Friction and wear characteristics of polyetheretherketone (PEEK): A review

A H Mir and M S Charoo*
Department of Mechanical Engineering, National Institute of Technology, Srinagar.
Email:*shaficharoo123@nitsri.net

Abstract. PEEK is a colourless organic thermoplastic polymer which is used for tribological applications. It is seen as a potential replacement to metal and ceramic tribo-components due to excellent property profile. Various reinforcements like carbon fibers, Al₂O₃, SiC, WS₂, ZrO₂, etc have been incorporated in PEEK to improve its wear resistance and to aid its further applications by improving its anti-wear properties. This study presents a review of the tribological properties of PEEK and its composites in dry as well as aqueous environments. The friction and wear characteristics of PEEK and its composites are discussed in the proceeding sections. The role of various fillers in improving the friction and wear characteristics of PEEK is enlightened. The current research trends in PEEK tribology are also presented.

1. Introduction
Polyetheretherketone (PEEK), is a high-performance engineering polymer which is being seen as an emerging probable replacement for metals and alloys in aerospace, automotive and biomedical applications. It stems from the fact it has a good property profile which includes high toughness, high continuous service temperature, high melting point and high glass transition temperature. Further, it is easily processable by injection moulding [1],[2] and has high resistance to organic solvents, acids and bases accounting for its stable and inert chemical nature [3]. Moreover, it also possesses good mechanical and tribological characteristics which can be further improved by adding suitable fillers [4].

PEEK was first synthesised by Bonner in 1962 and since then researches have been extensively conducted on PEEK to know its nature and try and limit or eliminate its drawbacks as a tribological material replacement for metals and alloys. In practice, the approach traditionally has been to strengthen PEEK by incorporating fibres and filler particles in order to realise, entirely, the high-performance abilities of PEEK, which otherwise could not be achieved as PEEK-metal contacts may fail due to abrasion and/or scuffing for certain tribo-systems. Moreover, PEEK and its composites have also been tried as a tribo-material for aqueous environments [5],[6],[7],[8].

This paper presents a comprehensive review on the friction and wear characteristics of virgin PEEK and composites of PEEK with different fillers such as carbon, silica, titanium, etc. based compounds with the aim of providing a qualitative and quantitative assessment of the tribological properties of PEEK and PEEK based composites. Further the current focus of research is also summarised.

2. Friction and wear characteristics of PEEK and its composites
2.1. Polyetheretherketone
Youngchul lee investigated the physical properties of PEEK and reported the improvement of its tensile properties upon drawing. There was an increase of 3 and 6 times in the modulus and strength, respectively [9].
Stolarski reported the tribological performance of polyethereether ketone. The wear rate was observed to be very small irrespective of the contact configuration under sliding contact. Lubrication (using n-alkane and other boundary lubricants) was not found to be very effective. It was concluded that lubrication could be detrimental for the performance of the polymer. The main failure mode was found out to be the plastic flow and not fatigue, resulting due to its ability of energy dissipation. The rolling contact performance though improved upon lubrication[4].

Yamamoto et al. investigated the friction and wear of water lubricated PEEK. It was found that with water lubrication, the hardness at the sliding surface decreased but hardness of PEEK sample did not decrease by immersion in water. The wear of PEEK was promoted in water due to the hardness reduction[8].

Pei et al. studied the effects on PEEK friction and wear due to single asperity geometry. Scratch friction behaviour were strongly influenced by the tip geometry. During initial scratch cycles, plowing contributions to friction were significant. However, friction is dominated by shearing during the indenter is sliding in a groove. From the results, it was concluded that by limiting the curvature of the asperities on the counter-body could prevent the initial high friction and early failure of PEEK[10].

2.2 Carbon based PEEK composites
H. Voss and K. Friedrich studied the wear behaviour of short-carbon-fibre reinforced composites of PEEK under different wear loading[11]. There was no significant improvement detected in the wear resistance under abrasion of both these fibre reinforcements while altering p and v(pressure and velocity) of the tests. However, the wear rate was slightly increased where the loading of the fibres was higher in the composites. Carbon fibres were found to be superior to glass fibres in enhancing sliding wear resistance.

Z. P. Lu and K. Friedrich studied the wear and friction behaviour of different molecular weight virgin PEEK and PEEK blends with PTFE and PEEK and short carbon fibre composite. They reported that wear resistance was better in PEEK with higher molecular weight than with lower molecular weight. PTFE was included in the PEEK matrix and it resulted in the reduction of the coefficient of friction (lowest at 15 vol.%) and also lower wear rate (minimum at a volume fraction between 5% and 40%). 10-20% by volume of PTFE in PEEK was recommended for optimum results. Short carbon fibres (SCF) improved the wear resistance and also reduced the coefficient of friction up to an optimum concentration of 20 vol.%. The coefficient of friction was nearly half that of unfilled PEEK and decreased to a fourth at 150. More than 20 vol.% fibres of carbon sometimes caused stick slip behaviour at high testing temperatures[12].

Tribological assessment of PEEK reinforced with carbon nanofiber was studied and reported by Altstaedt et al. Homogenous dispersion and alignment were confirmed by electron microscopy when PEEK nanocomposite containing vapour-grown CNF (carbon nanofibers) were produced. Martensitic bearing steel and austenitic stainless steel were used as counterparts for unidirectional sliding tests. It was found that at loadings up to 10 wt.%, the PEEK and CNF matrix ductility was not affected corresponding to the good dispersion and interfacial bonding by the CNF. The wear rate was also reported to be lowered significantly due to the nanofiber wear debris lubricating effect[13].

A number of PEEK based composites, with PTFE and/or graphite blends and varied short carbon fibre blends were investigated by Zhang et al. PEEK+10 vol.% PTFE+10 vol.% graphite+20 vol.% carbon fibres proved to be the best composition for the lowest wear rate while being subjected to a contact pressure of 1 MPa under sliding speed of 1m/s[14].

Studies on the role of nano particles (nano-SiO2) on tribological performance of short carbon fibre reinforced PEEK were carried out by Zhang et al. showed that there was a remarkable reduction in the coefficients of friction due to the incorporation of the nanoparticles. The reduction, however, was more profound under pressures higher than 2 MPa. However, strong dependence of wear rate on apparent pressure was observed. The wear rate was largely increased by the incorporation of
nanoparticles below the pressures of 1 MPa while it was decreased under pressures above 2 MPa. The positive effect of the decrease of wear rate was found to be more pronounced at higher pressures and at higher velocities of the block on ring experimental setup. These results were attributed to the agglomeration of nanoparticles. These agglomerates, under lower pressure, lead to SCF abrasion. However, these agglomerates could be crushed into smaller scales by the counterpart at higher pressures which could lead to lower wear rate [15].

Zirconium dioxide nanoparticles and short carbon fibre reinforcements were used for PEEK composites by Zhong et al. and these composites were studied for sliding wear behaviour and mechanical properties, under water lubrication. Short carbon fibres improved the mechanical properties of the composite material as compared to pure PEEK and while zirconium dioxide particles also enhanced the stiffness and hardness, these degraded the composite impact strength. The wear behaviour of the PEEK/CF/ZrO$_2$ composites was excellent in water lubricated environment. The matrix was protected from severe abrasion by carbon fibres (carrying the main load). The introduction of nanoparticles of ZrO$_2$ inhibited efficiently the carbon fibre failure (by reducing shear stress and the stress concentration on the carbon fibres) [16].

The tribological behaviour of PEEK and carbon fibre composites under sea water lubrication was studied by Chen et al. Great improvement was found in the wear resistance of PEEK. 10 vol.% CF reinforced PEEK displayed the best results for wear resistance under sea water lubrication, even under the conditions of heavy loading [17].

Nano-SiO$_2$ particles and short carbon fibres were used as reinforcements for PEEK and the tribological performance of these hybrid composites was studied by Molazemosseinietal. SCFs and nano-SiO$_2$ resulted in significant hardness improvement in the hybrid composites. Tribological testing was done to study the effect of content of nano-SiO$_2$ (1, 1.5 and 2 wt.%) while maintaining SCF content (20 vol.%) and remarkable reduction of coefficients of friction was observed under all applied pressures (2, 3.75, 6.25 and 10 MPa). However, a strong dependence on the applied pressures was observed for wear resistance enhancement [18]. Contrary to the trend observed in PEEK/SCF composites, PEEK/SCF/2wt.%SiO$_2$ showed a decreasing rate of wear while contact pressure was increased.

Rolling contact fatigue and wear of PEEK and its composites with short fibre was investigated by Avanzini et al. by applying different levels of contact pressure to aim, roller-shaped specimens. Composites of PEEK with short fibre exhibited lower rate of wear as compared to the unfilled PEEK specimens as expected, owing to lesser adhesion occurrence [19].

Sliding wear failure modes were investigated by Schroeder etals. analysing three materials (PEEK, CF reinforced PEEK and PTFE+graphite+CF filled PEEK composites) in their work. Reciprocating scuffing tests (linear), reciprocating sliding tests (constant load) and micro-abrasion tests were carried out on these PEEK based composites to identify whether scuffing or abrasion was the mode of failure. Analysis of the test result was carried using SEM and light interferometry assessing the wear track morphology. PEEK showed a large wear rate during the reciprocating sliding tests and also very low scuffing resistance thus implying to fail under abrasion mechanisms. Carbon fibre reinforced PEEK also exhibited very low scuffing resistance but showed higher wear resistance for abrasive and sliding wear resistance. The analysis of the surfaces indicated the protection against abrasion by carbon fibre presence. PTFE/Graphite/CF/PEEK however showed a decreased friction coefficient and higher scuffing and abrasion resistance to wear. The wear rate for reciprocating sliding tests was almost non-measurable suggesting a protective tribo-layer transfer between the surfaces [20].

PEEK filled with graphene, carbon nanotubes (CNT) and tungsten disulphide (WS$_2$) based nano particles (WS$_2$F and WS$_2$N) was analysed for friction and wear behaviour by Kalinet al. [21]. It was found out that WS$_2$-based nanoparticles showed better wear performance than carbon-based nanoparticles. The wear rate, compared to pure PEEK, was improved by 10% when WS$_2$F was used as the PEEK reinforcement and by 60% when WS$_2$N was used. Adding CNT, however, deteriorated
the wear behaviour of the composite by 20% and in case of GNP, it deteriorated by as much as three times. The coefficient of friction, on the other hand, was lower in case of WS$_2$F and CNT addition than when WS$_2$F or GNP was added to PEEK.

2.3 Other reinforcements
Polyetheretherketone reinforced with nano-sized TiO$_2$ was investigated for its tribological behaviour by Kurdi et al. The lowest specific wear rate in both dry and water lubricated conditions was exhibited by composites with 5% TiO$_2$ containing PEEK composite as compared to pure PEEK and other concentrations of TiO$_2$ (10% and 15%). The coefficients of friction were found to be better in water lubrication but wear resistance was superior in dry sliding environment [7].

Improved tribological behaviour of nanometer Si$_3$N$_4$ filled polyetheretherketone corresponding to the improvement in the transfer film characteristics was reported by QiHua Wang et al. It was found that a thin and uniform transfer film was formed on the ring surface of plain carbon steel in a block on ring set up for the study of friction and wear characteristics of Si$_3$N$_4$ filled PEEK composites. 7.5 wt. % Si$_3$N$_4$ in PEEK gives lower coefficient of friction and minimized wear rate for all loading conditions [22].

ZrO$_2$ filled PEEK composites was studied on a block on ring set up with plain carbon steel ring. The effect of difference in the size of the particles of ZrO$_2$ was reported in this study by Qhua Wang et al. Larger sized ZrO$_2$ particles exhibited less friction reduction due to the poor adhesion of the composite transfer film (to the counter surface). Small sized particles of ZrO$_2$ formed a thin, uniform film which adhered strongly to the counter surface thus resulting in reduced friction and wear rate. 7.5 wt.% of ZrO$_2$ exhibited the lowest wear rate at all loading conditions. Particle size less than 15 nm of ZrO$_2$ showed effective results in the reduction of wear. Increase in size of nanometer ZrO$_2$ particles increased the wear rate of nanometer ZrO$_2$ filled PEEK [23].

Wang et al. also studied the effect of nanometer SiC filler on PEEK’s tribological behaviour in both dry. Alcohol was used to mix PEEK with SiC, which was removed upon drying of the samples. The coefficient of friction decreases sharply till the SiC wt.% reaches 7.5 and then gradually till it reaches its lowest value at 20 wt.% of SiC. The wear coefficient decreases sharply till the concentration of SiC is below 2.5 wt.%. Between 2.5 wt.% and 10 wt.% of nanometerSiC in PEEK, the wear coefficient keeps nearly unchanged. Above 10 wt.% of SiC, the wear coefficient increases almost linearly with the increase in content of nanometerSiC. 7.5-10.0 wt.% was inferred to be optimum content of SiC filler for lowest friction and wear coefficients under no external lubricated conditions [24].

Kuo et al. experimented with PEEK filled with nano-alumina or silica (15-30 nm) with varying wt.% (2.5-10 wt.%). It was found out that nanocomposites exhibited optimum hardness improvement (about 50%) at 5-7.5 wt.% of Al$_2$O$_3$ or SiO$_2$. This range also improved the tensile strength and the elastic modulus (21% and 36% respectively) while compromising on the tensile ductility of the composite. No apparent reaction was also reported between the PEEK matrix and the nanoparticles during the composite formation [25].

NanometerSiC effect on tribological behaviour of nanometerSiC filled PEEK composites under water lubrication was reported by Wang et al. The improvement in the wear resistance of SiC filled PEEK composites over pure PEEK was found excellent at all loading conditions. Under water lubrication, severe ploughing was observed on the surface of unfilled PEEK. The surface of the counterpart (plain carbon steel) was rough and the PEEK transfer on it was discontinuous, indicating inadequate transfer film formation. NanometerSiC filled PEEK composites, however, formed a thin and uniform transfer film on the counterpart under water lubrication. Wear rate obtained was lower and adhesion, scuffing and water erosion also subsided [6].

Zirconia nanofiller was dispersed in the PEEK polymer matrix and experimented upon by Mishra et al. and it was found that the basic and functional properties of the polymer matrix were enhanced. No change in the glass transition temperature was observed though. Uniform dispersion of zirconia
nanofiller was also revealed by SEM studies [26].

Glass fibre reinforced PEEK composite was studied by E.Z. Li et al. for its tribological performance. 30 wt.% of short GF was incorporated in PEEK and the tribological performance of the composite was compared with that of pure PEEK. The GF/PEEK showed much better wear resistance as compared to pure PEEK, however, the friction coefficient and wear loss exhibited a gradually increasing trend and the tended to be a stable state with the increase in applied load and sliding time. The tensile and flexural strengths were also significantly increased [27].

Tribological behaviour of PEEK reinforced with carbon fibre sliding against ceramic (silicon carbide) under sea water lubrication was investigated by Zhan et al. An evident running in process was revealed and also friction and wear resistances were found to be outstanding. Adhesive wear and mechanical ploughing were the main mechanisms exhibited. With the increase in contact pressure, the coefficient of friction first shows a decreasing trend and then fluctuates. The wear rate also shows a similar trend for increasing contact pressure [28].

3. Current focus of research

The researchers are currently on the development of novel nano composites. Nano composites of PEEK with newly developed compounds [29], [30] for viability at extreme (vacuum, hydrogen and cryogenic) environments are being investigated. Hybrid soft-hard nano-fillers for PEEK are also being analysed for improvement in tribological properties of PEEK [31]. Biomedical applications (medical, dentistry and prosthesis) [32], [33], [34], [35], [36], [37] of modified PEEK with different environment friendly and non-toxic compounds are also being comparatively studied.

Another current research focus is tribology of PEEK and its composites in aqueous environments. As a matter of fact, virgin PEEK exhibits relatively reduced wear resistance with water lubrication. However, it has been observed that the addition of nano-fillers in PEEK matrix shows improved wear resistance in aqueous environments. Researchers are working on developing novel nano-fillers which can impart improved mechanical tribological characteristics to PEEK which is a potential candidate for tribo-components like propeller shaft bearings of ships and sub-marines, having excellent corrosion resistance, good chemical stability and low water absorption.

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