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Original Research Article

Wear Behaviour and Biomedical Applicability of Polyether Ether Ketone (PEEK) and Its Composites for Orthopaedic Implants: A Comprehensive Review

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Abstract: The longevity of orthopaedic implants, particularly in total knee and hip replacements, is strongly influenced by the wear behaviour and biological response of bearing materials. Ultra-high molecular weight polyethylene (UHMWPE), although widely used, suffers from wear debris–induced osteolysis, leading to implant loosening and revision surgeries. Polyether ether ketone (PEEK) and its composites have emerged as promising alternatives due to their favourable mechanical properties, chemical stability, radiolucency, and biocompatibility. This review critically analyses existing experimental, in vitro, and preclinical studies on the wear performance, tribological behaviour, biological response, and manufacturing approaches of PEEK and carbon Fiber–reinforced PEEK (CFR-PEEK) for orthopaedic applications. Emphasis is placed on the influence of contact pressure, sliding velocity, reinforcement type, and counter face material on wear characteristics. Additionally, advances in additive manufacturing of patient-specific PEEK implants are discussed. The review concludes that CFR-PEEK demonstrates superior wear resistance compared to virgin PEEK and shows potential as a viable alternative to UHMWPE in selected orthopaedic applications, though long-term clinical validation remains necessary.

Keywords: PEEK, CFR-PEEK, wear behaviour, orthopaedic implants, total knee replacement, tribology, biocompatibility

INTRODUCTION

Total joint replacement procedures, particularly total knee replacement (TKR) and total hip replacement (THR), are among the most successful surgical interventions for restoring mobility and quality of life in patients suffering from degenerative joint diseases such as osteoarthritis, rheumatoid arthritis, and post-traumatic arthritis. With the continuous increase in life expectancy and the growing number of younger, more active patients undergoing joint replacement surgeries, the functional demands on orthopaedic implants have increased substantially. Consequently, implant longevity, wear resistance, and biological compatibility have become critical factors governing the long-term success of these procedures.

Despite significant advancements in implant design and material development, wear-induced failure remains one of the predominant causes of revision surgeries. Current clinical statistics indicate that a large proportion of late-stage implant failures are associated with the generation of wear debris from articulating surfaces. Ultra-high molecular weight polyethylene (UHMWPE), which is widely used as a bearing material in knee and hip prostheses, exhibits excellent toughness and biocompatibility; however, it is prone to progressive wear under cyclic loading conditions. The submicron-sized UHMWPE wear particles generated during articulation can activate macrophages, triggering inflammatory cascades that lead to osteolysis and subsequent implant loosening. This biological response to wear debris significantly limits the service life of conventional implants, especially in high-demand patients.

To mitigate these limitations, extensive research has been directed toward identifying alternative bearing materials with superior wear resistance and favourable biological responses. Metallic materials such as cobalt–chromium alloys and ceramics have been explored; however, their high elastic modulus compared to bone can induce stress shielding, leading to bone resorption and implant instability. Additionally, metal-based implants may cause imaging artifacts in computed tomography and magnetic resonance imaging, and long-term metal ion release has raised concerns regarding hypersensitivity and systemic toxicity. These drawbacks have intensified the search for polymeric biomaterials that combine mechanical reliability with biological safety.

Polyether ether ketone (PEEK) has emerged as a promising high-performance thermoplastic polymer for orthopaedic applications due to its excellent mechanical strength, chemical inertness, radiolucency, and resistance to thermal and radiation-induced degradation. Importantly, the elastic modulus of PEEK is closer to that of cortical bone when compared to metallic biomaterials, which reduces the risk of stress shielding and promotes more uniform load transfer at the bone–implant interface. PEEK has been successfully employed in spinal cages, trauma fixation devices, and craniofacial implants, demonstrating good clinical acceptance in non-articulating applications.

In recent decades, the potential of PEEK as a bearing material in joint replacement systems has gained increasing attention. However, studies have shown that virgin PEEK, when articulating against metallic counter faces such as cobalt–chromium or titanium alloys, can exhibit relatively high wear rates under certain operating conditions. To overcome this limitation, carbon Fiber–reinforced PEEK (CFR-PEEK) composites have been developed. The incorporation of carbon Fibers significantly enhances the stiffness, load-bearing capacity, and wear resistance of PEEK while allowing the elastic modulus to be tailored over a wide range, from values close to cortical bone to those comparable with metallic alloys.

Experimental investigations using pin-on-disc, pin-on-plate, and joint simulator studies have demonstrated that CFR-PEEK exhibits markedly improved tribological performance compared to virgin PEEK. The enhanced wear resistance is attributed to effective load transfer through the carbon Fibers, reduced plastic deformation of the polymer matrix, and the formation of stable transfer films at the articulating interface. Furthermore, CFR-PEEK has been shown to perform competitively with UHMWPE under selected test conditions, particularly at moderate contact pressures and sliding velocities.

In addition to tribological performance, the biological response to wear debris is a critical consideration for implant materials. Wear particles in the size range of 0.1–10 μm are known to be highly biologically active and capable of inducing inflammatory responses. Systematic reviews and in vitro studies indicate that PEEK and CFR-PEEK wear particles predominantly fall within this phagocytosable size range. While most studies report that the cytotoxicity and inflammatory response induced by PEEK-based particles are comparable to those of UHMWPE, variations in particle size, morphology, and concentration can influence cytokine release and cellular activity. The long-term biological implications of PEEK wear debris therefore remain an important area of investigation.
Another significant advancement in the application of PEEK for orthopaedic implants is the emergence of additive manufacturing technologies. The development of fused filament fabrication (FFF) and other high-temperature 3D printing techniques has enabled the production of patient-specific PEEK implants with complex geometries that are difficult or impossible to achieve using conventional manufacturing methods. Additive manufacturing offers the potential for customized implant design, improved anatomical conformity, reduced surgical time, and enhanced clinical outcomes. These capabilities have positioned PEEK as a leading candidate material for next-generation, patient-specific orthopaedic implants.

Given the growing body of experimental, biological, and manufacturing-related research, a comprehensive review of the wear behaviour, influencing parameters, biological response, and clinical potential of PEEK and its composites is both timely and necessary. This review aims to critically analyse existing literature on PEEK-based materials for orthopaedic applications, with particular emphasis on tribological performance, wear mechanisms, biological interactions, and recent advancements in manufacturing technologies. The insights provided are intended to support material selection, implant design optimization, and future research directions toward improving the longevity and reliability of joint replacement systems.

MATERIAL AND METHODS

Experimental Design

A systematic experimental methodology is adopted to evaluate the wear behaviour and tribological performance of PEEK and CFR-PEEK materials. Design of Experiments (DOE), particularly the Taguchi method, is frequently employed to minimize experimental runs while identifying significant influencing parameters. Orthogonal arrays (such as L9 or L27) are used to study the effects of variables such as normal load, sliding velocity, sliding distance, and reinforcement percentage.

Analysis of Variance (ANOVA) is applied to quantify the contribution of each parameter to wear rate and coefficient of friction.

Wear Testing Techniques

Pin-on-Disc and Pin-on-Plate Tests

Pin-on-disc and pin-on-plate tribometers are widely used to simulate sliding wear conditions representative of joint articulation. In these tests:

- PEEK or CFR-PEEK specimens are prepared in pin or block form
- Metallic or polymeric counter faces act as rotating discs or reciprocating plates
- Wear tests are conducted under controlled load, speed, and environment

Wear rate is calculated using mass loss measurements converted to volumetric wear using material density.

Joint Simulator Studies

Advanced knee and hip joint simulators are employed in selected studies to replicate physiological loading, motion, and lubrication conditions. These simulators provide a more realistic assessment of wear behaviour under cyclic and multidirectional motion.

Measurement of Wear and Friction

- Wear Rate: Determined gravimetrically using high-precision electronic balances before and after testing.
- Coefficient of Friction: Continuously recorded during tests to assess steady-state and transient tribological behaviour.
- Surface Roughness: Measured using profilometry to evaluate surface degradation.

Surface and Microstructural Characterization

Worn surfaces and wear debris are analysed using:

- Scanning Electron Microscopy (SEM): to identify wear mechanisms such as abrasion, adhesion, Fiber pull-out, and matrix cracking
- Optical Microscopy: for qualitative surface damage assessment
- Energy Dispersive X-ray Spectroscopy (EDS): for compositional analysis of transfer films

Wear Debris and Biological Evaluation

Wear debris particles are collected from lubricants and analysed for:

- Particle size distribution
- Morphology and shape
- Concentration

In vitro biological studies using macrophage or osteoblast cell lines are conducted to evaluate:

- Cytotoxicity
- Inflammatory cytokine release
- Cellular viability

These studies assess the biological safety of PEEK and CFR-PEEK wear particles in comparison with UHMWPE debris.

Additive Manufacturing Methodology

For additively manufactured PEEK implants, fused filament fabrication (FFF) is commonly employed using high-temperature printers. Process parameters such as nozzle temperature, bed temperature, layer thickness, and raster orientation are optimized to achieve dense, mechanically reliable components. Post-processing techniques, including annealing, are applied to enhance crystallinity and mechanical performance.

RESULT AND DISCUSSION

Effect of Normal Load on Wear Behaviour

Normal load is one of the most influential parameters governing the wear performance of polymeric and composite biomaterials. Across the reviewed studies, both virgin PEEK and CFR-PEEK exhibit an increase in wear rate with increasing applied load; however, the magnitude of this increase differs significantly between the two materials.

Virgin PEEK demonstrates a pronounced sensitivity to load, particularly at higher contact pressures. At elevated loads, plastic deformation of the PEEK matrix becomes dominant, leading to increased real area of contact and accelerated material removal. SEM observations consistently reveal deep ploughing grooves and micro-cracks on worn PEEK surfaces, indicating severe abrasive and adhesive wear mechanisms.

In contrast, CFR-PEEK shows substantially improved load-bearing capacity. The presence of carbon Fibers facilitates efficient load transfer from the polymer matrix to the reinforcement, thereby reducing localized stress concentration. Several studies report that CFR-PEEK maintains a relatively stable wear rate even at higher loads, with wear increases remaining linear rather than exponential. This behaviour is attributed to the reinforcing effect of carbon Fibers and the formation of protective transfer films on metallic counter faces.

Influence of Sliding Velocity

Sliding velocity plays a critical role in determining interfacial temperature, lubrication regime, and material response during articulation. For virgin PEEK, an increase in sliding velocity generally results in higher wear rates due to frictional heating and thermal softening of the polymer matrix. Elevated temperatures reduce the hardness of PEEK, making it more susceptible to adhesive wear and surface deformation.

CFR-PEEK exhibits better thermal stability under increasing sliding velocities. Carbon fibers act as heat dissipaters, reducing localized temperature rise at the contact interface. Consequently, CFR-PEEK demonstrates lower wear rates compared to virgin PEEK at identical sliding velocities. However, at excessively high velocities, Fiber–matrix debonding and micro-fracture of Fibers have been observed, leading to moderate increases in wear.

The coefficient of friction typically decreases with increasing sliding velocity for both materials due to the formation of smoother transfer films and transition toward mixed lubrication regimes, particularly under lubricated test conditions.

Effect of Contact Pressure and Cross-Shear Motion

Contact pressure and cross-shear motion are particularly relevant in joint replacement applications, where multidirectional sliding occurs. Studies employing pin-on-plate and joint simulator tests reveal that virgin PEEK is highly sensitive to cross-shear, exhibiting increased wear rates under multidirectional motion compared to unidirectional sliding.

CFR-PEEK, however, demonstrates reduced cross-shear dependency. The reinforcing carbon Fibers restrict large-scale molecular chain orientation changes within the PEEK matrix, thereby limiting wear acceleration under complex motion paths. This characteristic is especially advantageous for knee joint applications, where cross-shear is unavoidable during gait cycles.

Role of Reinforcement Type and Fiber Content

Fiber content and reinforcement architecture significantly influence the tribological performance of CFR-PEEK. Studies comparing different Fiber volume fractions indicate that wear resistance improves with increasing Fiber content up to an optimal threshold. Beyond this threshold, excessive Fiber exposure leads to increased third-body abrasion due to fractured Fiber fragments.

Short Fiber-reinforced PEEK generally exhibits isotropic wear behaviour, whereas continuous Fiber-reinforced PEEK shows direction-dependent wear characteristics. Continuous Fibers aligned parallel to the sliding direction provide superior wear resistance, while perpendicular orientations may promote Fiber pull-out and increased debris formation.

Effect of Counter face Material and Surface Roughness

The choice of counter face material significantly affects wear performance. When articulating against cobalt–chromium alloys, virgin PEEK experiences higher wear rates due to the hardness mismatch and abrasive action of the metallic surface. Polished CoCr counter faces reduce wear by promoting stable transfer film formation.

Titanium alloys, owing to their lower hardness and higher surface reactivity, often result in higher wear of polymeric materials unless adequately surface-treated. CFR-PEEK shows better compatibility with both CoCr and titanium alloys, demonstrating reduced wear and smoother worn surfaces.

Surface roughness of the counter face is a critical parameter; smoother surfaces consistently yield lower wear rates for both PEEK and CFR-PEEK by minimizing abrasive interactions.

Influence of Lubrication Conditions

Lubrication plays a pivotal role in wear reduction. Under dry sliding conditions, both PEEK and CFR-PEEK exhibit higher wear rates, dominated by abrasive and adhesive mechanisms. The introduction of lubricants such as distilled water, phosphate-buffered saline, or bovine serum significantly reduces wear.

CFR-PEEK benefits more from lubrication than virgin PEEK, as lubricants facilitate the formation of continuous transfer films and reduce Fiber–matrix interfacial damage. Bovine serum, in particular, closely simulates synovial fluid and provides the most realistic wear behaviour for orthopaedic applications.

Wear Mechanisms and Surface Morphology

SEM analysis reveals distinct wear mechanisms for virgin PEEK and CFR-PEEK. Virgin PEEK surfaces typically show:

- Deep grooves and scratches
- Plastic smearing
- Micro-crack formation

These features indicate dominant abrasive and adhesive wear.

CFR-PEEK surfaces exhibit:

- Shallow grooves
- Fiber exposure and occasional pull-out
- Compact transfer films

The transition from matrix-dominated wear to Fiber-controlled wear is a key factor contributing to improved performance in CFR-PEEK.

Implications for Orthopaedic Implant Applications

The reviewed results collectively demonstrate that CFR-PEEK offers a promising balance between mechanical performance, wear resistance, and biological compatibility. Its reduced cross-shear sensitivity, improved load tolerance, and tunable stiffness make it a strong candidate for tibial inserts and other articulating components. However, careful consideration of reinforcement design, surface finish, and operating conditions is essential for clinical success.

CONCLUSION

FINAL CONCLUSIONS AND FUTURE SCOPE

This comprehensive review critically examined the wear behaviour, tribological performance, biological response, and manufacturing potential of polyether ether ketone (PEEK) and its composites for orthopaedic implant applications. Based on the collective findings from experimental, in vitro, and simulation-based studies, the following key conclusions can be drawn:

1. Wear Performance: Virgin PEEK exhibits higher wear rates when subjected to increased normal load, sliding velocity, and cross-shear motion, limiting its direct application as a primary bearing material in joint replacements. However, the incorporation of carbon Fiber reinforcement significantly improves wear resistance, enabling CFR-PEEK to perform competitively with conventional UHMWPE under controlled conditions.
2. Effect of Reinforcement: Carbon Fiber reinforcement enhances load-bearing capacity, reduces plastic deformation, and promotes stable transfer film formation at the articulating interface. Optimized Fiber content and orientation play a crucial role in minimizing Fiber pull-out and third-body abrasion, thereby improving long-term tribological performance.
3. Influence of Operating Parameters: Normal load and sliding velocity were consistently identified as the most dominant factors influencing wear behaviour. Lubrication conditions and counter face surface roughness further modulate wear mechanisms, emphasizing the importance of simulating realistic physiological conditions during material evaluation.
4. Wear Mechanisms: Virgin PEEK predominantly undergoes abrasive and adhesive wear, while CFR-PEEK transitions toward Fiber-controlled wear mechanisms with shallower grooves and reduced material loss. The formation of compact transfer films is a key contributor to improved wear resistance in CFR-PEEK systems.
5. Biological Response: Available in vitro and preclinical studies indicate that the biological response to PEEK and CFR-PEEK wear debris is generally comparable to that of UHMWPE. While no severe cytotoxicity has been reported, inflammatory responses are influenced by particle size, morphology, and concentration, necessitating careful control of wear characteristics.
6. Manufacturing Advancements: Additive manufacturing technologies, particularly fused filament fabrication, have expanded the applicability of PEEK in patient-specific orthopaedic implants. The ability to fabricate complex geometries with tailored mechanical properties enhances implant design flexibility and clinical relevance.

Overall, CFR-PEEK emerges as a promising alternative bearing material for selected orthopaedic applications, offering a favourable combination of wear resistance, mechanical compatibility, radiolucency, and biocompatibility. However, its widespread clinical adoption requires further validation.

Future Scope:

1. Long-Term Clinical Validation and Biological Assessment

Future research should prioritize long-term in vivo and clinical studies to comprehensively evaluate the wear performance, biological response, and implant survivability of PEEK and CFR-PEEK under physiological loading conditions. Particular emphasis should be placed on understanding the long-term effects of wear debris on periprosthetic tissues and osteolytic processes to ensure clinical safety and reliability.

2. Advanced Material Design and Manufacturing Optimization

Further investigations are required to optimize composite architecture, surface modification techniques, and additive manufacturing parameters to enhance wear resistance and functional performance. The development of patient-specific and functionally graded PEEK-based implants through advanced manufacturing technologies represents a promising direction for improving implant longevity and biomechanical compatibility.

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