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PEEK-Polymer for Dental Implants: A Concise Review

ZUZANA MITAĽOVÁ[1*], JÁN DUPLÁK[1], DARIANA DUPLÁKOVÁ[1], DUŠAN MITAĽ[1], JULIÁNA LITECKÁ[2]
[1]Technical University of Košice, Faculty of Manufacturing Technologies with seat in Prešov, Department of Automobile and Manufacturing Technologies, Štúrova 31, Prešov 080 01, Slovakia
[2] University of Prešov, Faculty of Humanities and Natural Science, Department of Physics, Mathematics and Technologies, 17. Novembra 15, Prešov 080 01, Slovakia

Abstract: *The biomaterials applicable in dental implantology, or implantology generally, are subject to specific requirements, namely biocompatibility, osseointegration, resistance to fracture/ oxidative degradation/ long-term compressive stress/ hydrolisis in boiling water, suitable morphology, suitable physical properties (including mechanical properties), aesthetics, etc. When selecting a suitable material for dental implants, it is also necessary to consider the patient's current health condition and possible complications when placing titanium implants and alloys. If there is a risk of an allergic reaction or hypersensitivity to any of the components of the metal prosthesis, the placement of a semi-crystalline thermoplastic implant - called polyetheretherketone, abbreviated PEEK - is a possible option. Such a wide range of stiffness means that PEEK formulations can be produced with modulus values similar to cortical bone. PEEK is classified as a High Performance Polymer of polymer pyramide (such as Polysulfones polybutylene terephthalate). PEEK can be applied for dental abutment and dental body. This article summarises basic information on the structure and properties of PEEK polymer, advantages/ disadvantages (compared to metal - titanium restorations), application and general information from the examined field.*

Keywords*: dental implants, polyetheretherketone, high-performance polymres*

1. Introduction

Bioengineering research has led to significant advances in dental restorative materials research. Implantology is an interdisciplinary research area where collaboration between clinicians and materials engineers is essential. The term implant refers to an "artificial" object inserted into a living organism (replaces the natural tooth root and supports dental crowns, bridges and removable dentures). A dental implant can be made of metals and their alloys (titanium) or metal-free versions: ceramics (based on zirconium dioxide: ZrO_2, trade name: Zirconia) and polymers. When selecting dental implant materials, an emphasis is placed on physical properties (including mechanical), resistance in various respects (abrasion/ oxidative degradation/ long-term compressive stress), biocompatibility, resistance to in vivo degradation, and aesthetic considerations. The process by which the applied material is firmly fixed and anchored to the bone is called *osseointegration* (the fixation is preserved even under implant stress). Despite the considerable advantages of titanium in dental implantology, its insertion may involve the risk of an allergic reaction (reaction follows the presence of ions originating from the corrosion process of the implant; these may enter the digestive tract or contact the skin/ mucosa). Ions, in combination with native proteins, cause hypersensitivity reactions. The following study has been conducted concerning this issue: *Allergies to Titanium Dental Implants: What Do We Really Know About Them? A Scoping Review* [1].

An alternative solution is inserting a thermoplastic called polyetheretherketone, abbreviated PEEK. Compared to Ti, the advantages of PEEK polymer are as follows:

- its aesthetic properties - it does not have metallic coloring,

-and radiolucency (PEEK creates no artifacts, allowing good visualization and evaluation of bone by imaging method - CT, MRI scan, X-ray).

**email: zuzana.mitalova@tuke.sk*

Technically speaking, based on the classification by structure (crystalline/ amorphous), heat resistance and production, PEEK is classified as a High-Performance Polymer. High-performance engineering polymers are specialty polymers that include the following: acetal copolymer (POM-C), polyetheretherketone (PEEK), polyphenyl sulfone (PPSU), polysulfone (PSU), polyphenyl sulphide (PPS), polyvinylidene fluoride (PVDF), polyetherimide (PEI), polydimethylsiloxane (PDMS), thermoplastic polyurethane (TPU) and thermoplastic elastomer (TPE) (Figure 1). These polymers are located at the top of the polymer pyramid, with about 300 members of a given group [2].

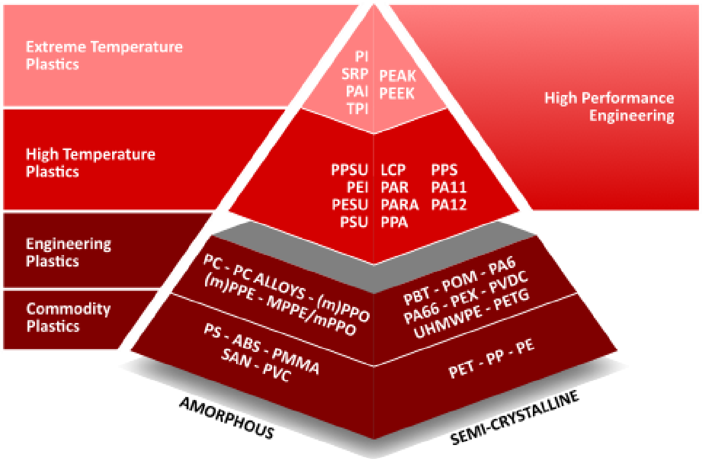

Figure 1. Polymer pyramid: commodity plastics, engineering plastics and high performance engineering plastics

PEEK polymer manufacturers (+ product trade names) are as follows: Greene, Tween & Co. (Arlon), Solvay Advanced Polymers, L.L.C. (AvaSpiere^{TM}, Kadel®, Ketaspire^{TM}), Gharda Chemicals Limited (Gatone^{TM}), Victerx PLC (Victrex®) [3].

2. Materials and methods

2.1. Polyetheretherketone (PEEK)

PEEK (abbreviation of the chemical name of polyetheretherketone), this plastic was developed in the 1980s for industrial applications in the manufacture of aircraft, piston parts, cable insulation and turbine blades (by Victrex, Victex has continually pioneered new PEAK-based polymers). PEEK is a member of the PEAK "family of polymers". PEAK polymers are produced by polycondensation of halogenated benzophenones with alkaline hydroquinone salts. High purity of the source materials is a priority in the polycondensation process. PEEK represents the most prominent representative of this group with a specific gravity of 1.3 g.cm^{-3} (according to ASTM D792), melts around 350°C. It is a semi-crystalline thermoplastic without color with an approximate crystallinity of 30-35% and glass transition temperature Tg = 143°C. Combining an aromatic structure with ketone groups provides a high modulus and long-term oxidative and thermal stability. The ether bonds provide flexibility, toughness and simplification of the processing process. PEEK has high chemical resistance and resistance to hydrolysis in hot water and steam. However, it shows lower resistance to UV radiation [2], [4, 5]. PEEK chemical structure (Figure 2).

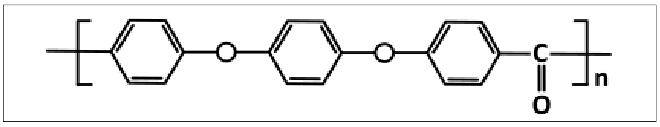

Figure 2. PEEK chemical structure

The tensile strength of PEEK ranges from 90-100 MPa (depending on molecular weight and polymer manufacturer), and the tensile modulus is approximately 3-4 GPa (ASTM D638/ ISO 527-2/1A). The properties can be modified by adding carbon/ glass fiber and ceramic microparticle fillers. Mechanical properties of unfilled and reinforced PEEK (Table 1). The resulting properties of PEEK composite implants are influenced by the following variables: the fibers' chemical composition, shape/dimensions, percentage volume and orientation. For example, depending on the percentage volume of carbon fibers in the PEEK matrix, the tensile modulus can vary over a relatively wide range of values from 18 to 150 GPa. The disadvantage of applying carbon fibers is the color of the resulting component - black color [6, 7].

Adding inorganic-ceramic microparticles to the PEEK matrix produces a composite material referred to as Bio-HPP, structure Figure 3 (Bio-High-Performance Polymer). Ceramic filler has a grain size of 0.3-0.5 µm; particle size influences polishing ability and minimum chances of dental plaque formation. The elastic modulus of Bio-HPP is 4000 MPa, flexural strength > 150 MPa (no material failure), hardness = 10 HV 5/20 and thermocycling 10 000 cycles 5°C/55°C under DIN EN SIO 10477. Bio-HPP is extremely resistant to abrasion and has excellent anti-discoloration properties and color stability (application: dental bridges, implant-based dentures and individual abutment) [8].

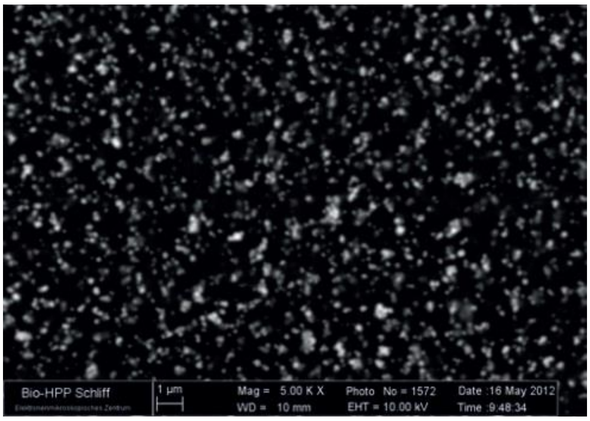

Figure 3. Structure of BioHPP (Bredent) [9]

PEEK is an adequate substitution for traditional Ti implants. Young's elasticity modulus is significantly lower than Ti or Ti alloys. In the case of FEM analysis (Finite Element Models), this minimizes potential stress shielding-related problems most commonly associated with Ti implants [10].

Table 1. Mechanical properties of cortical bone/ PEEK and composite material: PEEK with carbon fibres, study

Material	**Parameter**		
	Tensile strength (MPa)	Young's modulus (GPa)	Study
PEEK (unfilled)	90.3	3.7	[11]
CFR-PEEK (CFR = Carbon Fibre Reinforcement)	120	18	[12]
Bone (cortical bone)	80-150	16-23	[13]
Titanium (according grade I-IV)	240-550	102-104	[7, 14]

Note: Values can be different in relation to study and structures (in case of reinforcement material by percentage volume ratio of fibres).

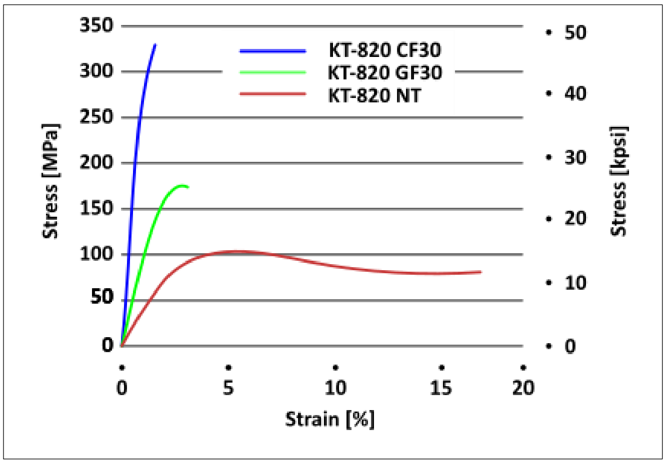

Figure 4. Stress-strain curves (room tempertaure): PEEK (unfilled, KT-820 NT)/ GFR-PPEK (PEEK + 30 % glass fiber/ CFR-PEEK (PEEK + 30 % carbon fibre) [15]

The addition of reinforcement causes a significant increase in tensile modulus (Figure 4). Carbon fiber is more effective than glass fiber in increasing modulus [15].

2.2. Properties of PEEK polymer

Others properties of PEEK:

- the structure of polyarylletherketones (including PEEK) ensures that the material is unreactive, resistant to thermal/chemical and postirradiation degradation (resistant to solvents and petrochemicals, PEEK dissolves only in sulfuric acid and is subject to the degradative effects of nitric acid) [16];

- autoclaving (pressurized steam) is a sterilization method for medical devices. Green and Cartwright (2004) exposed PEEK-OPTIMA® LT1 to 134°C steam at 2 Bar pressure for 1000 h. The authors concluded no significant changes in mechanical properties (a moderate increase in the tensile strength, flexural strength and modulus values and a slight reduction in the strain to failure). PEEK polymer is classified as a high-temperature sterilization-resistant material (implants must be sterilized prior to application and must also withstand years of exposure to environments at body temperature) [6, 17];

- biocompatibility indicates that the material under study is non-toxic, non-mutagenic, non-carcinogenic and non-immunogenic. Studies support the biocompatibility of PEEK (and its composites) as a group of biomaterials in bulk form. The bioactivity of PEEK can be improved in two ways: surface modification and composite preparation [18, 19];

- adhesion of bacteria to the surface of polymer PEEK presents a difficult, complex issue (biofilm formation on the implant surface in five stages is shown in Figure 5). An important factor concerning adhesion is surface topography, for PEEK implants is determined by the manufacturing method (machining or injection moulding) and applied post-manufacturing treatment. After machining PEEK polymers, the surface is relatively rough, leading to increased bacterial adhesion (in vitro) to the surface. In contrast, in the case of implant manufacturing by injection moulding - the surface is smooth, and the surface adhesion is relatively low. Available strategies to reduce biofilm on PEEK material are described in a study entitled: *Strategies to Reduce Biofilm Formation in PEEK Materials Applied to Implant Dentistry-A Comprehensive Review* by Brum et al. [6, 20, 21];

- PEEK implants showed excellent fatigue resistance. A study by Lee et al. reported the suitability of GFR-PEEK composite for both anterior and posterior dental implants concerning maximum bite force and cyclic loading [22];

- good abrasion resistance (test method: pin-on-disk, weight loss of unreinforced PEEK = 0.004 g, weight loss of GFR-PEEK = 0.001 g) [23];

- impact resistance values increase with increasing molecular weight (there is a clear correlation between molecular weight and impact resistance), but the increased crystallinity and polymer ageing lead to reduced toughness [15];

- PEEK is characterized by high creep resistance at temperatures below the *Tg* (glass transition temperature → 143°C) [9].

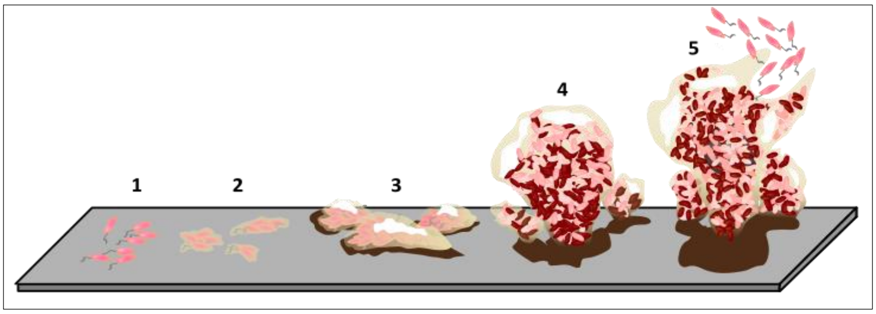

Figure 5. Biofilm development (1 stage - attachment, 2 stage - irreversible attachment and cell-cell adhesion, 3 - proliferation, 4 - maturation, 5 - dispersion) [20]

2.3. PEEK polymer applications

Regarding biocompatibility and bioinertness, the use of PEEK is possible for (Figure 6) [4, 16, 24]:

-creation of partial skull prostheses (surgical body implants),

-implants to stabilize the pelvis,

-intervertebral disc and vertebral body prostheses (e.g. Cerv-XTM implant to support the intervertebral space in the cervical spine from C3 to C7 to promote spinal fusion),

-dentures/ dental implants,

-valve stents,

-non-implants - due high-temperature re-sterilization - application of PEEK medical devices such as surgical instruments.

Figure 6. From left side: PEEK milled implants (derived from CT data for reconstruction), PEEK implant abutment, JUVORA dental PEEK, lumbar interverterbal implants from PEEK with roughened osteoconductive surface (implant IMPLASPIN from LASAK company) [25-28]

2.3. PEEK advantages and disadvantages

Advantages: the modulus of elasticity of PEEK material is comparable to that of human bone. According to ASTM D790 (at temperature 23°C), its value is 3.66 GPa; by applying the appropriate type of reinforcing fibers - it can be increased several times (e.g. PEEK + 30 % glass fibers → modulus of elasticity = 10.3 GPa). This ensures the stability of the PEEK implant (this close or matched elastic modulus weakens or eliminates the stress shielding effect between implant and bone). In addition, it also confers adequate resistance to fracture. PEEK can transmit X-rays, CT or MRI scans without artifacts (it is easy to identify the position of the implant and document the healing process in the bone). In the case of dental implants, it is also an advantage that PEEK-based materials do not generate heat when in contact with a high-speed rotary cutting bur [16, 29-31].

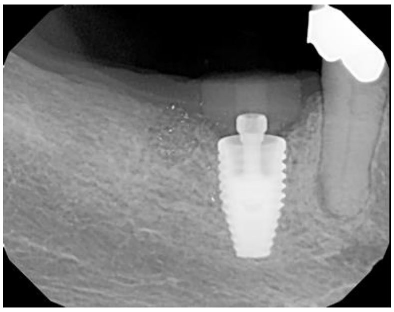

Figure 7. NobelParallel^{TM} CC WP implant (PEEK) [32]

Disadvantages: PEEK (pure, unfilled) demonstrates a low resistance to bending fatigue and bad cell adhesion. For improving osseointegration of PEEK material, there are 3 options [33-35]:

-surface functionalization with bioactive agents (physical or chemical);

-incorporation of bioactive material (as coating or composite material. Example: the addition of inorganic zirconium dioxide microparticles with a diameter < 0.5 µm produces BioHPP;

-or the formation of a porous 3D structure on the surface (Figure 8).

Figure 8. Bone integration (porous PEEK firmy NuVasive) [36]

4. Conclusions

Titanium (and its alloys: Ti-6Al-4V or Ti-6Al-7Nb) is a frequently applied material in prosthetic dentistry. Its disadvantage is the “recipient's” exposure to allergic reactions. Alternatives are zirconium dioxide-based materials or synthetic materials from the PEAK group of polymers. One of the representatives is polyetheretherketone - PEEK. The material is characterized by high functional capability, excellent mechanical properties, high chemical resistance, resistance to radiation/stress cracking, dimensional stability, and last but not least; it does not show a change in mechanical properties after repeated sterilization cycles. Its biocompatibility and bioinertness can be applied in the manufacture of various types of implants and the manufacture of surgical instruments, valvular stents, laparoscopic instruments, etc.

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