

# A Polyaryletherketone Biomaterial for use in Medical Implant Applications

**Dr. Stuart Green**

Victrex plc, Victrex Technology Centre, Hillhouse International, Thornton Cleveleys, Lancashire, FY5 4QD

**Jörg Schlegel**

Victrex Europa GmbH, Zangasse 6, D-65719 Hofheim Germany

## ABSTRACT

A polyaryletherketone biomaterial launched by Victrex® in 1998 and marketed as PEEK-OPTIMA™, is suitable for medical implant use, enabling device manufacturers to make high performance implants with tailored properties that are compatible with modern medical imaging techniques. This family of products, manufactured under conditions of 'no change' has been achieved using enhanced manufacturing procedures, backed-up with extra physical, chemical or mechanical testing at key stages of manufacture. Independent test laboratories have undertaken biocompatibility testing to the relevant parts of ISO 10993 and to USP plastics class VI with excellent results. DMF and MAF files containing the results of these tests have been lodged with the FDA. This paper describes aspects of PEEK-OPTIMA™ manufacture, testing and application.

## 1. INTRODUCTION

### 1.1 POLYMER ADVANTAGES

Since its introduction to the market in April 1998, PEEK-OPTIMA™ has gained increasing acceptance as a high performance implant material. Significant advantages over metals include: the elimination of imaging artefacts, the ability to view tissue/bone growth and repair using x-rays (which can often be obscured with metal parts) and, more generally in this and other applications, the avoidance of allergic tissue reaction to metallic ions. In diagnostics, as well as in postoperative inspection, it is increasingly important to monitor the healing process by modern imaging technologies, like

X-ray, CT or MRI. In an X-ray image, the intensive shadow produced by a metal implant overlaps the area of importance for the surgeon, making it difficult, or even impossible, to adequately inspect. This is similar in CT-imaging where metal implants create artefacts.

PEEK-OPTIMA™ LT polymer is transparent to X-rays and there are no artefacts created in CT images. Because plastics are non-magnetic MRI technologies still can be used with patients that have received a plastic implant. As for allergic reactions to nickel and other metal ions, owing to the high purity of PEEK-OPTIMA™ LT polymer the total amount of metallic ions is very low (ppm and ppb levels) so no allergic reactions are to be expected.

Surface modification technologies can be more easily applied to organic surfaces like PEEK-OPTIMA™ LT polymer than to metal surfaces, which offers additional benefits for components with direct blood contact.

Plastic Processing technology and suitable joining technology as well as more freedom in design and shape offer additional benefits.

### 1.2 PEEK-OPTIMA™ BIOMATERIAL

PEEK-OPTIMA™ is a polyaromatic semicrystalline thermoplastic (30-35% crystallinity typically) with a melting temperature of ~343°C, a crystallisation peak of ~160°C and a glass transition temperature of ~145°C. It can be readily melt processed by injection moulding and extrusion using conventional methods. Three natural (unfilled) grades are available as high, medium and low viscosity variants. All are based on the same basic formula  $(-C_6H_4-O-C_6H_4-O-C_6H_4-CO-)_n$

and are known generally as polyaryletherketones.

Natural, unfilled PEEK-OPTIMA™ is characterised by its high strength, its extreme resistance to hydrolysis and its resistance to the affects of ionising radiation [1]. PEEK™-OPTIMA™ can be repeatedly sterilised using conventional steam, gamma and ethylene oxide without significant deterioration [2].

### 1.3 COMPOUNDS

With the addition of a filler material by a process of compounding, which may be in the form of short carbon or glass fibres, the strength of natural unfilled polymer may be increased significantly in order to cater for greater stress-demanding applications. Stiffness tailoring to bone is also possible with the judicious selection of fibres or other fillers at an appropriate concentration. Such bone modulus matching may be important in applications for which stress shielding should be minimised.

Examples here include the hip stem, dental implants and other stressed bone/biomaterial interfaces. It is widely believed that stress shielding can lead to processes of localised bone remodelling and mass loss, resulting in implant loosening or in weakening of the bony area around the implant, which ultimately may lead to failure.

Figure 1 illustrates the stiffness of a range of implant materials, including short carbon fibre reinforced PEEK™, compared with human femur.

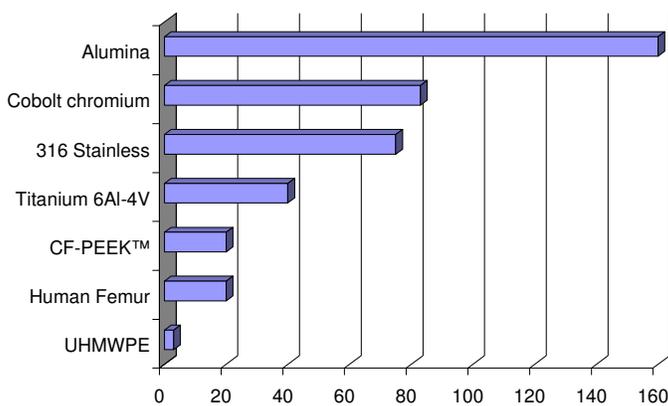


Figure 1.

Implant material stiffness in comparison to human femur

It can be seen from this that alumina ceramics and metals are substantially stiffer than bone whereas UHMWPE at about 3GPa is significantly less stiff. CF-PEEK™ displays about the same modulus with the appropriate selection of fibre type and concentration.

One example of the use of short carbon fibre reinforced polyaryletherketone materials in the body is as an interbody fusion device in the spine. Here, the use of this class of materials in combination with autologous bone, has been shown to provide clinical advantage in terms of more rapid and reliable fusion when compared with allograft bone [3]. The combination of carbon fibres and polyaryletherketone polymer provides a suitable load supporting structure that is translucent to x-rays yet which allows sufficient loads to be transmitted to the developing bone material within its core, stimulating bone formation. This application will be described in more detail later in this paper.

The amount of reinforcing material that can be added using conventional compounding methods (compounding extrusion) reaches a limit when increased viscosity, fibre attrition and poor fibre wet out with polymer lead to difficulties in injection moulding and to poor mechanical properties. The actual limit depends upon the particular polymer/reinforcement combination, the particular compounding screw design and the detailed operation of the compounding extruder. What results is an upper limit to the strength that can be attained using this method, with the effect that materials made in this way may be excluded from applications that demand the highest load bearing capability.

To overcome these limitations, high strength carbon/PEEK™ compounds have been developed with a high fibre content (up to 60% by volume) using pre-preg feedstock through a twin screw compounding extruder. Processing developments with these and similar materials make injection moulded parts such as hip stems a realisable prospect [4]. Indeed, design simulation for hip stems shows favourable stresses and deformations using carbon fibre materials compared with titanium alloys [5] yet despite this, metals currently remain dominant in this sector.

Apart from injection moulding, PEEK™ has been subject to further process development [6] involving a so-called squeeze forming process and fibre fractions up to 61% by volume in an 'endless' fibre format. This process has been used to create bone plate and screw devices with a tensile strength of the order of 300MPa to 400MPa (depending upon the type of fibre) and stiffness in three point bending testing of between 48GPa - 64GPa. Improved fatigue properties are also claimed for these materials [7].

With injection moulded carbon fibre reinforced PEEK™ at more conventional fibre concentrations promising results have been achieved as the bearing surface in an

acetabular cup application [8] with lower wear rates and lower maximum stress/yield stress ratio's reported compared with air-irradiated UHMWPE.

Apart from carbon fibres, other possible material combinations include PEEK™ and titanium as in the Mathys PhysioLogic hip development [9], PEEK™/hydroxyapatite mixtures providing potential biomaterials for orthopaedic applications [10] and glass fibre composites that show 'proliferation and osteocalcin production of human osteoblastic cells' [11]. All of these examples serve to demonstrate the diversity of material forms possible with PEEK-OPTIMA™

Biocompatibility is a critically important concern in materials selection for implant applications. PEEK™ has been assessed in a number of published studies [12-15] and Victrex have undertaken biocompatibility and biostability testing in accordance with ISO 10993 as will be reported here. In summary, PEEK-OPTIMA™ is found to be non-cytotoxic and the foreign body response is similar to that found for UHMWPE.

## 2. PHYSICAL PROPERTIES – resistance to chemical environment and sterilisation

### 2.1 Basic properties

Some key basic mechanical properties for natural unfilled PEEK-OPTIMA™ LT are given in Table 1.

Table 1.

Basic Mechanical Properties of PEEK-OPTIMA™ LT1

Property	Test Method	Units	Value
Tensile Strength	ISO 527	MPa	97
Flexural Strength	ISO 178	MPa	170
Flexural Modulus	ISO 178	GPa	4.1
Notched Impact Strength	ISO 180	KJ/m <sup>2</sup>	>5

The test specimens were injection moulded using standard moulding conditions and tested at ambient temperature (23°C). The tensile specimens were formed as ISO 527 type 1B specimens and were tested at a cross-head speed of 50mm per minute using an Instron 5567 fitted with a 30 kN load cell. In the case of the

notched impact tests, the notches were machined, rather than moulded and testing was completed using a Zwick type 5113.300 pendulum impact rig, fitted with a 1 joule hammer.

Compared with many other polymers, PEEK™-OPTIMA™ shows a remarkable combination of strength, stiffness and toughness properties, and it is precisely for this and biocompatibility reasons that the material is of such high interest for implant use. Furthermore, the material can be injection moulded, extruded and machined, giving device manufacturers greater flexibility in manufacturing process selection than would be the case with other types of materials.

Some mechanical properties for carbon fibre reinforced PEEK-OPTIMA™ with different fibre concentrations are shown in Table 2. Here, the test methods are as indicated in Table 1. All concentrations are weight %.

Table 2.

Basic Mechanical Properties

Short Carbon Fibre Reinforced PEEK-OPTIMA™

Property	20%	25%	30%
Tensile Strength	200	209	228
Flexural Strength	288	290	324
Flexural Modulus	15	17	19
Notched Impact Strength	11	9	9.5

Considerably increased strength and stiffness is apparent as compared with natural unfilled material, as would be expected in common with other fibre/polymer systems.

### 2.2 CHEMICAL RESISTANCE

PEEK-OPTIMA™ LT polymer displays excellent chemical resistance.

To demonstrate this, injection moulded tensile bars were immersed in several different, medically relevant, chemical environments for 7 days at 23, 100 and 200°C where possible. Upon removal, samples were dried and tested in accordance with ASTM-D-638 at ambient temperatures. The measured values of tensile strength were compared with control samples and the response ranked. In Table 3 the results are displayed as an 'A' (no attack, little or no absorption) or 'B' (slight attack)

rating. In none of the cases tested was a ‘C’ rating (severe attack) recorded.

30-day exposure of PEEK-OPTIMA™ LT polymer to environments used to simulate body contact fluids, i.e. sodium chloride solution, glycerol, vegetable oil and an alcohol has shown no effect on the mechanical properties of the material. Compression test on PEEK™ /carbon fibre composites after soaking in physiological saline for up to 5000hrs duration confirm the stability of PEEK™.

Victrix plc is not aware of any commonly used disinfectant or chemical cleaning agent that attacks or initiates stress cracking in PEEK-OPTIMA™ LT.

Table 3.  
Chemical resistance of PEEK™ to medically relevant chemical environments

Chemical	23°C	100°C	200°C
Acetic acid (conc)	A	A	A
Hydrochloric acid (conc)	A	A	
Sulphuric acid <40%	A	A	B
Ethylene glycol	A	A	B
Glycols	A	A	
Methanol	A	A	
Acetone	A	A	
Formaldehyde	A	A	
Aqueous ammonia	A	A	A
Sodium hydroxide 50%	A	A	A
Ethylene oxide (EtO)	A		
Vegetable oils	A	A	
Vaseline	A		
Bleach	A	A	
Brine	A	A	
Detergent solutions (non-phenolic)	A	A	
Urea	A	A	
Fatty acids	A	A	
Sewage	A	A	
Soap solution	A		
Starch	A	A	

### 2.3 STEAM STERILISATION

The chemical structure of polyaryletherketones ensures that they are extremely stable against hydrolysis, even at elevated temperatures. PEEK™ and carbon fibre PEEK™ composites can be steam sterilised repeatedly without degrading mechanical properties [2,16].

### 2.4 RADIATION RESISTANCE

Gamma radiation is sometimes selected as a means of sterilising medical devices. With polymeric materials, as a result of radiation induced cross-linking and/or chain scission, often this can lead to weakening and embrittlement. The resilient chemical structure of PEEK™ makes it very tolerant to gamma radiation. A comparative bar chart is shown in Figure 2, in which the dose for a slight (5%) reduction in flexural strength is recorded for a number of different medical thermoplastic materials.

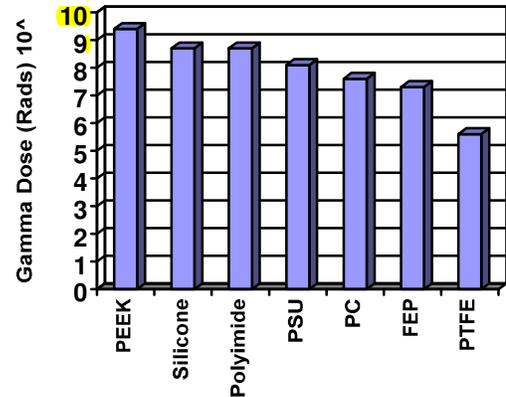


Figure 2.

PEEK™ polymer shows good resistance to gamma radiation sterilisation compared with other polymers.

Note that the dose scale is logarithmic and that PEEK™ displays the highest resistance to gamma radiation induced strength reduction.

### 3. BIOLOGICAL SAFETY- TOXICOLOGY

Victrix manufacturing have undertaken an extensive investigation of PEEK-OPTIMA™ LT polymers in accordance with the ISO 10993 standards to demonstrate their toxicological safety for implantation.

Cytotoxicity (L929-proliferation, ISO 10993-5) and the potential to release substances in cytotoxic concentrations by steam, EtO and gamma irradiation sterilisation cycles, using worst-case conditions (3 cycles each of steam, EtO and Gamma radiation) has been investigated. Extensive chemical analysis of sterilised and non-sterilised samples has been undertaken according to ISO 10993-18 and residual EtO has been measured according to ISO 10993-7.

### 3.1 CYTOTOXICITY TESTING

PEEK™-OPTIMA LT1 and LT2 test specimens were extracted (light protected) with dimethylsulfoxide (DMSO) in complete cell culture medium (DMEM-FBS) for 7 days at 37°C. A surface area to volume ratio of 9cm<sup>2</sup>/ml 1.5% DMSO in DMEM-FBS was used.

Control samples were prepared (7.5% v/v DMSO positive control and 1.5% DMSO in DMEM-FBS incubated at 37°C for 7 days negative control). Suspensions of L 929 mouse cells were then added to controls and different concentrations of extract and these were incubated for 72hrs at 37°C. The protein content of each sample was measured using a colorimetric assay method. There was found to be no inhibition of L-929 cell proliferation. *The results from this study indicate that there is no release of substances in cytotoxic concentrations from either sterilised or non-sterilised PEEK-OPTIMA™ and this is true for all of the sterilisation methods used.*

Biostability has been investigated using similarly prepared specimens, sterilised with gamma radiation, co-incubated on a confluent L929 monolayer cell culture for 11 weeks before testing and afterwards examined for the release of cytotoxic substance in L-929 culture as described. Worst case conditions compared to actual standard requirements were used to characterise the material solubility and to ensure high sensitivity detection of toxic leachable substances on a cellular level. (Maximum dose 75,9kGy, 7 days extraction time, high surface area to volume ratio and organic solvent was added to extraction medium). *No release of substances in cytotoxic concentrations was observed, confirming the stability of this material.* Implantation tests to demonstrate long-term biostability with pre-aged PEEK-OPTIMA™ LT test specimens are ongoing. Interim 3-month implantation results indicate that the biological response is similar to implant grade UHMWPE.

Further biological effects, which depend on design, surface properties, material/tissue, and material/material interactions are not covered by this assessment and shall be evaluated by the manufacturer of the final device based on clinical application.

### 3.2 CHEMICAL ANALYSIS

The results of our chemical analysis, undertaken by a leading independent testing laboratory, confirm the inert properties of PEEK-OPTIMA™ LT. We can show using simulated-use extraction in ethanol-water 1:20 at 40°C for 72hrs that the daily dose of leachable ingredients and leachable substances is below 0.1µg/g (detection limit of the analytical equipment used). An analysis of the total amount of *potentially* leachable substances, measured using gas chromatography of an organic solvent extract, obtained at high temperature, indicates there is no evidence that any harmful ingredients are contained in PEEK-OPTIMA™ LT which may be released during lifetime exposure.

Sterilisation has no impact on the material solubility and the EtO residues are within the limits specified in ISO 10993-7, even following 3 times repeated sterilisation.

Victrex plc holds at the Food and Drug Administration (FDA) Drug and Device master-files (DMF) solely for PEEK-OPTIMA™ LT polymer. These data are in addition to USP VI and toxicity reports of substances used in the manufacture contained in the drug and device masterfiles. Device manufacturers may consult the FDA with permission from Victrex plc to get access to these data.

## 4. PRODUCTION AND QUALITY ASSURANCE

### 4.1 POLYMERISATION AND FILTRATION

PEEK-OPTIMA™ LT polymer feedstock is manufactured on the polymer plant at Victrex's head office in the UK by the high temperature reaction of 4-4 difluorobenzophenone, hydroquinone and sodium carbonate in a diphenyl sulphone solvent. After washing with acetone and water to remove the solvent and reaction bi-products, what results is a white granular powder. Batch selection offers the tightest specification on melt viscosity and melt stability. Subsequently, the polymer powder is melt filtered, extruded and granulated into moulding pellets in a filtered air environment that reflects the conditions of a class 100,000 clean room (Figure 3).



**Figure 3**

PEEK-OPTIMA™ LT is melt-filtered and packaged under a class 100,000 clean room atmosphere.

#### 4.2 QUALITY ASSURANCE

Melt filtration removes particulate inclusions. Compared with Victrex industrial grades, the level of plant cleanliness during the production of PEEK-OPTIMA™ has been enhanced prior to and during the melt filtration operation. Victrex manufacturing procedures have been modified substantially, compared with the standard operating procedures for industrial products, in order to reflect our increased attention to contamination risk and quality assurance. Plant preparation, clean down and inspections at the start of a PEEK-OPTIMA™ campaign and the procedures for on-line inspection of potential contamination have been greatly enhanced in line with the requirements for good manufacturing practice. The frequency of quality inspections has been increased and each batch of polymer produced is checked against key parameters measured by ICP-MS, FTIR, DSC and GPC to give our customers increased confidence in product quality. Further to this, Victrex have identified the critical polymerisation parameters that influence the resultant material and have agreed not to change these parameters for the production of PEEK-OPTIMA™ LT polymers. This offers confidence for long-term customer projects and underlines the long-term supply guarantee Victrex is offering for this material.

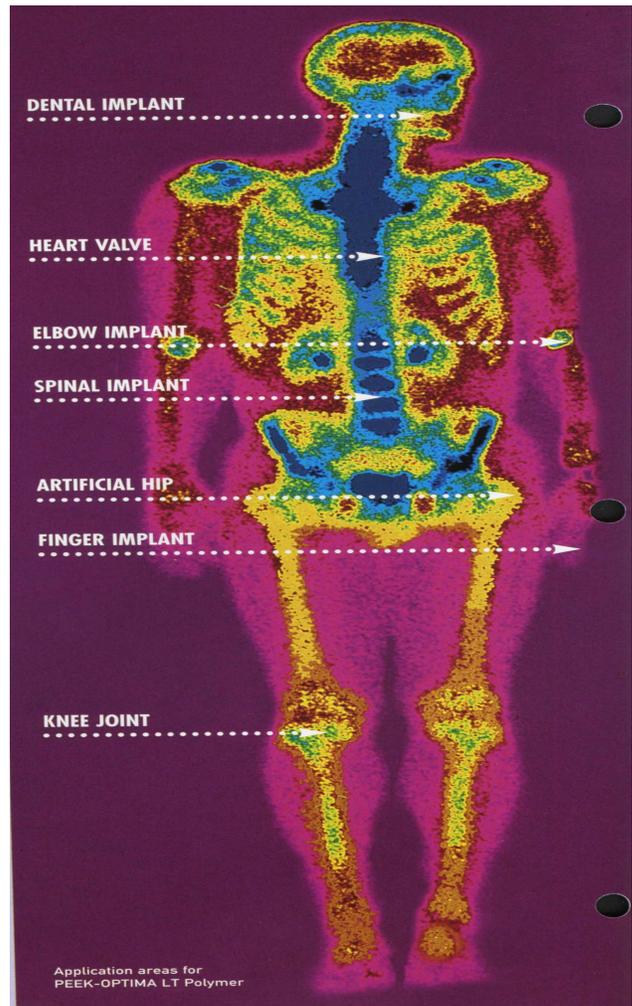
To ensure that the product remains of a high purity quality, the material is directly packaged after melt filtration in double lined, tamper proof drums, suitable for clean-room production.

Victrex plc is certified ISO 9001. All mechanical parameters, thermal transitions and density are double-checked on all batches of PEEK-OPTIMA™ LT polymer by an independent accredited laboratory.

## 5. MEDICAL APPLICATIONS

### 5.1 PEEK-OPTIMA™ POTENTIAL

The remarkable mechanical, chemical resistance and biocompatible properties offered by PEEK-OPTIMA™ LT polymer, compounds and long fibre composites make it an attractive material to be considered for implant use. In consequence, these materials are undergoing evaluation for a variety of different implant applications. Developments are in progress in nearly every area of application where titanium is presently being used. The most important activities are based on orthopaedic applications for structural implants: in joint replacement systems and in spine surgery (especially for cages used in vertebral fusion surgery). Other developments are ongoing in cardiovascular applications, like heart valves and pacemakers, in dental implants for fixation of artificial teeth, housings for electronic devices, sensor housings and others (Fig.4).

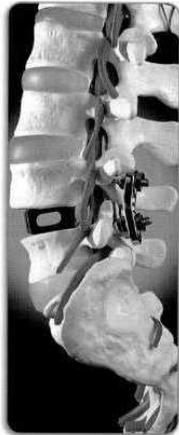


**Figure 4**

The potential application areas for Victrex® PEEK-OPTIMA™ LT polymer are wide-ranging.

## 5.2 SPINE CAGE

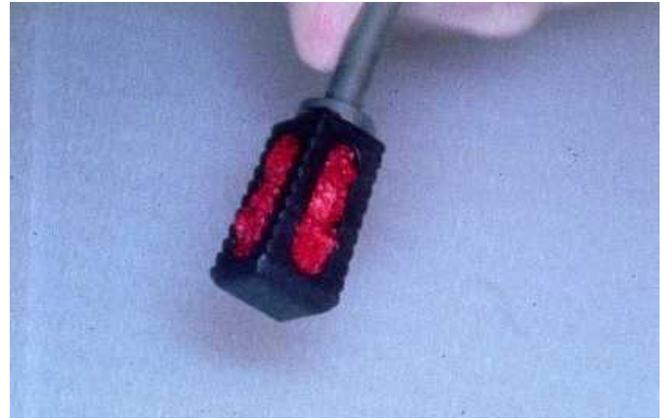
Titanium and PEEK-OPTIMA™ LT compounds materials are in use for interbody lumbar fusion cage implants. Figure 5 illustrates a Posterior Interbody Fusion Device (PLIF) located in the region between two vertebrae.



**Figure 5**

Model showing the location of a PLIF

The advantage of a plastic cage over a metallic one is x-ray translucency, allowing visualisation of the progress of healing by normal radiographic techniques. A further advantage is the reduced implant stiffness, which is more adapted to the stiffness of the surrounding bone. This reduces stress concentrations that are transferred to the bone and stimulates the healing process. In this device, living bone matter from the patient's hip is placed in the hollow core (Fig 6) and the device is inserted between the vertebrae, replacing the worn, diseased or damaged disc. Solid bone forms over time, creating a bony bridge between the adjacent vertebrae, effectively immobilising the joint and fusing the vertebrae together.



**Figure 6**

Carbon-fibre-reinforced implants for lumbar interbody fusion filled with autologous bone.

## 5.3 BONE SCREWS AND PINS

New developments in fibre reinforced composite processing (with a PEEK-OPTIMA™ LT thermoplastic matrix) offer new application possibilities. Bone screws and pins (Fig.7) made out of composite materials offer mechanical values that are similar to titanium or implantable Co-Cr alloys. The flexural strength of these screws and pins is higher than 1000 MPa.



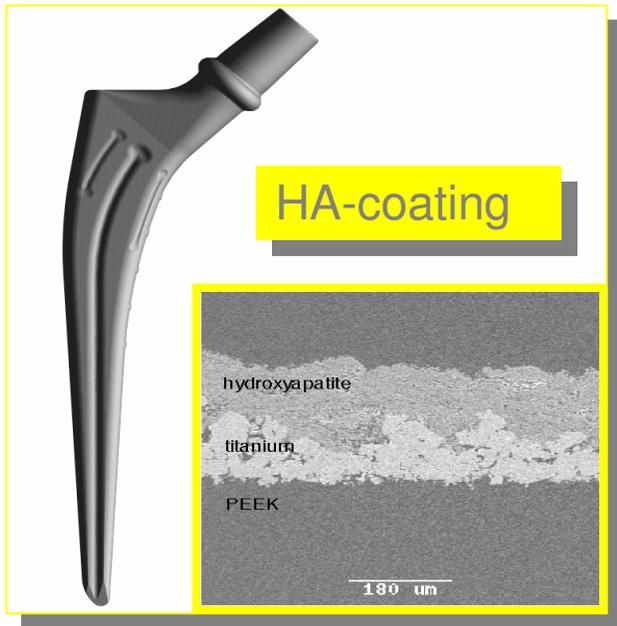
**Figure 7**

Bone screws and pins made out of thermoplastic PEEK-OPTIMA™ LT matrix and reinforced with an endless-carbon fibre system. (Icotec AG, CH)

## 5.4 HIP IMPLANTS

Injection moulding processes with high fibre volume fractions have been developed. This has allowed further developments in the manufacture of high strength (stress critical implants. One such development is an injection moulded hip prostheses (Fig.8).

This prosthesis offers full inspection possibilities by all common visual inspection methods like x-ray, CT and MRI technology. Further the stiffness of the prosthesis is adapted to match that of the surrounding bone, which prevents stress shielding and is regarded as a support for short-term and long-term stability of the system.



**Figure 8**

Injection-moulded hip prostheses based on a thermoplastic PEEK-OPTIMA™ LT matrix compounded with carbon-fibre. Hydroxyapatite coating is possible by using plasma-coating technology (ETH Zürich, CH).

## 5.5 INTRACARDIAC PUMPS FOR MINIMAL INVASIVE SURGERY

The rotor in a biventricular, intracardiac pump system is a further application that was realised by using this high performance polymer. The pump (Fig. 9) can be inserted into the heart through the femoral artery or the femoral vein. This device replaces the heart-lung machine and is less invasive than the existing technologies. The rotor rotates at 34000 revolutions per minute and is able to pump up to 4.2 l/min.



**Figure 9**

The rotor of a micro-axial pump for intracardiac left and right ventricular assistance is made out of Victrex PEEK™ polymer (Impella AG, FRG).

## 6. CONCLUSION

PEEK-OPTIMA™ LT polymer is being investigated for a wide range of medical devices, for long-term implantation and for short-term body contact. The unique combination of biocompatibility, X-ray and CT translucency and MRI compatibility, adjustable mechanical performance, chemical resistance, sterilisation options and the ability to be easily thermally processed makes PEEK-OPTIMA™ LT an interesting alternative material versus titanium or other implantable materials.

## ACKNOWLEDGMENTS

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## REFERENCES

1. Victrex PEEK-OPTIMA™ Product Guide.
2. Andres T.E. and Griffiths I., *Proceedings of 1998 SPE Annual West Regional Meeting, Anaheim, CA* (Soc. Pet. Eng. Richardson, TX, USA, 1998) PP 203-7
3. Brantigan J.W. et al., *Spine* 19, No.13 pp 1436-1444

4. Semadeni M., *Process Development and Materials Optimisation of Injection Moulded Anisotropic (CF/PEEK) Hip Joint Endoprosthesis Stems*. PhD Thesis, ETH No 13177, submitted to the Swiss Federal Institute of Technology, Zurich. 1999.
5. Yildiz H., Chang F., and Goodman S., *J. Biomed Mater Res*, 39, 102-119, 1998
6. Thomas P., et. al., *SAMPE EUROPE/JEC*, Conference 1999, Paris, 13-15 April.
7. Tognini R., et. al., *Twelfth International Conference on Composite Materials (ICCM-12)*. 1999, Paris, France.
8. Polineni V.K., et. al., *Alternative Bearing Surfaces in Total Joint Replacement*, *ASTM STP 1346*, J.J.Jacobs and T.L. Craig, Eds., American Society for Testing and Materials, 1998.
9. Esbach L Nonresorbable polymers in bone surgery, *Injury, Int.J. Care Injured* 31 (2000) S-D22-27.
10. Meenan B.J., McClorey C. and Akay M., *Journal of Materials Science: Materials in Medicine* 11 (2000) PP 481-489.
11. Lin T.W. et. al., *Society for Biomaterials 23<sup>rd</sup> Annual Meeting*, New Orleans, LA, April 30-May 4, 1997.
12. Williams D.F., McNamara A. and Turner R.M., *J.Mater. Sci. Lett.* 6 (1987) 188.
13. Jockisch K.A., Brown S.A., Bauer T.W. and Merritt K., *J. Biomed. Mater. Res.* 26 (1992) 133-146
14. Morrison C., McNair R., McDonald C., Wykman A., Goldie I. and Grant M.H., *Biomaterials* 16 (1995) 987
15. Sevostianov I.B., *Composite Structures* 43 (1998) 109
16. Kwerteng K.B. and Stark C., *SAMPE Quarterly*, October 1990

## DISCLAIMER

The information contained in this paper is based on our general experience and is given in good faith. The data supplied within this publication is subject to the errors associated with the testing standards followed. Application specific test work is strongly recommended for all PEEK-OPTIMA™ LT polymer components.

## CONTACT

For further information on PEEK-OPTIMA™ LT polymer please contact our world-wide headquarters, Victrex Technology Centre, Hillhouse International, Thornton Cleveleys, Lancashire, FY5 4QD, UK. Tel: 01253 897700, Fax: 01253 897781 or visit us on our web site [www.victrex.com](http://www.victrex.com).