Polyether Ether Ketone (PEEK) Properties and Its Application Status

Xuanzhe Ling*, Xishuang Jing, Chengyang Zhang and Siyu Chen
School of Mechanical Engineering & Automation, BeiHang University, BeiJing, China

*Corresponding author

Abstract. The physical, chemical and mechanical properties of polyether ether ketone (PEEK) materials have been comprehensively analyzed. Based on methods for reinforcing modification of PEEK, this review has investigated the application status of PEEK materials, summarized the current production and research and development status quo of PEEK at home and abroad and suggested that the application of PEEK should be promoted.

Keywords: PEEK Properties; Modification; Application; Research and development.

1. Introduction
PEEK is a kind of high-performance special engineering plastics developed by British ICI in 1977 and industrialized by British Victrex Company in the early 1980s. It is called the tip of pyramid plastics industry[1]. PEEK has a structural regularity due to the presence of rigid benzene rings on the macromolecular chain, compliant ether bonds, and carbonyl groups that increase intermolecular forces[2]. It has the advantages of high heat-resistant grade, radiation resistance, chemical resistance, high impact strength, good wear resistance and fatigue resistance, flame retardant, excellent electrical properties, which makes it be widely used in the fields of aerospace, electrical and electronic, medical, energy, power, machinery, automotive, paints and coatings and become an indispensable key material.

2. Properties of PEEK
PEEK is an aromatic crystalline thermoplastic polymer and is composed of repetitive units of polyaryletherketone. The melting point of PEEK is of 334°C; its glass transition temperature (Tg) is of 143°C; the maximum achievable crystallinity is about 48%, usually between 20% and 30%, and its density in the amorphous state is of 1.265 g/cm3 with the density at maximum crystallinity state being of 1.320 g/cm3. PEEK has the following outstanding performance[3-4]:

2.1. Excellent Heat Tolerance
PEEK can be used at 250°C for a long period of time, with an instant operating temperature of up to 300°C, and almost doesn’t experience decomposition at 400°C for a short period of time. Compared with other high-temperature resistant plastics such as polyimide (PI), polyphenylene sulfide (PPS), polytetrafluoroethylene (PTFE), and polyphenylene oxide (PPO), its upper limit of operating temperature is higher by nearly 50°C.

2.2. Eminent Mechanical Properties and Dimensional Stability
The comparison of PEEK and several typical high temperature plastics is shown in Table 1. PEEK can maintain high strength at high temperatures with bending strength up to 24MPa at 200 ºC and bending strength and compressive strength up to 12-13MPa at 250 ºC, which is particularly suitable for manufacturing components that can work continuously at high temperatures. PEEK has high rigidity,
good dimensional stability and small linear expansion coefficient, which is very close to metallic aluminum. Furthermore, PEEK also has a good creep resistance, which can withstand great stress during operation, thereby, producing no significant elongation due to the extension of time.

2.3. Good Hydrolysis Resistance
PEEK can resist chemical damage from water or high pressure water vapor. Under high temperature and pressure conditions, PEEK components can operate seamlessly in an aqueous environment while still maintaining good mechanical properties. If continuously soaked in water at 100°C for 200d, its strength remains almost unchanged. PEEK has a very low water absorption, which can be used in pressurized hot water or steam at 300°C.

2.4. Excellent Chemical Resistance
PEEK whose corrosion resistance is similar to nickel steel, can resist the corrosion of most chemicals even at high temperatures. Only the concentrated sulfuric acid can dissolve PEEK under normal conditions.

Table 1. The properties of several typical high-temperature resistance plastics.

| Properties                        | Categories |
|-----------------------------------|------------|
|                                   | PEEK  | PTFE | PPO  | PI   |
| Tensile strength/MPa             | 97.4  | 20.3 | 66.5 | 116.2|
| Tensile modulus/GPa              | 2.8   | 0.4  | 2.7  |
| Flexural strength/MPa            | 142.1 | 12.9 | 109.7| 176.2|
| Flexural modulus/GPa             | 3.7   | 2.0  | 3.3  |
| Compression strength/MPa         | 130   | 12   | 100  | 148  |
| Charpy Notched Impact Strength/ kJ·m⁻² | 4.44  | 0.16 | 0.09 | 0.10 |
| Linear expansion coefficient/10⁻⁵K⁻¹(10-180°C) | 4.8   | 11   | 5.6  | 4.8  |
| Thermal distortion temperature /°C(1.82MPa) | 152   | 55   | 190  |

2.5. Good Flame Retardant Performance
PEEK can reach up to the grade of UL94V-0, it owns the properties of self-extinguishing, and releases less smoke and toxic gases under the flame conditions.

2.6. Good Electrical Performance and Strong Radiation Resistance
PEEK maintains its electrical performance over a wide range of frequencies and temperatures. Since PEEK has a very stable chemical structure, its components can also operate well under high doses of ionizing radiation; it has strong resistance to gamma irradiation, surpassing that of polystyrene, which is the most resistant to radiation in general-purpose resins. It can be used to make a high-performance wire that maintains good insulation ability even when the γ-irradiation dose reaches 1100 Mrad[5].

2.7. Better Toughness
PEEK is a plastic that has both toughness and rigidity which are balanced. It has the most eminent fatigue resistance to alternating stress among all plastics, comparable to that of alloy materials.

2.8. Excellent Friction and Wear Resistance
PEEK can maintain high wear resistance and low coefficient of friction at 250°C. It can provide excellent wear resistance under various conditions of pressure, temperature, speed and relatively rough contact surface, and can reach the grade of polyimide material; the abrasion loss of the grinding between the polyetheretherketone pure resin and H10 wheel material is of 2.7×10⁻⁴g; while the abrasion loss of the grinding between polyetheretherketone pure resin and S17 wheel material is of 9.7 × 10⁻⁴g.
2.9. Having A Certain Degree of Self-lubrication
PEEK has outstanding sliding properties in all plastics and is suitable for applications that require stringent low coefficient of friction and wear resistance. In particular, blended modified grades such as carbon fiber, graphite, and PTFE, each having a ratio of 10%, or 30% CF-reinforced grades, which are both grades with excellent sliding properties.

2.10. Good Processing Performance
PEEK has a good processing performance. Although it is a super high temperature resin, it can be processed by various processing methods such as injection molding, extrusion molding, compression molding, blow molding, melt spinning, rotational molding, powder coating due to its properties of high temperature fluidity and high thermal decomposition temperature.

3. Reinforced Modification of PEEK
In order to meet the needs of high-precision, heat-resistant, corrosion-resistant, wear-resistant, fatigue-resistant, and impact-resistant in manufacturing parts of the engineer ing, the composite strengthening modifications of compounding, filling, fiber lamination are often carried out on the basis of PEEK to obtain more superior materials. PEEK can be blended with polymers such as polytetrafluoroethylene (PTFE), polyethersulfone (PESU), liquid crystal polymer (TLCP), polyetherimide (PEI), etc.; it can also be blended with carbon fiber (CF), glass fiber (GF), whiskers to achieve compound reinforcements, thereby, forming more superior composite materials; it can also fill micron and nanoscale inorganic particles, such as Al2O3, CuO, etc., in order to improve its tribological properties, while improving the properties of rigidity, dimensional stability and impact strength of PEEK, thereby further expanding its scope of application [6-9].

PEEK-based thermoplastic composites are a new type of high-performance, low-cost, environmentally-friendly composite material that combines the advantages of PEEK, such as low density, high strength, fast processing, and recyclability, and according to the requirements, the processed products have the advantages of large design freedom, stable size, low warpage and fatigue resistance. According to the maximal fiber retention size in the material, thermoplastic composites can be divided into three types:

3.1. Discontinuous Fiber Reinforced Thermoplastic Composites
Include chopped fiber reinforced engineering plastics (maximum fiber retention size is of 0.2-0.6mm). The performance improvement of chopped fiber reinforced thermoplastic composites has some limitations, but the manufacturing cost is low because it is easy for contour machining and can be easily manufactured into complex products; it has good thermal stability and creep resistance, and thus accounts for the largest share (more than 1/3) in the entire thermoplastic composite materials.

3.2. Long Fiber Reinforced Thermoplastic Composites
Long fiber-reinforced thermoplastic composites refer to composites with a maximum fiber retention size of 5-20 mm. Foreign companies such as RTP of USA and Kawasaki of Japan have realized the industrialized production of long fiber reinforced thermoplastic composites and applied them to non-structural parts that require high strength and lightweight to replace parts of aluminum alloy materials. In 2012, Beijing Nashengtong New Material Technology Co., Ltd. realized the industrialized production of LFT carbon fiber composite materials in China and applied it to wind power blades, electric vehicle wheels and other products.

3.3. Continuous Fiber Reinforced Thermoplastic Composites
Continuous fiber-reinforced thermoplastic composites refers to composites with a maximum fiber retention size of more than 20 mm (>20 mm). Compared to the other two kinds of thermoplastic composites, continuous fiber reinforced thermoplastic composites are a kind of higher performance lightweight new material with superior performance and complicated technologies. It can adapt to the basic requirements of aircraft materials, such as, lightweight materials, modularization of parts and components, and recyclability.
4. Application of PEEK Material

4.1. Applied in Aerospace Industry
PEEK mainly substitutes aluminum and other metallic materials for manufacturing various aircraft parts, thereby, reducing the degree of fire hazard of aircrafts. PEEK can be used to manufacture fuel filters, bolts, nuts, and bobbins. In 1980, the Imperial Chemical Industries Ltd (ICI)'s PEEK prepreg APC-2 was put on the market and afterwards it was used to make the advanced aerospace thermoplastic composites with the most practical values. PEEK has better radar transmission and dielectric transmission characteristics. When radar waves are transmitted to these resin matrix composites, the crawling electromagnetic waves are not easily formed. This material has excellent microwave absorbing properties which can attenuate pulses with frequencies from 0.1 MHz to 50 GHz, thus partially PEEK-based composite materials are used in many advanced fighter aircrafts. In addition, APC-2 is a unidirectional reinforcement grade of Celion G40-700 carbon fiber and PEEK multifilament hybrid yarns, and is particularly suitable for the production of helicopter rotors and missile shells.

The main application results are as follows: CF/PEEK is applied to most of the bow-type luggage baffles of Airbus series airplanes (Fig. 1) and suction inlet bottom plates of aircraft pumps, F-117A aircraft empennage, and C-130 aircraft fuselage belly panels. Rafale aircraft fuselage skin, V-22 aircraft front landing gear door, A-400M fuel tank covering cap, etc.; Airbus uses GF/PEEK extensively to produce cable ducts, cable hooks, and fans inside the propeller; the whole fuel tank covering cap of A380 is manufactured using CF/PEEK and GF/PEEK materials; the F-22 main landing gear door is produced using IM7/PEEK (APC-2) [10].

![Figure 1. The bow-type luggage baffles of Airbus airplanes and High performance gear made of PEEK.](image1)

4.2. Applied in Automotive Industry
At present, 40% of the produced PEEK resin in the international market is used in the automotive industry where PEEK's good friction resistance and mechanical properties have been exploited (Fig. 1). It can replace stainless steel and titanium alloys for the production of the components, such as, engine inner covers, bearings, gaskets, seals, and suspension bearing bush pistons skirts, and clutch rings, it can also be used in automotive transmissions, brakes, air conditioning systems, and engine rams.

![Figure 2. The wafer holder.](image2)

4.3. Applied in Electronic and Electrical Fields
The electronic field is the second largest application field of PEEK resin, accounting for about 25% of the total production. Particularly in the transmission of ultrapure water, the pipes, valves and pumps made of PEEK resin are used to make ultrapure water stay away from pollution, which has been widely used abroad. PEEK can be used in fittings and valves of the ultra-pure water system in the semiconductor industry and other ultrapure industries, such as inlaid plugs, high-reliability connectors, cable plugs, junction boxes, wiring lead-outs, plate-cage coils, battery housings, IC packaging. PEEK not only has excellent electrical insulation properties, but also has superior processing and chemical properties. Parts
and components made from it can withstand the high-temperature environment of thermal welding and secondary processed can be carried out in a variety of ways. Therefore, as shown in Figure 2, PEEK resin can be used for wafer holder dielectric films, connectors, printed circuit boards, and high temperature connectors. PEEK is also used in the electronics industry for the transmission and storage of μg/L ultrapure water such as pipes, valves, pumps and containers. At present, many foreign VLSI production has been using PEEK resin[11].

4.4. Applied in Energy Industry
PEEK is a kind of plastic resin which is high temperature resistant, non-hydrolyzable and radiation resistant. The temperature for long-term continuous use is of 250°C, and it can still maintain good mechanical performance and electrical insulation at an irradiation dose of 1100 Mrad. Therefore, it can be used as a high-performance material in nuclear reactors, warships and other environment-intensive fields, such as electromagnetic wires, cables, coil bobbins, connectors, and valves. In the oil exploration and production industry, PEEK can be used to manufacture probes with special geometry, connectors for oil extraction.

4.5. Applied in Machinery and Chemical Industry
PEEK has good mechanical properties, and has good performance in chemical resistance, abrasion resistance and high temperature resistance, which can withstand pressures up to 2.5 MPa and temperatures of up to 260°C. PEEK is insoluble in all solvents other than concentrated sulfuric acid. In the chemical industry and other processing industries, PEEK resins are commonly used to make compressor’s valves, piston rings, seals, and various chemical pumps and valve components. Replacing stainless steel with such material to make a vortex pump impeller significantly reduces wear and noise levels, thereby, achieving a longer service life. In addition, typical PEEK products include bearing retainers, metal bearing liners, clutch parts, power brake vacuum parts, pulley loader blades, photocopying machinery parts, protection jackets for boiler’s pH meters, microscope lampshades, wire brackets around motors, battery slots for rockets, bolts, nuts, laboratory tweezers, etc.

4.6. Applied in the Fields of Medical Treatment
PEEK resin can withstand up to 3,000 cycles of autoclaving at 134°C, thereby, making it suitable for use in surgery and dental equipment; under the circumstances of hot water, steam, solvents, and chemical reagents, it can exhibit superior performances in high mechanical strength, good stress resistance and hydrolytic stability, thereby, enabling it to be used to manufacture various medical devices requiring high-temperature steam sterilization; it can be used in medical reactor valve bushings; which has the advantages of light weight, non-toxicity, corrosion resistance, etc.; also it is the material which is the closest to the bone of human body and can be organically combined with the body. The use of PEEK resin instead of metal to make human bones is another important application in the fields of medical treatment thereby, achieving far-reaching significance and value, and the very attractive potential application prospects[12].

4.7. Applied in Field of Coatings
Through electrostatic spraying, fluidized bed spraying and plasma coating, the superfine powder of PEEK resin can be coated on the metal surface, which can greatly improve the performances in corrosion resistance, wear resistance, insulation and heat protection of metal parts and components. It is suitable for pure water equipment and pipes, medical appliances, food industry components, electric iron bottom and cookers, etc. [13].

5. Conclusion
The application prospects of PEEK material are broad and bright, and PEEK is an indispensable key material for the development of cutting-edge science and technology. However, China’s cognition of PEEK is not so extensive that the application and development of PEEK products in the civilian sector can only be considered to be at the very beginning, and even not to be started yet. The application of PEEK in the industry should be vigorously promoted to increase the application volume. We must clearly understand that the product upgrade is not only to be done, but must be done as soon as possible.
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