced friction coefficients recorded during sliding tests are mainly due to the formation of stable lubricating transfer layers and the enhanced load-carrying capacity provided by nanotube reinforcement. Earlier studies have also shown that CNT-based composites display lower friction because they promote the formation of uniform tribo-films and reduce adhesive contact between the mating surfaces [33, 34]. Surface temperature rise: The surface temperature was recorded using a non-contact measurement technique. Better heat dissipation helps in reducing thermal softening and postpones the initiation of wear mechanisms driven by high temperature. This behavior is consistent with earlier studies that report on CNT-reinforced PAEK systems, where improved thermal stability has shown to play a key role in controlling temperature-related wear effects [33, 68–70]. Tooth deformation and fatigue behavior: Mechanical testing showed that PAEK/MWCNT gears experience lower tooth deformation and exhibit better fatigue life. These improvements are directly linked to the higher elastic modulus, increased crystallinity, and restricted polymer chain movement introduced by the addition of nanotubes. Similar findings have been reported in previous studies on CNT-reinforced polymer composites, where improved resistance to cyclic loading and enhanced fatigue performances are observed [20, 26, 28]. Noise and vibration characteristics: The increase in structural stiffness with reduced variations in friction produces lower vibration and noise during gear operation. This behavior aligns well with earlier studies that have reported improvements in dynamic mechanical properties and damping characteristics due to the incorporation of CNTs in polymer systems [71–73]."

7. CONCLUSIONS

This review has presented the latest developments

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in polymer composite materials for gear applications, with a focus on high-performance PAEK-based systems reinforced with MWCNTs nanomaterial. The discussion showed that PAEK polymers provide excellent mechanical strength, thermal stability, wear resistance, and chemical durability, which are required properties for gears operating under cyclic loading conditions and frictional heating environments. The incorporation of MWCNTs and particularly functionalized MWCNTs further improves load transfer, wear behavior, thermal conductivity, and fatigue resistance. The review highlights that processing methods play an important role in achieving these improvements, as uniform nanotube dispersion and strong interfacial bonding are necessary for consistent performance. Although substantial progress has been made in improving bulk material properties, direct evaluation of gear-level behavior remains limited. Key parameters such as contact fatigue, tooth deformation, meshing temperature, and long-term durability under realistic operating conditions including different loads, speeds, and temperatures still need further investigation. Overall, MWCNT-reinforced PAEK composites emerge as strong candidates for advanced gear applications due to their remarkable mechanical and thermal performance. Future research should focus on systematic gear-level testing and durability assessment to ensure their reliable application in practical engineering systems."

REFERENCES

[1] Wu, J., Wei, P., Zhu, C., Zhang, P., Liu, H., Development and application of high strength gears, Int. J. Adv. Manuf. Technol., 2024, 132, 3123–3148.

[2] Boral, P., Gołębski, R., Kralikova, R., Technological aspects of manufacturing and control of gears Review, Materials, 2023, 16, 7453–7468.

[3] Walton, D., Goodwin, A.J., The wear of unlubricated metallic spur gears, Wear, 1998, 214, 245–252.

[4] Davies, D.P., Gittos, B.C., Gear steels for future helicopter transmissions, Proc. Inst. Mech. Eng. G – J. Aerosp. Eng., 1989, 203, 113–121.

[5] Senthilvelan, S., Gnanamoorthy, R., Effect of rotational speed on the performance of unreinforced and glass fiber reinforced nylon 6 spur gears, Mater. Des., 2007, 28, 765–772.

[6] Reitschuster, S., Illenberger, C.M., Tobie, T., Stahl, K., Application of high-performance polymer gears in light urban electric vehicle powertrains, Forsch. Ingenieurwes., 2022, 86, 683–691.

[7] Joshi, M.D., Goyal, A., Patil, S.M., Goyal, R.K., Tribological and thermal properties of hexagonal boron nitride filled high-performance polymer nanocomposites, J. Appl. Polym. Sci., 2017, 134, 44409–44418.

[8] Rong, C., Ma, G., Zhang, L., Song, Z., Chen, Z., Wang, G., Ajayan, P.M., Effect of carbon nanotubes on the mechanical properties and crystallization behaviour of poly (ether ether ketone), Compos. Sci. Technol., 2010, 70, 380–386.

[9] Pantano, A., Modica, G., Cappello, F., Multiwalled carbon nanotube reinforced polymer composites, Mater. Sci. Eng. A, 2008, 486, 222–227.

[10] Zhou, C., Wang, S., Zhuang, Q., Han, Z., Enhanced conductivity in polybenzoxazoles doped with carboxylated multi-walled carbon nanotubes, Carbon, 2008, 46, 1232–1240.

[11] Hosur, M.V., Rahman, T., Brundidge-Young, S., Jeelani, S., Mechanical and thermal properties of amine functionalized multi-walled carbon nanotube epoxy-based nano-composites, Compos. Interfaces, 2010, 17, 197–215.

[12] Srimurugan, R., Ramnath, B.V., Ramanan, N., Elanchezhian, C., Study on mechanical and metallurgical properties of glass fibre reinforced PMC gear materials, Mater. Today Proc., 2019, 18, 3250–3257.

[13] Mao, K., A new approach for polymer gear life prediction considering wear, Wear, 2007, 262, 432–441.

[14] Senthilvelan, S., Gnanamoorthy, R., Effect of rotational speed on the performance of unreinforced and glass fiber reinforced nylon 6 spur gears, Mater. Des., 2007, 28, 765–772.

[15] Hou, X., Hu, Y., Hu, X., Jiang, D., Poly (ether ether ketone) composites reinforced by graphene oxide and silicon dioxide nanoparticles: Mechanical properties and sliding wear behavior, High Perform. Polym., 2018, 30, 406–417.

[16] Chen, J., Liu, B., Gao, X., Xu, D., A review of the interfacial characteristics of polymer

[DOI: 10.22068/ijmse.3474]

nanocomposites containing carbon nanotubes, RSC Adv., 2018, 8, 28048–28085.

[17] Mao, K., Chetwynd, D.G., Milson, M., A new method for testing polymer gear wear rate and performance, Polym. Test., 2020, 82, 106323–106330.

[18] Patil, S.S., Karuppanan, S., Evaluation of the effect of friction in gear contact stresses, Lect. Notes Mech. Eng., 2020, 1, 227–242.

[19] Kalin, M., Kupec, A., The dominant effect of temperature on the fatigue behaviour of polymer gears, Wear, 2017, 376–377, 1339–1346.

[20] Remanan, M., Rao, R.S., Bhowmik, S., Varshney, L., Abraham, M., Jayanarayanan, K., Hybrid nanocomposites based on polyaryl ether ketone, boron carbide and multi-walled carbon nanotubes: Evaluation of tensile, dynamic mechanical and thermal degradation properties, e-Polymers, 2016, 16, 493–503.

[21] Herzog, C., Wolf, M., Schubert, D., Drummer, D., In situ investigation of the influence of varying load conditions on tooth deformation and wear of polymer gears, Forsch. Ingenieurwes., 2022, 86, 545–555.

[22] Dhajekar, R.M., Jogi, B.F., Nirantar, S.R., Preparation and characterization of PAEK-based polymer nanocomposites in the presence of MMT clay as nanofiller to study tensile and impact properties, Mater. Today, Proc., 2018, 5, 2214–2220.

[23] Attar, M.A., Development and wear analysis of poly (aryl ether ketone) spur gear, Int. J. Res. Appl. Sci. Eng. Technol., 2021, 9, 38–50.

[24] Peng, C., Recent advances on high-performance polyaryletherketone materials for additive manufacturing, Adv. Mater., 2022, 34, 2200123–2200135.

[25] Shivamurthy, B., Murthy, K., Anandhan, S., Tribology and mechanical properties of carbon fabric/MWCNT/epoxy composites, Adv. Tribol., 2018, 2018, 1508145–1508156.

[26] Kulthe, M.G., Goyal, R.K., Butee, S.P., Creep, recovery and dynamic mechanical properties of PEK/MWCNT nanocomposites, Mater. Sci. Eng. B, 2022, 282, 115752–115760.

[27] Ravindran, L., Sreekala, M.S., Anilkumar, S., Thomas, S., Effect of MWCNT carboxylation on mechanical, thermal and morphological behaviour of phenol formaldehyde nano-composites, J. Compos. Mater., 2021, 55, 1151–1166.

[28] Patel, V., Joshi, U., Joshi, A., Oza, A.D., Prakash, C., Linul, E., Campilho, R.D.S.G., Kumar, S., Saxena, K.K., Strength evaluation of functionalized MWCNT-reinforced polymer nanocomposites synthesized using a 3D mixing approach, Materials, 2022, 15, 7263–7278.

[29] Gan, D., Lu, S., Song, C., Wang, Z., Mechanical properties and frictional behavior of a mica-filled poly (aryl ether ketone) composite, Eur. Polym. J., 2001, 37, 1359–1365.

[30] Padhan, M., Marathe, U., Bijwe, J., Tribology of poly (ether ketone) composites based on nano-particles of solid lubricants, Compos. B Eng., 2020, 201, 108323–108331.

[31] Zhang, Y., Sun, X., Niu, Y., Xu, R., Wang, G., Jiang, Z., Synthesis and characterization of novel poly (aryl ether ketone) s with metallophthalocyanine pendant unit from a new bisphenol containing dicyanophenyl side group, Polymer, 2006, 47, 1569–1574.

[32] Remanan, M., Kannan, M., Rao, R.S., Bhowmik, S., Varshney, L., Abraham, M., Jayanarayanan, K., Microstructure development, wear characteristics and kinetics of thermal decomposition of hybrid nanocomposites based on polyaryl ether ketone, boron carbide and multi-walled carbon nanotubes, J. Inorg. Organomet. Polym. Mater., 2017, 27, 1649–1663.

[33] Panda, J.N., Bijwe, J., Pandey, R.K., Attaining high tribo-performance of PAEK composites by selecting the right combination of solid lubricants in appropriate proportions, Compos. Sci. Technol., 2017, 144, 139–150.

[34] Panda, J.N., Bijwe, J., Pandey, R.K., Variation in size of graphite particles and its cascading effect on the performance properties of PAEK composites, Compos. B Eng., 2020, 182, 107641–107649.

[35] Panda, J.N., Bijwe, J., Pandey, R.K., Role of micro- and nano-particles of hBN as a secondary solid lubricant for improving tribo-potential of PAEK composite, Tribol. Int., 2019, 130, 400–412.

[36] Goyal, R.K., Tiwari, A., Mulik, U.P., Mechanical and thermal properties of poly (ether ether ketone) nanocomposites filled with inorganic nanoparticles, Compos. Sci. Technol., 2007, 67, 1347–1354.

[37] Remanan, M., Poly (aryl ether ketone)-based individual, binary and ternary nanocomposites

[DOI: 10.22068/ijmse.3474]

for nuclear waste storage: Mechanical, rheological and thermal analysis, Mater. Res. Express, 2018, 5, 105306–105315.

[38] Li, J., Zhang, X., Song, H., Wang, Q., Synergistic effects of carbon nanotubes and ceramic particles on the tribological performance of PEEK composites, Compos. Sci. Technol., 2014, 92, 91–98.

[39] Letzelter, E., Guingand, M., De Vaujany, J.P., Schlosser, P., Experimental investigation of thermal and mechanical behaviour of polymer gears under dry running conditions, Tribol. Int., 2011, 44, 191–201.

[40] Letzelter, E., Guingand, M., De Vaujany, J.P., Schlosser, P., A new experimental approach for measuring thermal behaviour in the case of nylon 6/6 cylindrical gears, Polym. Test., 2010, 29, 1041–1051.

[41] Yildirim, A., Seçkin, T., In situ preparation of polyether amine-functionalized multi-walled carbon nanotube nanofillers as reinforcing agents, Adv. Mater. Sci. Eng., 2014, 2014, 356920–356928.

[42] Azdast, T., Hasanzadeh, R., Tensile and morphological properties of microcellular polymeric nanocomposite foams reinforced with multi-walled carbon nanotubes, Int. J. Eng. Trans. B Appl., 2018, 31, 504–510.

[43] Rhee, E., Hasanzadeh, R., Azdast, T., A multi-criteria decision analysis on injection moulding of polymeric microcellular nano-composite foams containing multi-walled carbon nanotubes, Plast. Rubber Compos., 2017, 46, 155–162.

[44] Chouit, F., Guellati, O., Boukhezar, S., Harat, A., Guerioune, M., Badi, N., Synthesis and characterization of HDPE/N-MWNT nanocomposite films, Nanoscale Res. Lett., 2014, 9, 288–295.

[45] Farrash, S.M.H., Rezaeepazhand, J., Shariati, M., Experimental study on amine-functionalized carbon nanotubes' effect on the thermomechanical properties of CNT/epoxy nanocomposites, Mech. Adv. Compos. Struct., 2018, 5, 41–48.

[46] Mittal, G., Rhee, K.Y., Mišković-Stanković, V., Hui, D., Reinforcements in multi-scale polymer composites: Processing, properties, and applications, Compos. B Eng., 2018, 138, 122–139.

[47] Hussein, S.I., Abd-Elnaiem, A.M., Asafa, T.B., Jaafar, H.I., Effect of incorporation of conductive fillers on mechanical properties and thermal conductivity of epoxy resin composites, Appl. Phys. A, 2018, 124, 475–483.

[48] Yetgin, S.H., Effect of multi-walled carbon nanotubes on mechanical, thermal and rheological properties of polypropylene, J. Mater. Res. Technol., 2019, 8, 4725–4735.

[49] Chiang, C.-H., Jahan, K., Hidayat, M., Kumar, D., Cheng, C.-C., Evaluation of mechanical properties and damage sensing performance of functionalized carbon nanotube-modified epoxy–carbon fiber composites, Proc. SPIE, 2023, 12495, 124950R–124950Z.

[50] Ravindran, L., Sreekala, M.S., Anilkumar, S., Thomas, S., Effect of MWCNT carboxylation on mechanical, thermal and morphological behaviour of phenol formaldehyde nanocomposites, J. Compos. Mater., 2021, 55, 1151–1166.

[51] Ketikis, P., Ketikis, I., Klonos, P., Giannakopoulou, T., Kyritsis, A., Trapalis, C., Tarantili, P., The effect of MWCNTs on the properties of peroxide-vulcanized ethylene propylene diene monomer composites, J. Compos. Mater., 2023, 57, 2043–2058.

[52] Jadhav, P.N., Jadhav, S.P., Comparative study of mechanical properties of multi-walled carbon nanotubes and functionalized multi-walled carbon nanotubes/polyaryl ether ketone nanocomposites, Iran. J. Mater. Sci. Eng., 2023, 20, 215–223.

[53] Liang, Q., Wang, W., Moon, K.-S., Wong, C.P., Thermal conductivity of epoxy/surface-functionalized carbon nanomaterials, Proc. IEEE Electron. Compon. Technol. Conf., 2009, 59, 460–464.

[54] Ardjmand, M., Omidi, M., Choolaei, M., Effects of functionalized multi-walled carbon nanotubes on mechanical properties of epoxy nanocomposites, Orient. J. Chem., 2015, 31, 2291–2301.

[55] Nie, P., Min, C., Song, H.J., Chen, X., Zhang, Z., Zhao, K., Preparation and tribological properties of polyimide/carboxyl-functionalized multi-walled carbon nanotube nanocomposite films under seawater lubrication, Tribol. Lett., 2015, 58, 47–58.

[56] Hong, S.H., Kim, C.K., Changes in interfacial properties between poly (butylene terephthalate) and multi-walled carbon nanotubes bonded with various functional

[DOI: 10.22068/ijmse.3474]

groups, Polymer (Korea), 2018, 42, 87–92.

[57] Qazi, R.A., Khan, M.S., Siddiq, M., Ullah, R., Shah, L.A., Ali, M., Synthesis and characterization of functionalized MWCNTs/PMMA composites for relative humidity sensing devices, Polym. -Plast. Technol. Mater., 2020, 59, 1608–1620.

[58] Kashyap, A., Singh, N.P., Arora, S., Singh, V., Gupta, V.K., Effect of amino-functionalization of multi-walled carbon nanotubes on mechanical and thermal properties of epoxy nanocomposites, Bull. Mater. Sci., 2020, 43, 102–110.

[59] Goyal, R.K., Kapadia, A.S., Phenyltri methoxysilane-treated nano-silica-filled high-performance poly (ether ether ketone) nanocomposites, Compos. B Eng., 2013, 50, 135–143.

[60] Hou, X., Hu, Y., Hu, X., Jiang, D., Poly (ether ether ketone) composites reinforced by graphene oxide and silicon dioxide nanoparticles: Mechanical properties and sliding wear behaviour, High Perform. Polym., 2018, 30, 406–417.

[61] Zhou, L., Li, C., Wu, W., Xiong, C., Gao, Z., Functionalized carbon nanotube/polyimide nanocomposites with high energy density for high-temperature dielectric materials, J. Appl. Polym. Sci., 2023, 140, e53834.

[62] Petrica, M., Duscher, B., Koch, T., Archodoulaki, V.-M., Impact of surface roughness and contact pressure on wear behaviour of PEEK, POM and PE-UHMW, Wear, 2017, 376–377, 1208–1216.

[63] Ozsoy, I., Demirkol, A., Mimaroglu, A., Unal, H., Demir, Z., Influence of micro- and nano-filler content on the mechanical properties of epoxy composites, Stroj. Vestn. – J. Mech. Eng., 2015, 61, 601–609.

[64] Sasikumar, R., Jayavel, R., Effect of NH_2-functionalized MWCNT-sprayed carbon fiber on mechanical properties of carbon fiber-reinforced polycarbonate composites, J. Compos. Mater., 2023, 57, 1847–1861.

[65] Wu, T., Mei, X., Liang, L., Peng, X., Wang, G., Zhang, S., Structure–function integrated poly (aryl ether ketone)-grafted MWCNT/poly (ether ether ketone) composites with low percolation threshold for conductivity and electromagnetic shielding, Compos. Sci. Technol., 2022, 217, 109032–109040.

[66] Patel, V., Joshi, U., Joshi, A., Matanda, B.K., Chauhan, K., Oza, A.D., Burduhos-Nergis, D.P., Multi-walled carbon nanotube-reinforced PMMA nanocomposites: Experimental investigation of friction and wear properties, Polymers, 2023, 15, 2785–2796.

[67] Choi, E.Y., Kim, S.W., Kim, C.K., In situ grafting of poly (butylene terephthalate) onto multi-walled carbon nanotubes by melt extrusion and characteristics of their composites with poly (butylene terephthalate), Compos. Sci. Technol., 2016, 132, 101–107.

[68] Demircan, Ö., Compression-after-impact properties of glass fiber/epoxy/MWCNT composites, Res. Eng. Struct. Mater., 2019, 5, 213–221.

[69] Mohammed, J.Kh., Khdir, Y.Kh., Kasab, S.Y., Contact stress analysis of spur gears under different rotational speeds using theoretical and finite element methods, Acad. J. Nawroz Univ., 2018, 7, 213–220.

[70] Rajamani, G., Paulraj, J., Krishnan, K., Analysis of wear behaviour of graphene oxide–polyamide gears for engineering applications, Surf. Rev. Lett., 2017, 24, 1850018–1850026.

[71] Yan, X., Qiao, L., Tan, H., Liu, C., Zhu, K., Lin, Z., Xu, S., Effect of carbon nanotubes on mechanical, crystallization, electrical and thermal conductivity properties of CNT/CCF/PEKK composites, Materials, 2022, 15, 4950–4962.

[72] Dabees, S., Tirth, V., Mohamed, A., Kamel, B.M., Wear performance and mechanical properties of MWCNT/HDPE nanocomposites for gearing applications, J. Mater. Res. Technol., 2021, 12, 2476–2488.

[73] Gojny, F.H., Wichmann, M.H.G., Köpke, U., Fiedler, B., Schulte, K., Carbon nanotube-reinforced epoxy composites: Enhanced stiffness and fracture toughness at low nanotube content, Compos. Sci. Technol., 2004, 64, 2363–2371.