PROPERTIES GUIDE

VICTREX™ PEEK

THE FOUNDATION OF VICTREX INNOVATIONS

victrex

Contents

With over 30 years of focus and experience Victrex Polymer Solutions, a division of Victrex plc, is the world's leading manufacturer of high performance Polyaryletherketones (PAEK) including VICTREX™ PEEK polymer. Our product portfolio is one of the broadest range of polyaryletherketones on the market. We work with our customers and end users to deliver technology driven solutions to meet the challenges and opportunities they face and help them to achieve new levels of cost savings, quality and performance in the aerospace, automotive, electronics, energy, industrial, medical and semiconductor markets.

VICTREX PEEK polymer provides exceptional performance over a wide range of temperatures and extreme conditions. It is a linear, aromatic, semi-crystalline polymer widely regarded as one of the highest performing thermoplastics in the world. It provides a unique combination and range of high performance properties.

In addition to VICTREX PEEK polymer, we have two additional PAEK polymers, VICTREX HT™ polymer and VICTREX ST™ polymer that can maintain mechanical performance at increasingly higher temperatures in hostile environments.

When an end use application demands a combination of three or more performance properties our PAEK offer a tremendous material advantage with unmatched versatility. This ability to combine properties without sacrificing performance allows our materials to perform in a wide variety of operating conditions and broad range of applications.

Why Victrex PAEKs?

- Unique combination of properties
- Extensive grade range
- Processed using conventional processing equipment
- Conforming to global approvals and specifications
- Product consistency
- Security of supply
- Supported by expert technical teams globally

High Temperature Performance
Excellent high temperature performance, with glass transition temperatures ranging between 143°C - 162°C and melting temperatures between 343°C - 387°C.

Mechanical Strength & Dimensional Stability
Excellent strength, stiffness, long-term creep and fatigue properties.

Wear Resistance
High abrasion and cut through resistance combined with a low coefficient of friction.

Chemical Resistance
Withstands a wide range of acids, bases, hydrocarbons and organic solvents.

Hydrolysis Resistance
Low moisture absorption, resistant to steam, water and sea water, with low permeability.

Electrical Performance
Electrical properties which are maintained over a wide frequency and temperature range.

Low Smoke and Toxic Gas Emission
Inherently flame retardant without the use of additives. Low toxicity of combustion gases.

Purity
Exceptionally low outgassing and extractables.

Environmentally Friendly
Light weight, fully recyclable, halogen free, and RoHS compliant.

Ease of Processing
One of the highest performing materials melt processable using conventional thermoplastic processing equipment.

VICTREX™ PEEK
The broadest portfolio of polyaryletherketones, including VICTREX™ PEEK polymer. Victrex materials provide exceptional performance over a wide range of temperatures and extreme conditions.

APTIV™ Films
Victrex APTIV™ film provides all of the properties of VICTREX PEEK polymer in a flexible format and is regarded as the most versatile and high performing thermoplastic films available.

VICOTE™ Coatings
Eco-friendly VICOTE™ coatings, available in powder and aqueous dispersions, deliver resistance to high temperatures, exceptional scratch and wear resistance, high strength and durability.

Victrex materials are offered with different melt viscosities to meet specific thermoplastic process requirements: melt viscosity increases from the high flow PEEK 90 polymer to the standard viscosity PEEK 450 polymer. Products may be melt filtered into unfilled granules, milled into fine powders, or compounded using a variety of fillers as well as being available in finished forms such as stock shapes, fibres, films, pipes and coatings. Table 1 gives an overview of the Victrex Polymer Solutions' product portfolio.

Table 1: Victrex Polymer Solutions' Product Portfolio

VICTREX™ PEEK Polymers			
Melt viscosity - polymer	90	150	450
Unfilled Coarse Powder	90P	150P	450P
Unfilled Fine Powder		150PF	450PF
		150XF	
		150UF10	
Unfilled Granules	90G	150G / 150G903BLK	450G / 450G903BLK
Glass Fibre Filled	90GL30	150GL15	450GL15
	90GL60	150GL20	450GL20
		150GL30 / 150GL30BLK	450GL30 / 450GL30BLK
Carbon Fibre Filled	90CA30	150CA30	450CA20
	90HMF20		450CA30
	90HMF40		450CA40
Wear Grades		150FC30	450FC30
		150FW30	450FE20

	VICTREX HT™ Polymers	VICTREX ST™ Polymers
Unfilled Coarse Powder	HT P22 / P45	ST P45
Unfilled Fine Powder	HT P22PF / P45PF	
Unfilled Granules	HT G22 / G45	ST G45
Glass Fibre Filled	HT 22GL30	ST 45GL30
Carbon Fibre Filled	HT 22CA30	ST 45CA30

VICTREX™ Special Products		
Depth-filtered Granules	151G / 381G	Unfilled VICTREX PEEK for extreme purity requirements (fibre spinning, wire coating)
Premium Wear Grades	VICTREX WG™ Polymer WG101, WG102	Outperforming standard wear grades at higher speed / load applications
Electrostatically Dissipative	VICTREX PEEK-ES™ Polymer ESD101 and ESD201	Meeting specific ranges of resistivity

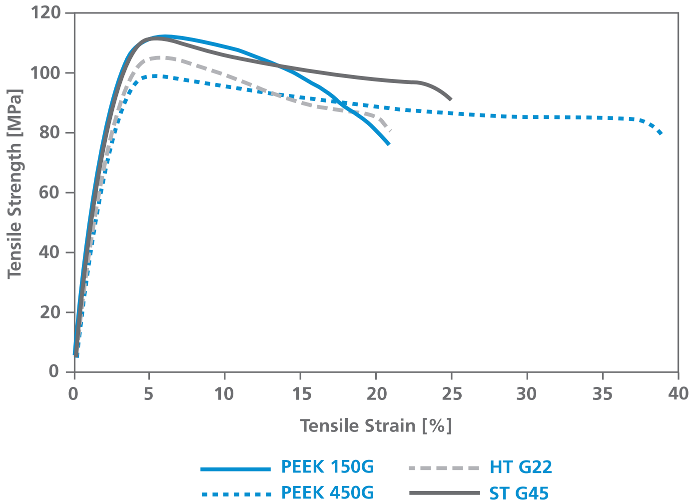
MECHANICAL PROPERTIES

Victrex materials are widely regarded as the highest performing thermoplastic polymers with good retention of mechanical properties over a wide range of temperatures and conditions.

TENSILE PROPERTIES

The tensile properties of Victrex polymers exceed those of most engineering thermoplastics. Tensile performance was evaluated according to ISO 527 and a comparative tensile plot of unfilled Victrex polymers is shown in Figure 1. These unfilled grades show ductile behaviour with a yield point of approximately 5% elongation and a tensile strength exceeding 100MPa.

Figure 1: Typical tensile stress-strain curves for unfilled Victrex polymers



Adding fillers increases strength and stiffness as shown in Figure 2 for a range of PEEK compounds. Filled compounds typically do not exhibit a yield point and therefore break in a brittle way. Tensile modulus, strength and elongation vary significantly depending on the type of filler and filler content.

Figure 2: Typical tensile stress-strain curves for PEEK compounds (450G for comparison)

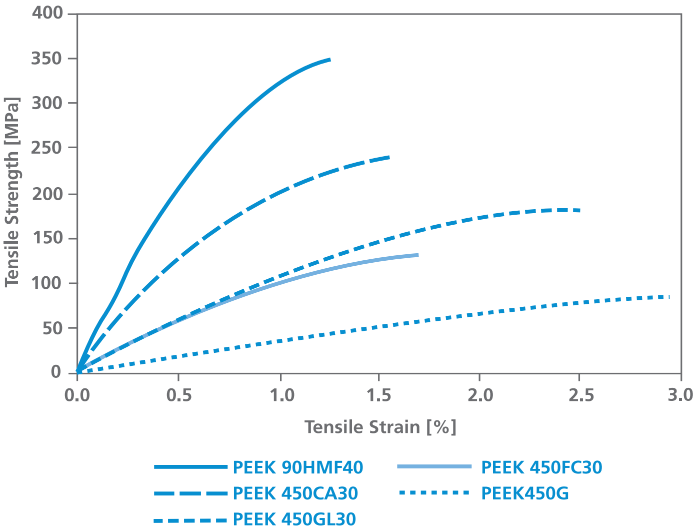
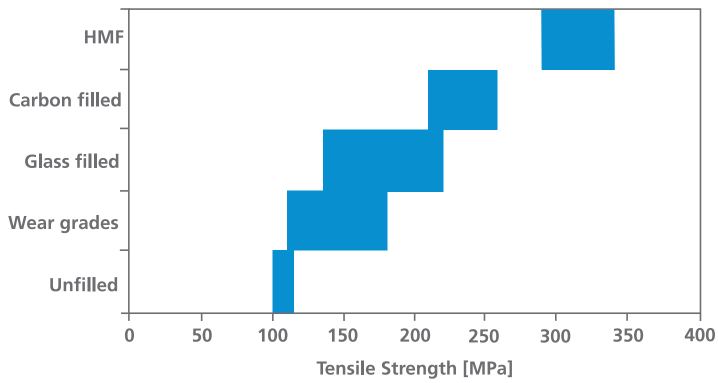


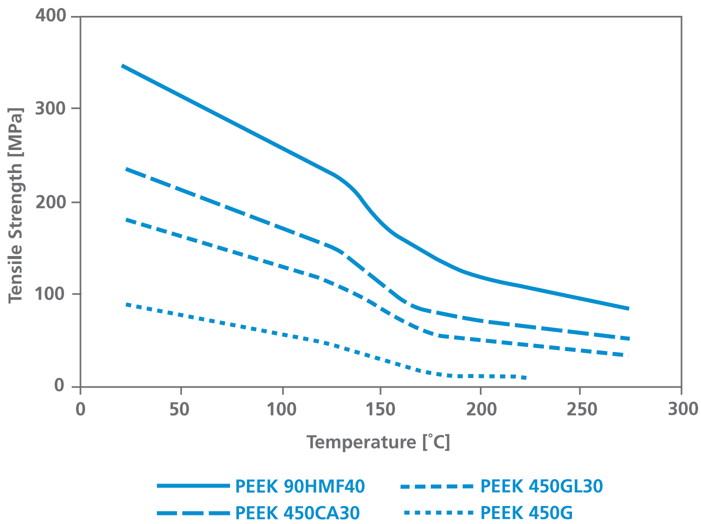
Figure 3 summarises the ranges of tensile strength for unfilled, glass fibre filled and carbon fibre filled materials as well as for wear grades.

Figure 3: Ranges of tensile strength of Victrex materials



Victrex materials are used to form structural components which experience or continually operate at high temperatures. Figure 4 shows a plot of tensile strength versus temperature for a range of Victrex materials and demonstrates a good retention of mechanical properties over a wide temperature range.

Figure 4: Tensile strength versus temperature of various Victrex materials

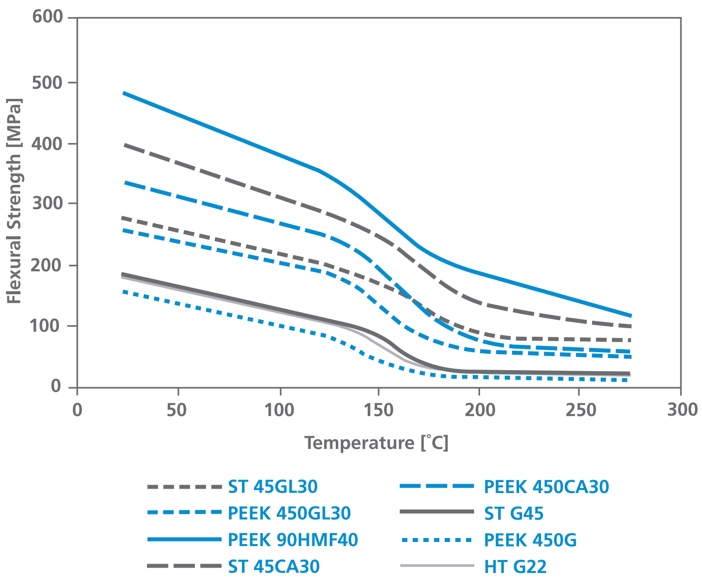


FLEXURAL PROPERTIES

Victrex materials exhibit outstanding flexural performance over a wide temperature range. Flexural strength was evaluated according to ISO 178 with the results plotted versus temperature in Figure 5.

As for all semi-crystalline polymers, flexural strength of Victrex materials is temperature dependent, with a pronounced step-change going through the glass transition (T_g). Even so, values of flexural strength of filled materials can achieve in excess of 200MPa at temperatures above T_g. The improvement in flexural strength retention in these graphs is explained by the increasing T_g going from PEEK, HT to ST.

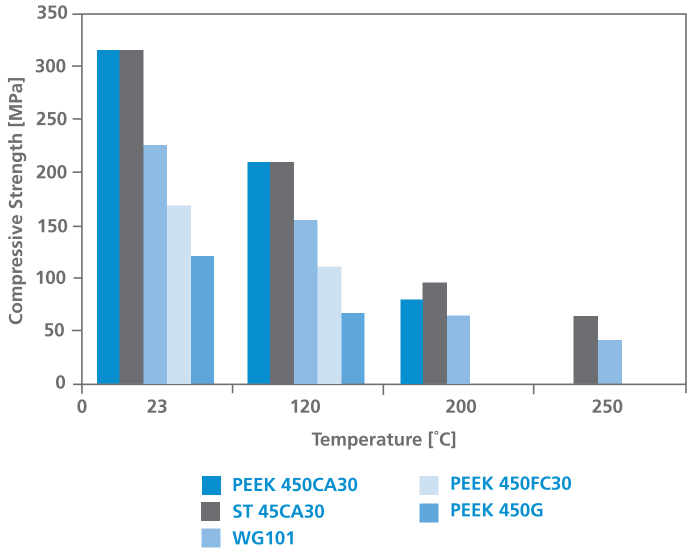
Figure 5: Flexural strength versus temperature of various Victrex materials



COMPRESSIVE PROPERTIES

Compressive strength was evaluated in accordance with ISO 604 at temperatures up to 250°C. Figure 6 shows compressive strength versus temperature for a range of Victrex materials with focus on grades typically used in wear and extreme high pressure applications, and unfilled PEEK 450G as reference.

Figure 6: Compressive strength versus temperature of a range of Victrex materials

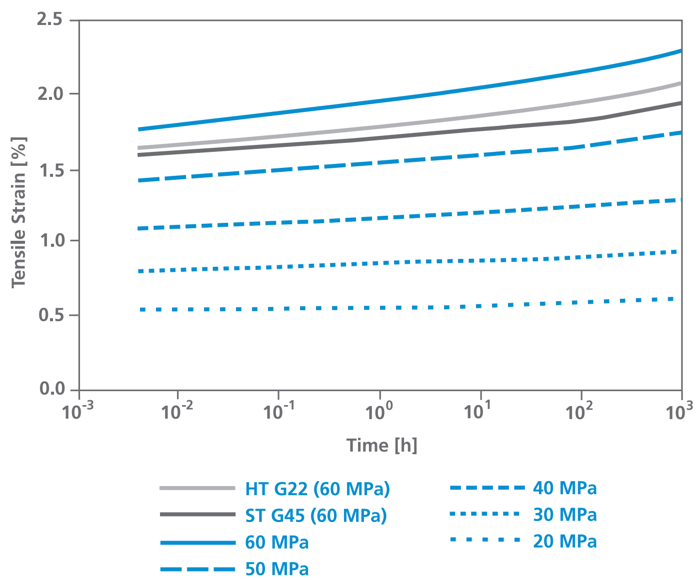


CREEP PROPERTIES

Victrex materials have outstanding creep resistance and may sustain large stresses over a useful service life with little time-dependent deformation. Creep is defined as the deformation observed versus time under a constant applied stress. Tensile creep was evaluated according to ISO 899 at 23°C over a period of 1000h.

Tensile creep results for PEEK 450G at 23°C are shown in Figure 7 for several constant stress levels ranging from 20MPa to 60MPa. HT and ST have been included at 60MPa for comparison. The instantaneous deformation (strain at short creep-times) correlates to the stress-strain relationship derived in a tensile test, accordingly creep curves start at higher elongations with increasing applied loads. HT and ST exhibit slightly lower creep at 60MPa compared to PEEK 450G.

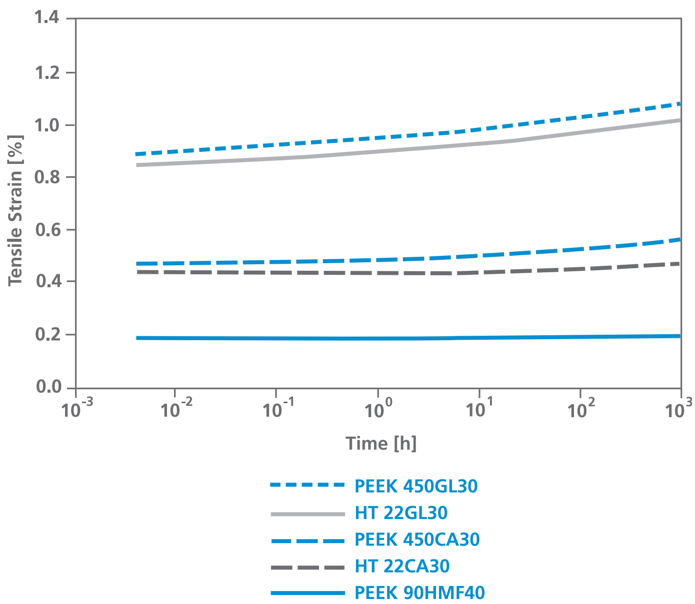
Figure 7: Tensile creep of PEEK 450G, HT and ST at 23°C



Adding fillers to unfilled polymer enhances mechanical performance such as strength and stiffness and therefore creep performance, with the increase dependent upon the type of filler and filler content. The high strength and stiffness characteristics of PEEK and HT compounds under conditions of creep are shown in Figure 8 at 23°C and a constant load of 90MPa.

PEEK 90HMF40, which has the highest strength and stiffness properties of all Victrex materials, demonstrates outstanding creep resistance. PEEK 450CA30 and PEEK 450GL30 are showing somewhat higher measurable time dependent creep at 90MPa compared to PEEK 90HMF40. HT compounds showed slightly improved creep performance opposed to PEEK based equivalents.

Figure 8: Tensile creep of PEEK and HT compounds at 23°C and constant stress of 90MPa

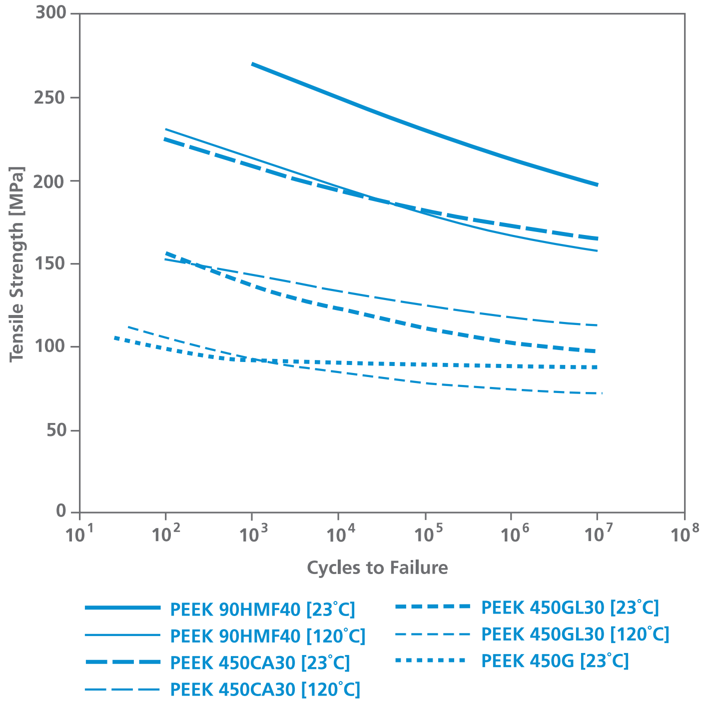


FATIGUE PROPERTIES

Fatigue may be defined as the reduction in mechanical properties during continued cyclic loading. Tensile fatigue was evaluated using ISO tensile bars stressed at 5Hz with a sine wave between 10 and 100% of predefined loads.

Figure 9 shows the excellent fatigue performance at 23°C and 120°C for a range of Victrex materials. PEEK 450G shows very little decay in a tensile fatigue situation at 23°C. Adding fillers to unfilled PEEK enhances fatigue stress levels significantly.

Figure 9: Tensile fatigue of a range of Victrex materials at 5Hz at 23°C and 120°C



IMPACT PROPERTIES

Impact testing is used to investigate the behaviour of materials under specific impact conditions and for estimating their toughness within the limitations inherent to the test conditions. There is a vast variety of test methods, low energy studies performed using pendulum geometry and high energy studies where failures are evaluated using falling weight apparatus. Pendulum geometry may use a cantilever support as in Izod testing (ISO 180) or a 3-point-bending configuration as in Charpy testing (ISO 179); with both using notched or un-notched impact bars.

Figures 10 and 11 show Izod and Charpy impact strength of edgewise loaded samples for a range of Victrex materials, notched and un-notched. Unfilled Victrex materials are extremely tough and do not break in un-notched configuration, Izod or Charpy. Adding fillers to PEEK enhances the notched toughness.

Figure 10: Izod Impact strength of various Victrex materials at 23°C

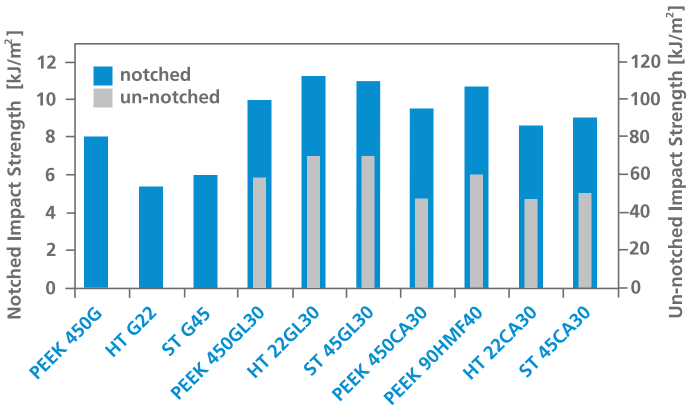
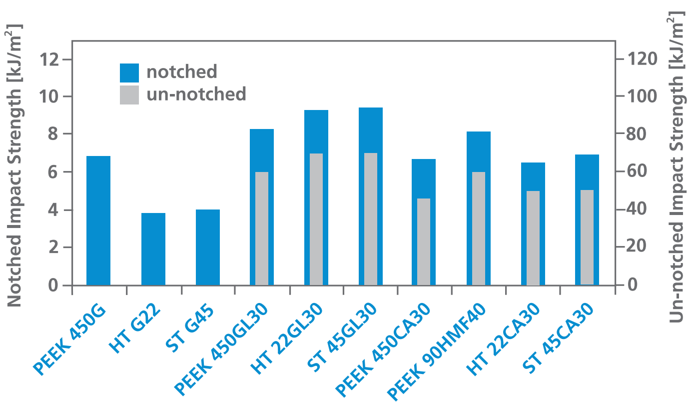


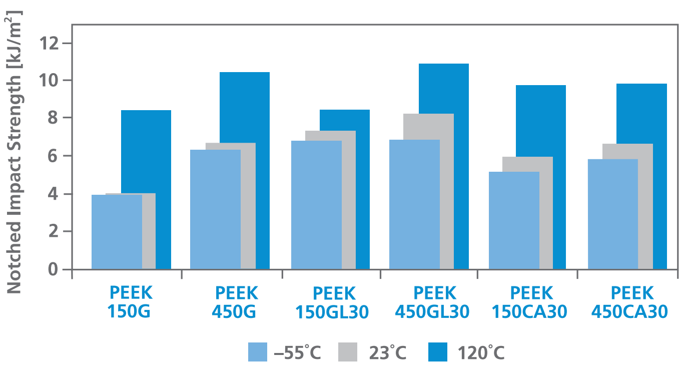
Figure 11: Charpy Impact strength of various Victrex materials at 23˚C



VICTREX™ PEEK polymer specified for aircraft landing gear hubcaps withstanding impacts of flying debris and has excellent environmental resistance in harsh conditions.

Impact properties are temperature dependent as shown in Figure 12 for a range of Victrex materials. An increase in toughness is measured as temperature increases from -55°C to +120°C.

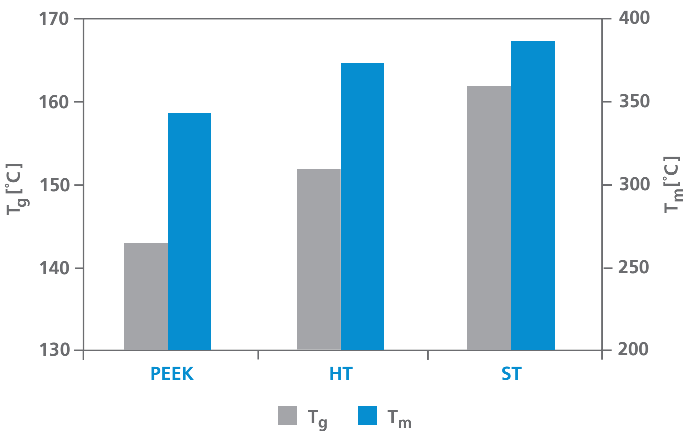
Figure 12: Notched Charpy impact strength versus temperature of various Victrex materials



THERMAL PROPERTIES

Victrex polymers have glass transition (T_g) and crystalline melting temperatures (T_m) in the range shown in Figure 13. Due to the semi-crystalline nature of these polymers a high degree of mechanical properties is retained close to their melting temperatures.

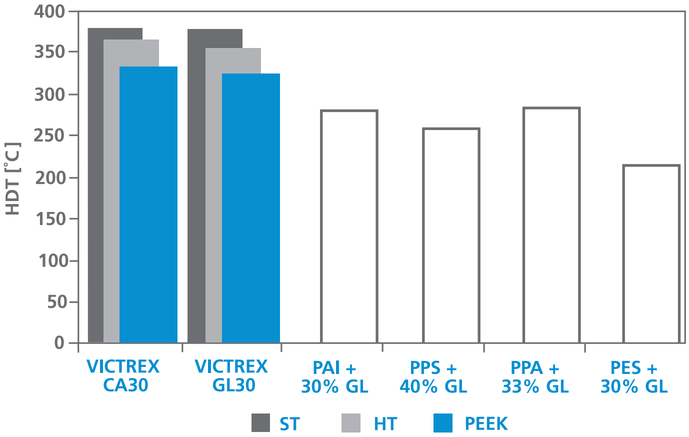
Figure 13: The glass transition (T_g) and crystalline melting temperatures (T_m) for Victrex polymers determined by DSC (ISO 11357)



HEAT DEFLECTION TEMPERATURE

The short term thermal performance of polymers may be characterised by determining the Heat Deflection Temperature (HDT, ISO 75) at which a defined deformation is observed in a sample under constant applied stress (1.8 MPa) at constant heating rate. Victrex materials have excellent stiffness at high temperatures and correspondingly have high HDT values when compared with other high performance polymers.

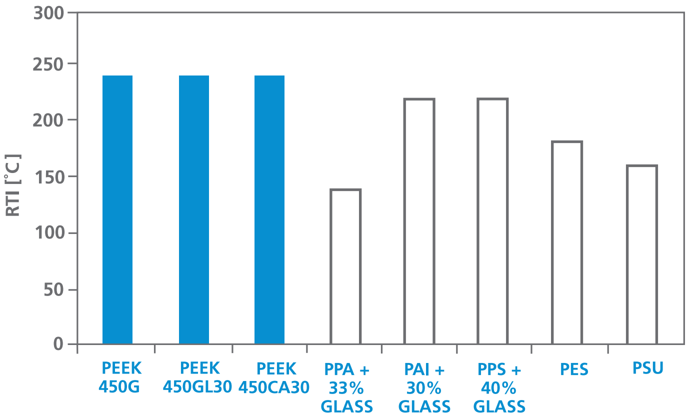
Figure 14: Heat deflection temperature (at 1.8 MPa) for Victrex materials and other high performance polymers



RELATIVE THERMAL INDEX

Polymers are subject to thermal degradation at elevated temperatures. These effects may be evaluated by measuring the Relative Thermal Index (RTI) as defined by Underwriters Laboratories (UL746B). This test determines the temperature at which 50% of a particular material property is retained compared to a control material whose RTI is already known (RTI typically corresponds to extrapolated times between 60,000 and 100,000 hours). The UL RTI rating for Victrex materials compared to other high performance polymers are shown in Figure 15.

Figure 15: Relative Thermal Index (RTI) – mechanical without impact – for a range of high performance materials



HEAT AGEING

The excellent retention of mechanical properties at various ageing temperatures in air for unfilled PEEK was determined as a measure of thermal ageing resistance. Results are shown in Figures 16 and 17. The initial increase in tensile strength observed in Figure 16 is a result of increased crystallinity due to annealing. The subsequent decrease in strength with time is due to thermal degradation.

Figure 16: Retained tensile strength of unfilled PEEK versus conditioning time at high temperatures

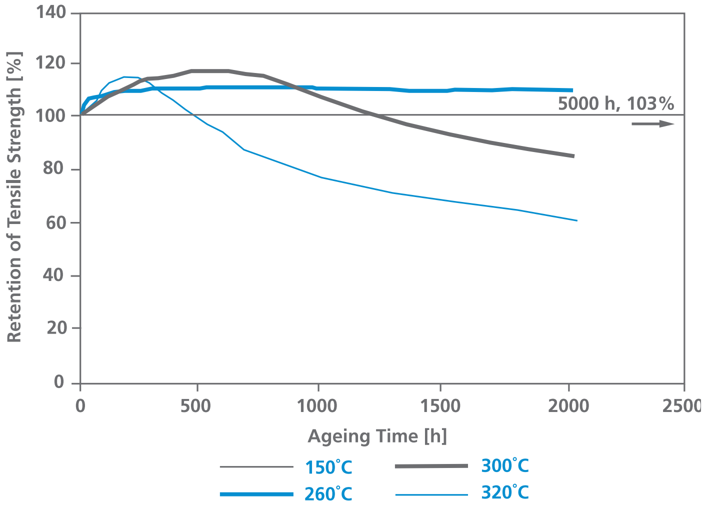
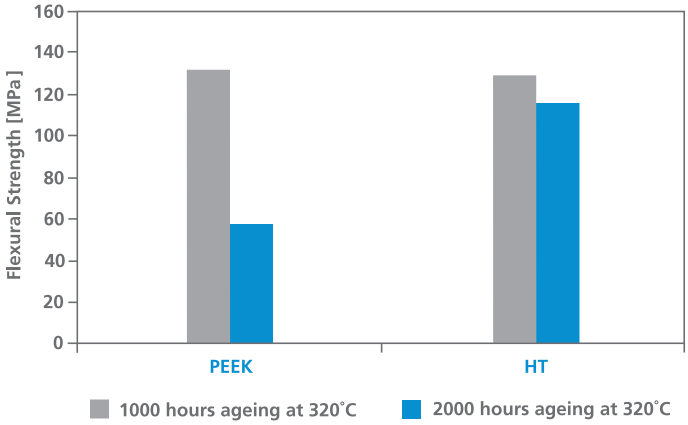


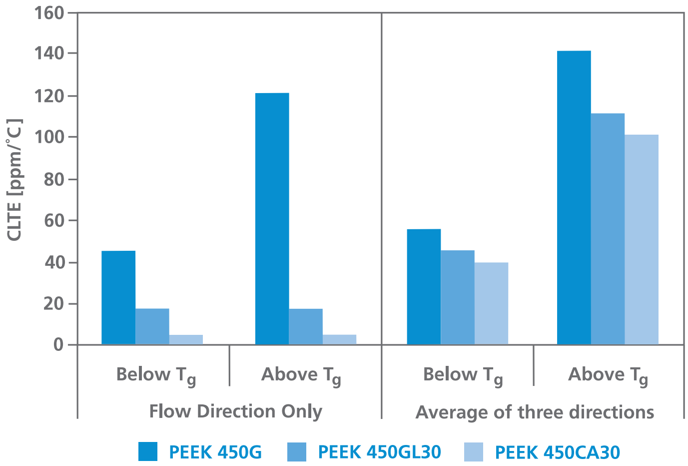
Figure 17: Retained flexural strength following high temperature ageing for unfilled PEEK and HT



COEFFICIENT OF LINEAR THERMAL EXPANSION

The Coefficient of Linear Thermal Expansion (CLTE) was measured according to ISO 11359. Materials were studied in three axes to fully characterise the anisotropic effects of filled grades. Figure 18 shows the variation in CLTE for standard PEEK grades in the flow direction and as an average of all three directions. Unfilled grades such as PEEK 450G are nearly isotropic and have little difference in expansion in different directions. However, glass fibre and carbon fibre-filled grades are anisotropic and as such have low expansion in the flow direction but significantly higher expansion transverse to flow. Also, there is a significant increase in CLTE as temperature is increased above T_g, with the difference lower for compounds, particularly in the flow direction.

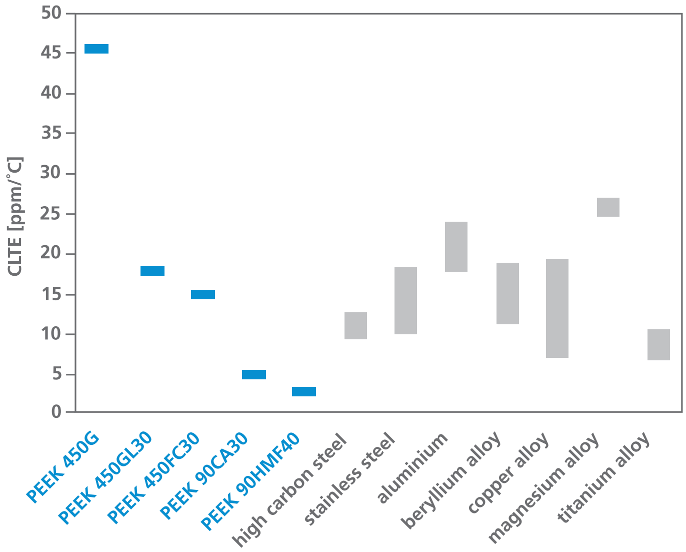
Figure 18: Coefficient of linear thermal expansion (CLTE) for various Victrex materials below and above T_g



VICTREX™ PEEK polymer was selected in a cooling jacket application due to the material's dimensional stability, low radio frequency (RF) losses, and its ability to be precisely machined resulting in a new 1-part design.

The CLTE of a range of Victrex materials below T_g in the flow direction are compared to various metals in Figure 19.

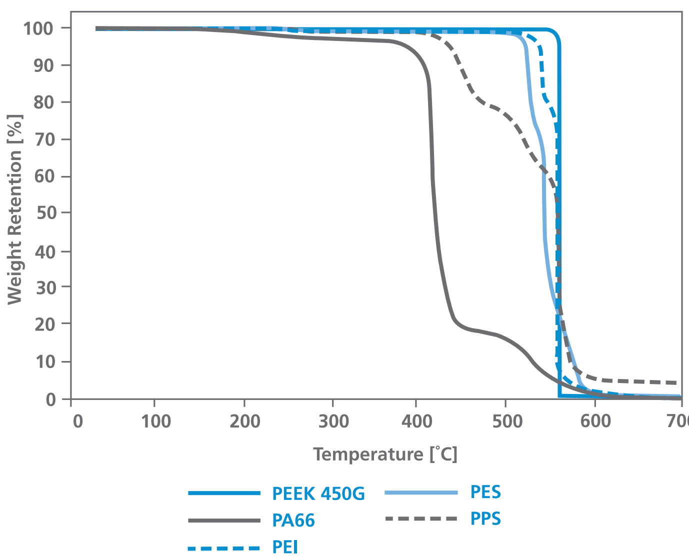
Figure 19: Coefficient of linear thermal expansion (CLTE) for various Victrex materials versus metals (flow direction, below T_g)



THERMAL STABILITY

Thermogravimetry (TGA) illustrates the thermal stability of PEEK in air. Degradation only starts above 550°C with insignificant levels of outgassing at lower temperatures as can be seen in the comparative plot of PEEK 450G and other high performance polymers in Figure 20.

Figure 20: Thermogravimetry (TGA) analysis of PEEK and other high performance polymers



RHEOLOGY

Like most thermoplastic materials the melt viscosity of Victrex materials is temperature dependent and shows shear thinning. A comparative plot of melt viscosity at a shear rate of 1000/s for a range of high performance polymers is shown in Figure 21. Although PEEK has one of the highest processing temperatures, the melt viscosity of PEEK 450G is in the range of polycarbonate melts.

Melt viscosity depends on base resin, filler type and filler level. Materials based on PEEK 450 have higher viscosity than those based on PEEK 150 and PEEK 90. Blending Victrex polymers with fillers such as glass or carbon fibre leads to higher viscosities as can be seen from Figure 22. Based on the high flow grade PEEK 90G compounds with up to 60 weight-% filler content are possible having a lower viscosity than 30% filled compounds of standard viscosity PEEK 450G. The wear grades with 30 weight-% fillers have viscosities similar to other 30% filled products shown in Figure 22.

Figure 21: Melt viscosity at a shear rate of 1000/s at typical processing temperatures for a range of thermoplastics

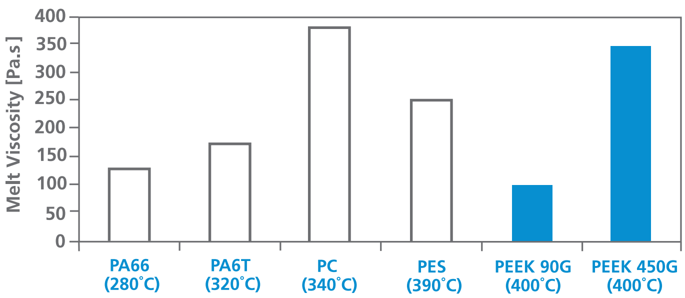
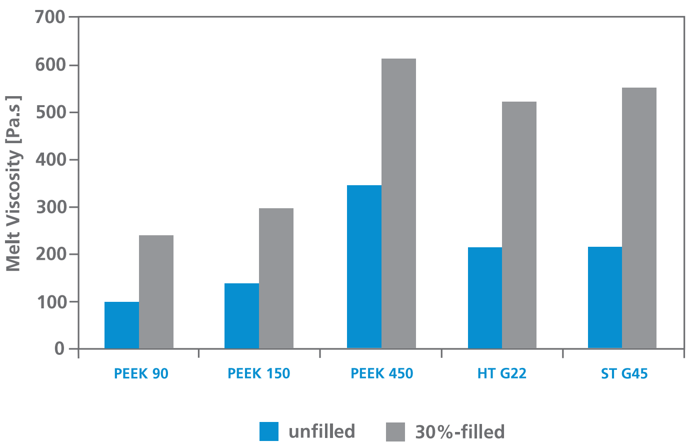
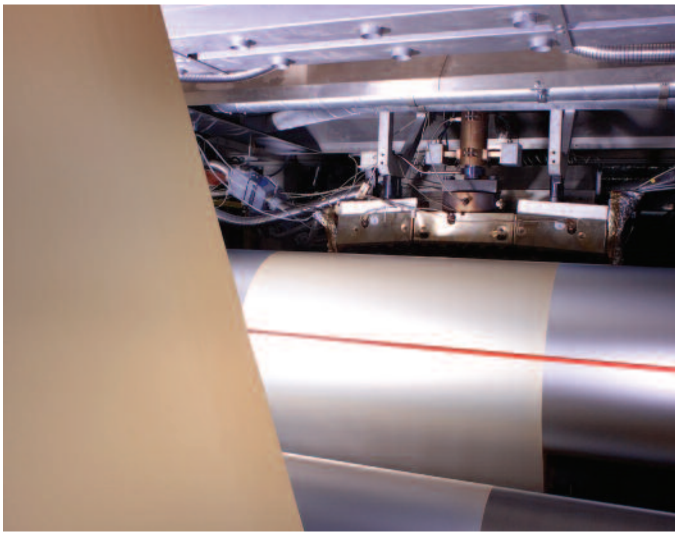
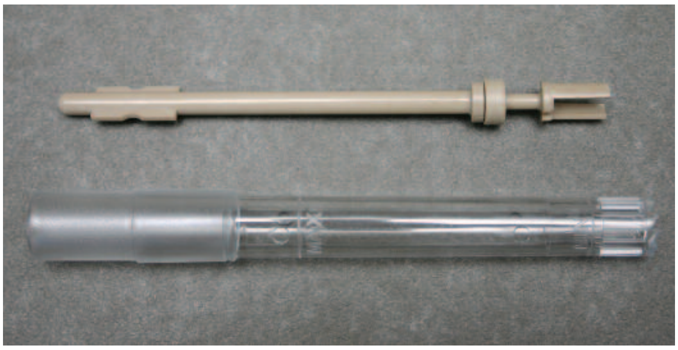


Figure 22: Melt viscosity (1000/s; 400 °C) of various Victrex materials (ST at 420°C)





Rheology of Victrex polymers is suitable for standard injection moulding as well as for critical melt processing technologies such as extrusion of APTIV™ films.



VICTREX™ PEEK polymer replaced steel in high-speed rotors and intricate bearing shells for dispersion instruments used in the medical industry.

FLAMMABILITY AND COMBUSTION PROPERTIES

Flammability can be defined as the ability of a material to support combustion, a flammable material being one which is easily ignited and burns rapidly.

Victrex materials are inherently resistant to combustion, and when they do burn, they produce few toxic or corrosive gases compared with other polymers. The addition of fillers (such as glass or carbon fibre) further improves Victrex materials inherent resistance to combustion.

IGNITION

The Glow Wire Test (IEC 695-2-1) assesses the material's resistance to ignition as well as the ability to self extinguish. Unfilled PEEK and its compounds achieve GWFI 960°C rating – they ignite at 960°C but self extinguish on removal of the glow wire.

FLAMMABILITY

The most widely accepted measure of flammability for plastic materials is the UL94-V vertical burn test which assess the ability of a plastic material to self extinguish once ignited – it is not a measure of the resistance to ignition. Unfilled PEEK 450G achieves UL94-V0 rating at 1.5mm. Glass or carbon fibre filled grades achieve UL94-V0 ratings at 0.5mm over a wide range of filler levels.

SMOKE DENSITY

Burning plastics generate smoke, generally from incomplete combustion. Smoke reduces visibility, making it more difficult to escape from a fire. The smoke levels of Victrex materials are over 95% lower than the limits specified in aviation flammability standards (example: Boeing BSS 7238).

SMOKE, TOXICITY AND CORROSIVITY

Burning plastics generate a range of toxic fire gases, including hydrogen cyanide (HCN), sulphur gases (SO_2, H_2S), nitrous gases (NO, NO_2) and carbon monoxide (CO). These can be more lethal than the fire itself, as they can incapacitate people rendering them unable to escape from the fire. Corrosive fire gases such as hydrogen fluoride (HF) and hydrogen chloride (HCl) will permanently damage sensitive electronic equipment.

The combustion products of Victrex materials are predominantly carbon dioxide (CO_2) and carbon monoxide (CO). The amount of CO is less than 5% of the limits specified in aviation toxicity standards (example Boeing BSS 7239, Airbus ATS-1000).

Toxicity data is usually reported as an amount relative to the amount of gas considered to be fatal to humans. Table 2 shows the result of tests carried out in NBS smoke chamber, which confirms that the only toxic gas generated in significant quantities is carbon monoxide.

Flame resistant VICTREX™ PEEK polymer replaces metal in aerospace P-clamps, saving weight and reducing installation time.

Table 2: Toxicity of Combustion Gases from NBS Smoke Chamber Test

	Test without flame [ppm]		Test with flame [ppm]		Maximum Allowable Concentration [ppm]	
	after 90s	after 4min	after 90s	after 4min	after 90s	after 4min
Carbon monoxide (CO)	Trace	1	30	100	3000	3500
Hydrogen Chloride (HCl)	0	0	0	0	50	500
Hydrogen Cyanide (HCN)	0	0	0	0	100	150
Sulphur-containing gases (H_2S, SO_2)	0	0	0	0	50	100
Oxides of Nitrogen (NO_x)	0	0	0.5	1	50	100
Hydrogen Fluoride (HF)	0	0	0	0	50	50

ELECTRICAL PROPERTIES

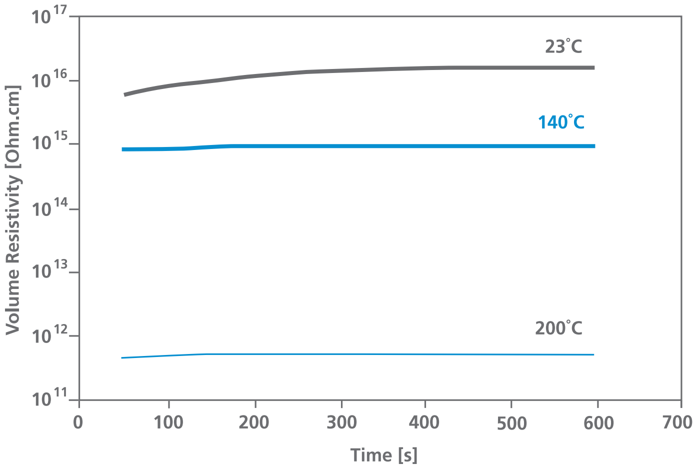
Victrex materials are often used as an electrical insulator with outstanding thermal, environmental resistance and mechanical performance.

VOLUME RESISTIVITY

The volume resistance of a material is defined as the ratio of potential difference [volts] parallel to the current in a material, to the current density [amps].

As with all insulating materials, the change in resistivity with temperature, humidity, component geometry and time may be significant and must be evaluated when designing for operating conditions. These effects are plotted for PEEK 450G in terms of volume resistivity versus electrification time and temperature in Figure 23. HT displays similar volume resistivity properties to PEEK 450G under these conditions.

Figure 23: Volume resistivity versus electrification time at various temperatures for PEEK 450G

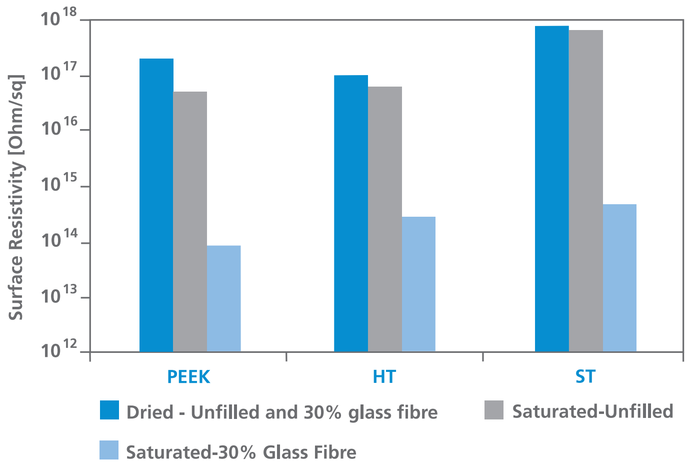


SURFACE RESISTIVITY

The surface resistance of a material is defined as the ratio of the potential difference between two electrodes forming a square geometry on the surface of a specimen and the current which flows between them. Victrex materials have a surface resistivity typical of high performance polymers.

Figure 24 shows the surface resistivity for Victrex materials tested in accordance with ESD S11.11 and the impact of moisture. In all cases the resistivity following immersion is reduced. Larger changes are seen for the filled compounds but PEEK, HT and ST still remain insulating.

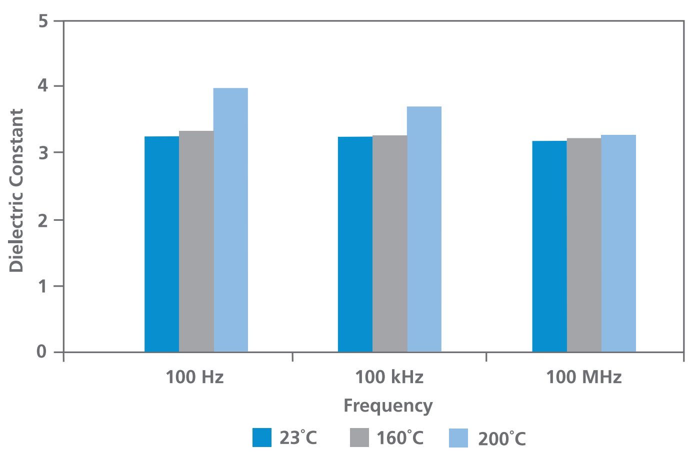
Figure 24: Influence of moisture uptake on the surface resistivity of Victrex materials



DIELECTRIC PROPERTIES

The dielectric constant (or relative permittivity) is the ratio of a material's permittivity to the permittivity of a vacuum. In polymers the dielectric constant is a function of frequency and temperature. Figure 25 shows the dielectric constant for PEEK 450G over a range of temperatures and frequencies.

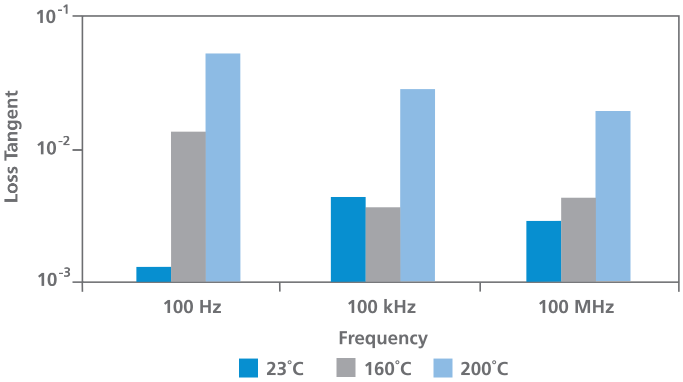
Figure 25: Dielectric constant of PEEK 450G at temperatures between 23˚C and 200˚C and frequencies between 100Hz and 100MHz

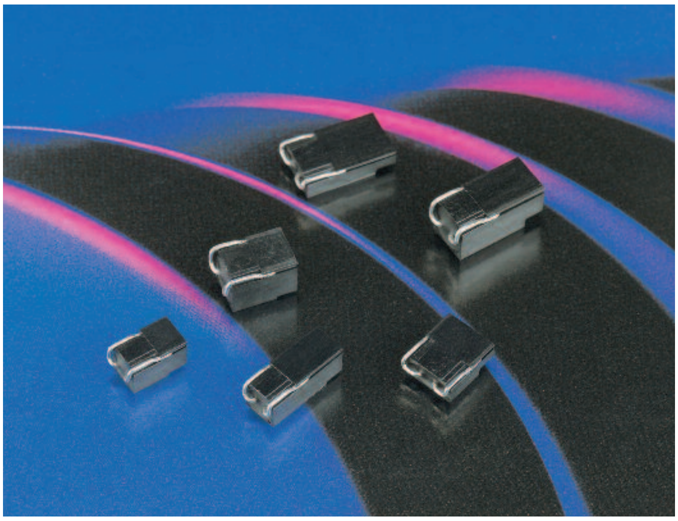


The Loss Tangent (dissipation factor) is expressed as the ratio of the Power Loss in a dielectric material to the Power transmitted through it.

The Loss Tangent for PEEK 450G over a range of temperatures and frequencies is shown in Figure 26. Results are comparable to other high performance materials.

Figure 26: Loss Tangent of PEEK 450G at temperatures between 23˚C and 200˚C and frequencies between 100Hz and 100MHz

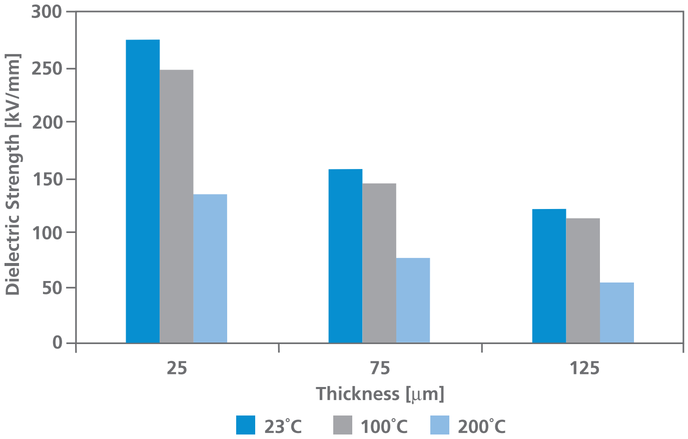


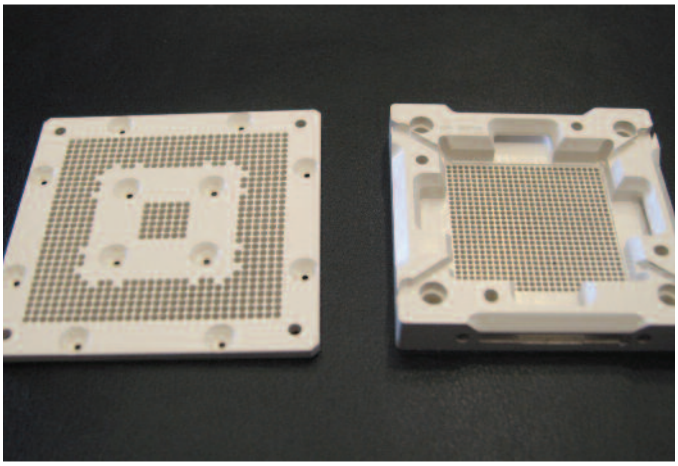


VICTREX™ PEEK polymer is being used for housings of aluminium electrolytic capacitors, meeting the requirements for lead-free soldering technologies in the electronics industry.

The dielectric strength is the voltage required to produce a dielectric breakdown in a material and is a measure of a material's electrical strength as an insulator. Apart from the material type the dielectric strength is also influenced by other factors including sample thickness and temperature. Figure 27 shows the dependency of dielectric strength on thickness and temperature in PEEK films.

Figure 27: Influence of thickness and temperature on the dielectric strength of crystalline PEEK film

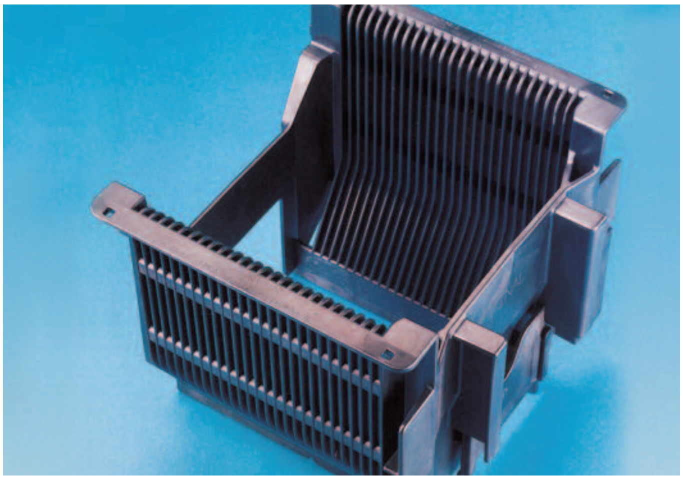




VICTREX™ PEEK polymer is enabling Back-End Test OEMs to enhance their performance with improved machinability to extremely fine pitches with low burr, excellent electrical properties including maintained dielectric properties over multiple cycles.

STATIC DECAY PROPERTIES AND DISSIPATIVE MATERIALS

The retention of a static charge on the surface of a material and the subsequent surface potentials are a concern in many electronic applications. Figure 28 demonstrates the response of three Victrex materials following exposure to a 9kV corona. The suitability of a material in a triboelectrical environment is indicated by the amount of charge that initially couples to the sample's surface and the time it takes to dissipate. The results show that PEEK 450G charges easier and decays slower. PEEK ESD101 is least susceptible to charging with the additional benefit of faster decay times [1/e refers to the time for the initial peak charge to decay to 36.8% of its value measured in seconds].



Wafer cassettes made with VICTREX™ PEEK-ESD™ polymer dissipate static charges in a controlled way, preventing damage to the wafer and preventing wafer contamination due to electrostatic attraction by reducing and preventing electrostatic accumulation.

Figure 28: Static decay characteristics of PEEK 450G, 450CA30 and ESD101

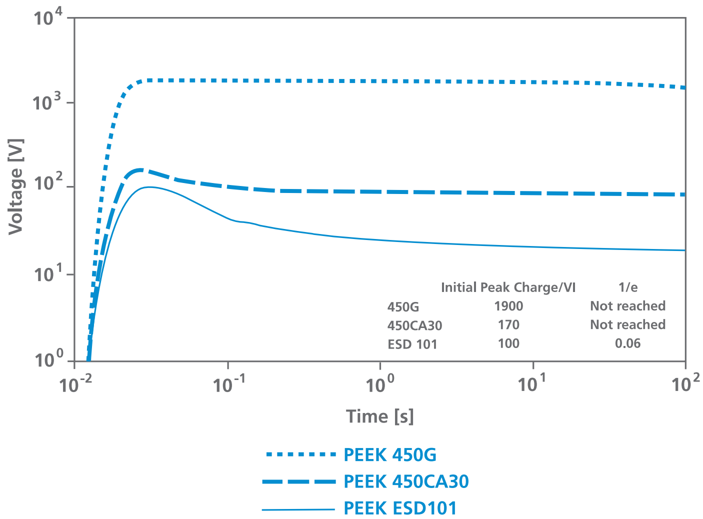
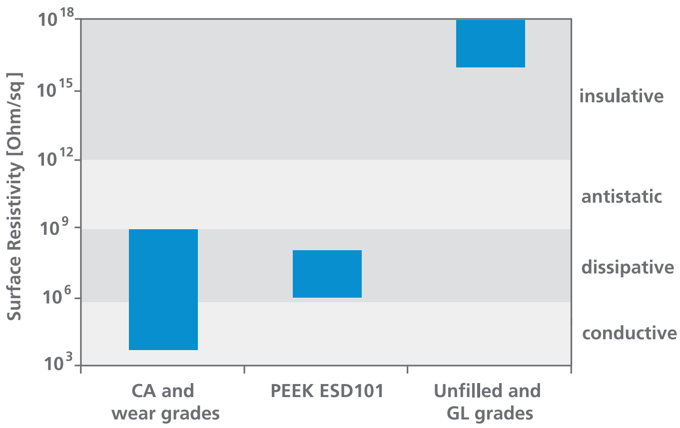


Figure 29: Schematic representation of the resistivity of Victrex materials



In terms of resistivity, PEEK ESD101 is dissipative. It offers tight control of surface resistance within the important ESD region of 10^6 and 10^9.

Other Victrex materials do not offer tight control of surface resistivity, and are either insulating like unfilled or glass filled materials, or they show a large variability of surface resistance within the conductive to dissipative region like carbon filled materials as shown in Figure 29.

Using VICTREX™ PEEK polymer in the manufacture of connectors and sensors allows for excellent dielectric properties over a wide range of temperatures and frequencies in combination with dimensional stability through the lead-free soldering process, mechanical strength, wear resistance and compliance to RoHS.

TRIBOLOGY

Tribology is the branch of engineering that deals with the interaction of contacting surfaces in relative motion under applied load; their design, friction, wear and lubrication.

Victrex materials are used for tribological components due to their outstanding resistance to wear under high pressure and velocity conditions.

FRICTION AND WEAR

Wear is the progressive loss of material from surfaces in relative motion to one another. Wear may make the surface smoother or rougher, due to a range of processes including surface fatigue, abrasive wear and adhesive wear. The lower the wear rate, the better the resistance to wear in that specific wear scenario. The Wear Rate is defined as the rate of height loss in a specific wear environment, but is often reported as Specific Wear Rate or Wear Factor (Wear Rate / (pressure x velocity).

The Wear Rate is influenced by the test conditions (pressure and velocity), it is therefore vital to know whether the Wear Factor is from high speed / low pressure or from low speed / high pressure testing.

Friction is the resistance to sliding motion between two surfaces. It is a dimensionless property (μ), varying with velocity, pressure, temperature, lubrication, the roughness and nature of the contacting surface.

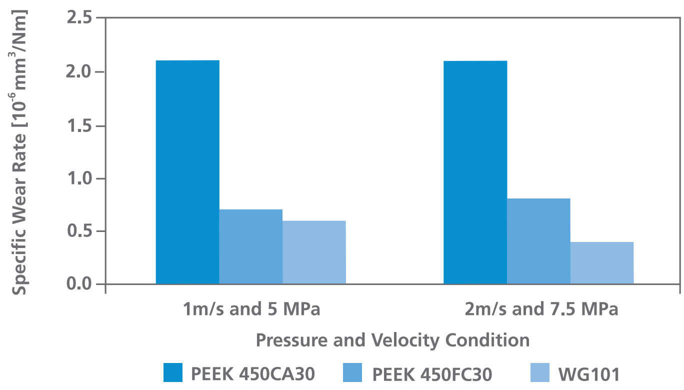
Frictional heating increases the temperature of the component especially in situations where there is limited possibility for heat to be removed from the system. As temperature increases above T_g, for a given material, there is a corresponding increase in wear rate (the material becoming softer).

BLOCK ON RING

The Block on Ring test geometry (ASTM G137) measures the wear resistance of polymers under dry sliding conditions. This configuration is better suited for measurement of steady state wear rates at high loads and speeds which would lead to overheating (premature failure by melting) in the ASTM D3702 thrust washer configuration. Despite the differences in testing configurations, a good correlation in the ranking of wear resistance is achieved between the two methods.

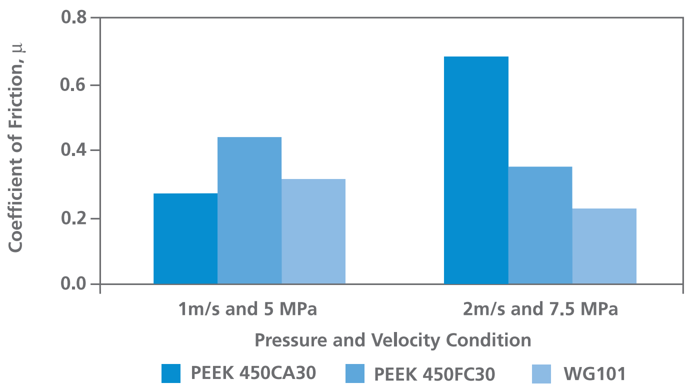
Block on Ring tests on a range of Victrex materials over the pressure and velocity range 5-15 MPa.m/s show that wear grades exhibit significantly lower wear rates than the PEEK 450CA30 reference as can be seen in Figure 30.

Figure 30: Specific wear rate of various Victrex materials tested using the Block on Ring method



There is little difference in the Coefficient of Friction at the low velocity and pressure condition. The Coefficient of Friction of lubricated compounds reduces at higher velocity and pressure conditions, but increases for the non-lubricated PEEK 450CA30 as shown in Figure 31.

Figure 31: Coefficient of Friction of various Victrex materials tested using the Block on Ring method



THRUST WASHER

The ASTM D3702 thrust washer test method (wear rate and coefficient of friction of materials in self-lubricated rubbing contact) is widely used in the automotive industry to compare and rank polymers.

Tests carried out at speeds of 1-4m/s and loads of 0.35-0.65MPa (PV levels 0.35-2.6MPa.m/s) show the effect of formulation on wear performance for a range of Victrex materials and can be seen in Figure 32.

Carbon fibre materials (CA and HMF codes) have reduced wear rate compared with glass fibre compounds (GL codes). Materials with wear additives (FC, FW and WG codes) show the lowest wear rates over these test conditions.

Figure 32: Average wear rates at low PV levels of various Victrex materials tested using the Thrust Washer method

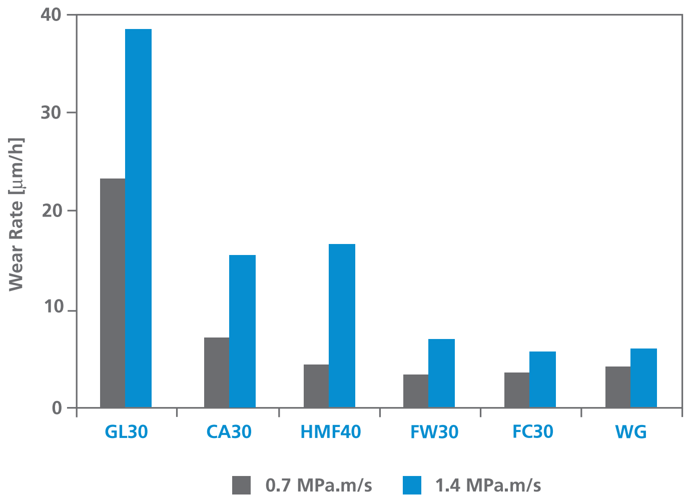
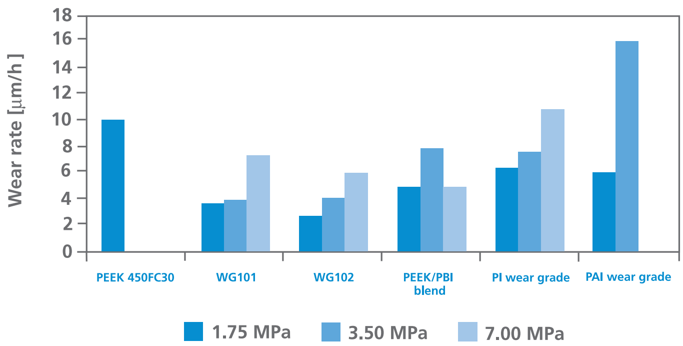


Figure 33 shows wear results from ASTM D3702 testing for Victrex compounds and other high performance polymers used in demanding tribological situations tested to destruction over speeds up to 6m/s. These results show that Victrex WG polymers have better wear performance than other high performance materials.

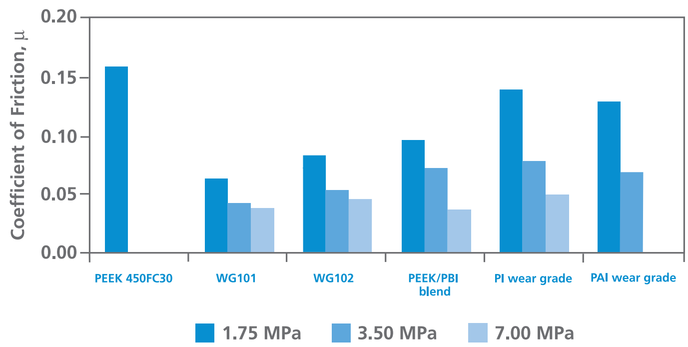
Figure 33: Wear rate of various Victrex materials compared to other high performance materials tested using the Thrust Washer method at 1m/s test speed



*VICTREX PEEK 450FC30 did not survive past the 1.75 MPa test condition, the PAI wear grade did not survive past the 3.5 MPa test condition

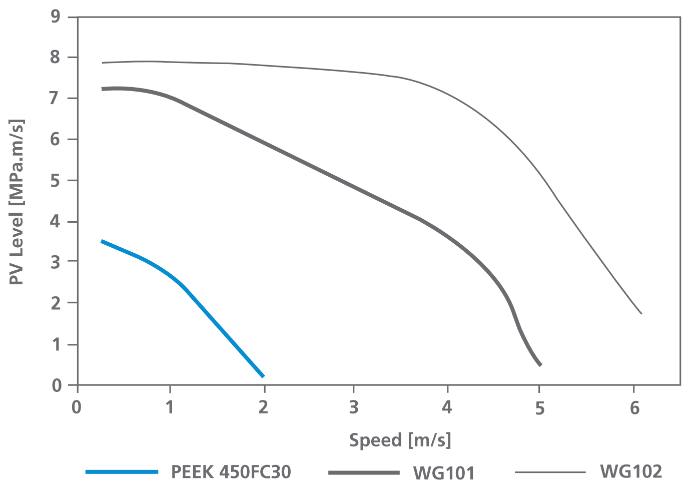
Figure 34 shows that Victrex WG polymers run with lower coefficient of friction than other high performance materials. Note that the coefficient of friction is four times higher than obtained with the block on ring (ASTM G137) method discussed previously.

Figure 34: Coefficient of friction of various Victrex materials compared to other high performance materials tested using the Thrust Washer method at 1m/s test speed



On the basis of ASTM D3702 testing, the application window for Victrex wear compounds is as shown in Figure 35. WG101 and WG102 can be used at significantly higher speeds and PV conditions than 450FC30. WG102 shows superior performance at the highest speeds tested.

Figure 35: Application window for Victrex wear grades



LIMITING PRESSURE AND VELOCITY

Materials used for tribologically sensitive applications are often ranked according to their Limiting PV (L*pv*). The L*pv* is the maximum pressure and speed condition a material survives before exhibiting excessive wear, interfacial melting or crack growth from ploughing. Materials in critical tribological interactions may undergo either a pressure or a velocity induced failure. A pressure induced failure occurs when the loading of a sample increases to the point at which the sample undergoes fatigue crack growth from an asperity removal. A velocity induced failure occurs at the point when the relative motion between surfaces is such that thermal work at the material interface is sufficient to catastrophically increase the wear rate.

Automotive wear test scenarios include applications where high loads are expected with relatively low speeds (such as thrust washers) as well as ones were high speeds are expected with relatively low loads (such as dynamic seals). Under the same PV conditions, thrust washers take higher loads but rotate much slower than dynamic seals.

Testing was carried out with a modified ASTM D3702 thrust washer geometry to obtain L*pv* data at low speeds / high loads and high speeds / low loads.

At low speeds / high loads, all materials tested survived beyond 20MPa load and 0.7m/s speed. Premium wear grades (WG101 and WG102) showed significantly lower coefficients of friction and counterface temperatures than standard Victrex wear materials (150FW30 and 450FC30).

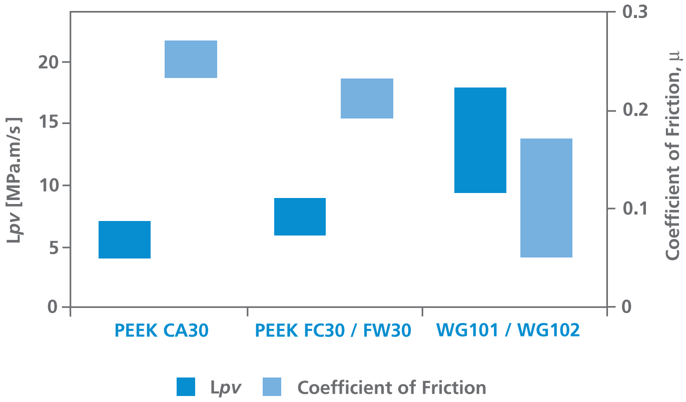
At high speeds / low loads, the compounds showed three different performance categories (with the same ranking as the ASTM G137 block on ring test from Figures 30 and 31), see Figure 36. All samples failed when counterface temperatures exceeded 300°C.

Carbon fibre reinforced, without wear additives (450CA30 and HT 22CA30), have low L*pv* (under 7 MPa.m/s) with high coefficient of friction (0.25).

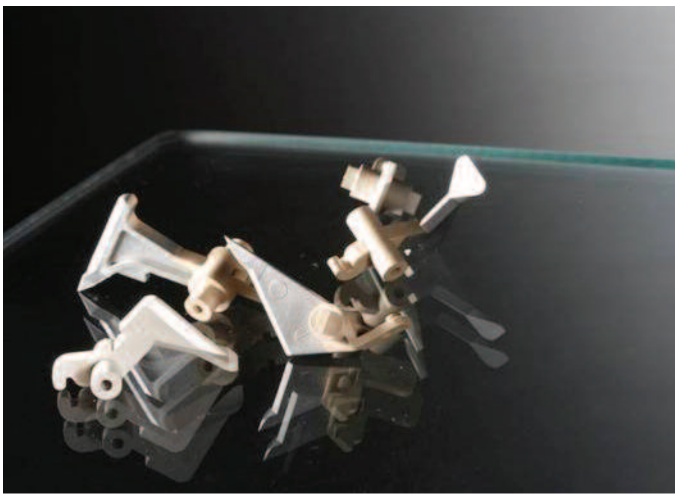
Standard Wear grades (150FW30 and 450FC30) have higher L*pv* (6-9 MPa.m/s) with lower coefficient of friction (0.20).

Premium wear grades (WG101, WG102) have significantly improved L*pv* (10-18 MPa.m/s) with much lower coefficients of friction (0.05-0.15). WG102 survived beyond the maximum load / speed combination in this test.

Figure 36: L*pv* and Coefficient of friction under high speed / low load conditions for Victrex materials



VICTREX™ PEEK polymer replaces iron in design of gears used in balance shaft modules to deliver durability, reliability and improve efficiency.



VICTREX™ HT™ polymer replaced metal with flouropolymer coatings in printer split finger eliminating the need for secondary processing providing high temperature performance in a tribological environment.

Selected for its ability to withstand the high temperatures of the sterilisation process and for its abrasion resistance, VICTREX™ PEEK polymer replaces stainless steel valves and housings in beverage bottling machines.

VICTREX™ PEEK polymer is used as a high-performance liner for wear resistant production tubing in the oil and gas industry exploiting PEEK's resistance to chemicals and gas permeation.

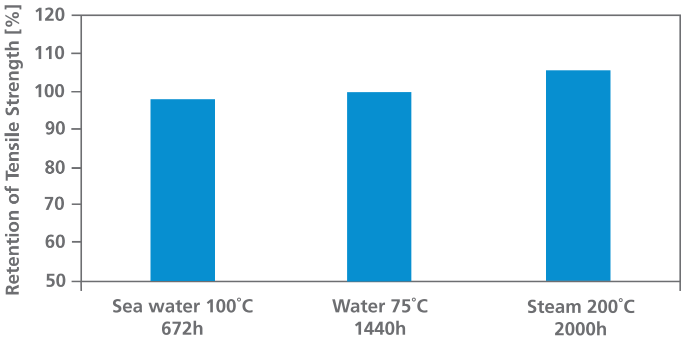
ENVIRONMENTAL RESISTANCE

Victrex polymers exhibit excellent all-round environmental resistance which is retained at elevated temperatures. This means that they can be used to form components which are used in highly aggressive environments such as those in down-hole oil and gas applications or in parts which are exposed to repeated steam sterilisation.

HYDROLYSIS RESISTANCE

Victrex high performance polymers are not attacked by prolonged exposure to water, sea water or steam which makes them an ideal choice for use in applications such as medical components, subsea equipment, and valve components.

Figure 37: Retention of Tensile Strength of PEEK as a function of time in water at 75°C, sea water at 100°C and steam at 200°C and 14 bar pressure



GAS AND LIQUID PERMEATION

PEEK provides an effective barrier to the permeation of fluids and gasses. The solubility of fluids and gasses, the diffusion through and the permeation from PEEK polymer are up to several orders of magnitude lower than other commonly used polymers. Although there is increased polymer chain movement with increased temperature the solubility of gasses remains almost constant with increasing temperature and there is little change in any of the permeation parameters as the glass transition temperature is exceeded. Furthermore, the effect of high pressure is minimal: for example a 100-fold increase in pressure produces only a 10-fold increase in permeation rate. The low solubility of various fluids and gases in PEEK combined with its high modulus ensures that it is not susceptible to the effects of Rapid Gas Decompression.

Table 3: Permeation rates of various common gases through 100µm crystalline PEEK film.

Gas	Permeation Rate $cm^3 m^{-2} day^{-1}$
Carbon Dioxide	420
Helium	1600
Hydrogen	1400
Methane	8
Nitrogen	15
Oxygen	76
Water Vapour	4

Extensive studies of the permeation of gases such as hydrogen sulphide (H_2S) through PEEK pipes have shown that PEEK provides superior barrier properties compared to other high performance polymers as shown in Table 4.

Table 4: Comparative permeation data for PEEK and other high performance polymers

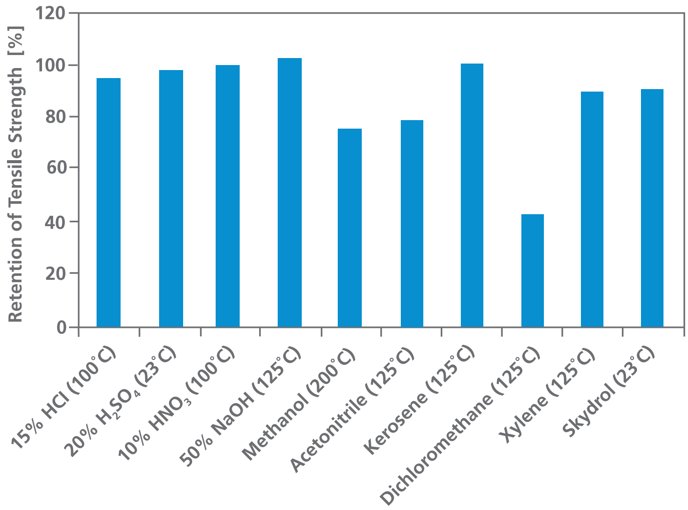
Material	Temperature (°C)	Permeation coefficient Q ($cm^2 s^{-1} atm^{-1}$)	Diffusion coefficient D ($cm^2 s^{-1}$)
PEEK	155	6.2×10^{-9}	6.5×10^{-8}
PEEK	110	1.2×10^{-9}	1.3×10^{-8}
PVDF	100	1.3×10^{-6}	Not available
PA 11	100	6.6×10^{-7}	0.8×10^{-6}

CHEMICAL RESISTANCE

VICTREX PEEK is widely regarded as having excellent resistance to a very wide range of chemical species over a range of temperatures, retaining high levels of mechanical properties and generally with little swelling or discolouration. As an indication of this broad chemical resistance, Figure 38 shows the retention of tensile strength for PEEK 450G after 28 days immersion in a range of chemicals at various temperatures.

A current chemical resistance list is available for download from our website www.victrex.com

Figure 38: Retention of tensile strength of PEEK 450G after 4 weeks immersion in a range of chemical species

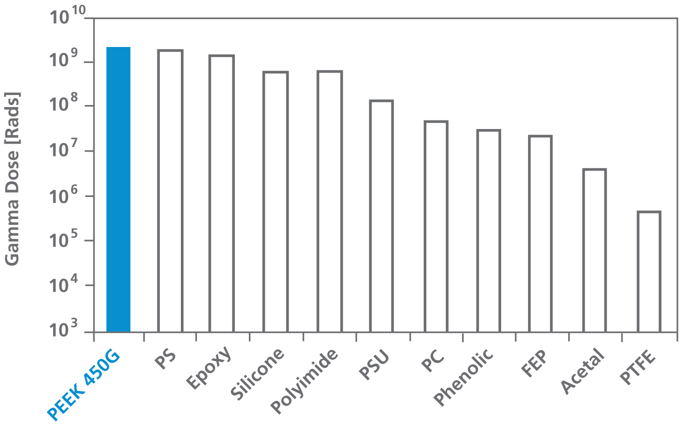


VICTREX™ PEEK polymer used in patented PEEK-SEP membrane technology for the purification of natural gas, VOC abatement and filtration of aggressive solvents in demanding separation applications.

RADIATION RESISTANCE

Thermoplastic materials exposed to electromagnetic or particle based ionising radiation can become brittle. Due to the energetically stable chemical structure of Victrex materials, components can successfully operate in, or be repeatedly sterilised by, high doses of ionising radiation. A comparative bar chart of PEEK 450G and other high performance polymers is shown in Figure 39, where the recorded dose is at the point at which a slight reduction in flexural properties is observed. The data shows that Victrex materials have greater resistance to radiation damage than other high performance polymers.

Figure 39: The oxidative gamma radiation dose at which a slight deterioration of flexural properties occurs



VICTREX™ PEEK polymer provides optimum dimensional stability and purity for wafer contact components in Front Opening Unified Pod (FOUP) silicon wafer technology.

OUTGASSING CHARACTERISTICS

Victrex materials are inherently pure with very small amounts of low molecular weight volatile organics. Table 5 shows data generated in accordance with ASTM E595. Victrex materials were heated to 125°C for 24h under a vacuum of $5x10^{-5}$ Torr. All values are expressed as a percentage of the weight of the test sample. ASTM E595 specifies acceptable limits for TML as 1.0% maximum and for CVCM 0.1% maximum.

Table 5: Outgassing characteristics of various Victrex materials

PEEK	%TML	%CVCM	%WVR
450G	0.26	0.00	0.12
450GL30	0.20	0.00	0.08
450CA30	0.33	0.00	0.12

TML – total mass loss – is the total mass of material that is outgassed from the test sample when maintained at a specific temperature for a specific time.

CVCM – collected volatile condensable material – is the quantity of outgassed matter from the test sample which is condensed and collected at a given temperature and time.

WVR – water vapour regained – is the mass of water regained by the test sample after conditioning at 50% relative humidity at 23°C for 24hours.

APPROVALS AND SPECIFICATIONS

Victrex materials are used extensively across a broad spectrum of applications including Aerospace (Commercial and Defence), Automotive, Marine, Industrial and Energy (Fossil Fuel and Renewable), where end-user approval is necessary to confirm compliance of the finished product to the end-users own standard or an international market sector standard. Specifications are met at various industry leaders such as Airbus, Boeing, Daimler-Chrysler, Bosch and the US Military. Table 6 summaries a number of important global approvals that Victrex materials meet.

Table 6: Summary of global approvals met by Victrex materials

WATER CONTACT

WRAS - (BS 6920)	VICTREX PEEK 450G, 450GL30, 450CA30 and 450FC30 meet the WRAS, (Water Regulations Advisory Scheme) - Effects on Water quality to BS 6920 for non-metallics being suitable for contact with, and for the manufacture of components of water fittings for use in contact with cold and hot water up to 85°C for domestic purposes.
DVGW - (W270)	VICTREX PEEK-unreinforced, GL30, CA30 and FC30 meet the DVGW-(German Association of Gas and Water), standard W270 for Microbial Enhancement on Materials to Come into Contact with Drinking Water – Testing and Assessment.

FOOD CONTACT

2002/72/EC	VICTREX PEEK - unfilled, unfilled black 903, GLxx, GLxx Blk, and VICTREX HT-unfilled comply with the regulations of the European Commission Directive 2002/72/EC and subsequent amendments up to 975/2009, and including the Regulation (EC) No 1935/2004, both in their relevant versions on materials and articles intended to come into contact with food (note - "xx" denotes addition level of filler).
FDA 21 CFR 177.2415	VICTREX PEEK - unfilled, unfilled black 903 GLxx, GLxx Blk, CAxx, FE20, FW30, and VICTREX HT-unfilled comply with the compositional requirements of the regulations for plastics for food contact FDA 21 CFR 177.2415, of the Food and Drug Administration (FDA) of the United States of America.
3A Sanitary Standard for Multiple Use Plastic Materials	VICTREX PEEK unfilled (all grades based on 90, 150, 380 and 450 viscosities), APTIV 1000 and 2000 series extruded films, and VICOTE 700 series milled powders.

FLAMMABILITY

UL94	VICTREX PAEK polymers and compounds conform to the general requirements of UL (Underwriters Laboratory) Flammability Standard 94-V. Grade specific details are available upon request from Victrex plc or through the UL website under reference QMFZ2.E161131.

GENERAL

ISO 9001:2008	The management system of Victrex Manufacturing Ltd has been assessed and certified to ISO 9001:2008 for the Design, Manufacture and Sale of High-performance Polyketones.
REACH	Victrex polymers are exempt from the REACH registration requirements. Monomers used in the polymer manufacture have been pre-registered in accordance with the requirements of REACH. To the best of our knowledge at this time, Victrex products do not contain any SVHC's-(Substance of Very High Concern) >0.1%w/w. It is our policy to monitor all new and existing suppliers to ensure we do not supply material containing Substances of Very High Concern >0.1%w/w.
RoHS	VICTREX PEEK, VICTREX HT, VICTREX ST and Compounds conform to the requirements of Directive 2002/95/EC (27th January 2003) on RoHS-(the Restriction of the use of certain Hazardous Substances in electrical and electronic equipment).
ELV	VICTREX PEEK, VICTREX HT, VICTREX ST and Compounds conform to the requirements of Directive 2000/53/EC for ELV-(End of Life Vehicles). Covering vehicles and end-of life vehicles, including their components and materials.
WEEE	Victrex materials, in conjunction with the Directive for RoHS, conform to the requirements of the European Directive 2002-96-EC for WEEE-(Waste Electrical and Electronic Equipment).
FM 4910 Approval	VICTREX PEEK-unfilled conforms to the requirements of the American National Standard for Cleanroom materials Flammability Test Protocol, ANSI/FM 4910. FM 4910 was developed to meet the need in the semiconductor industry for fire-safe materials.
MITI Approval	VICTREX PEEK has been approved to the MITI-(Ministry of Trade and Industry).
Environmental Policy	Victrex has an environmental policy and operates to an operating permit (reference number BU5640IA) issued and audited by the UK Environment Agency. We also have an internal environmental management system which is audited as part of our ISO 9001:2008 registration.

Victrex Polymer Solutions is constantly exploring new applications for our PAEK-based products, which is continuously increasing the number of approvals and specifications for our products.

Please contact your local Victrex Office or enquire via our website. www.victrex.com

	Condition	Test Method	Units	Unfilled			
				PEEK 90G	PEEK 150/151G	PEEK 381G	PEEK 450G
Mechanical Properties							
Tensile Strength	Yield, 23°C	ISO 527	MPa	110	110	100	100
	Break, 23°C						
	Break, 125°C						
	Break, 175°C						
	Break, 275°C						
Tensile Elongation	23°C	ISO 527	%	15	25	40	45
Tensile Modulus	23°C	ISO 527	GPa	3.7	3.7	3.7	3.7
Flexural Strength	23°C	ISO 178	MPa	180	175	170	165
	125°C			95	90	90	85
	175°C			20	19	18	18
	275°C			14	13	13	13
Flexural Modulus	23°C	ISO 178	GPa	4.3	4.3	4.2	4.1
Compressive Strength	23°C	ISO 604	MPa	120	120	120	120
	120°C			70	70	70	70
	200°C						
	250°C						
Charpy Impact strength	Notched, 23°C	ISO 179/1eA	kJ/m^2	4.0	4.0	6.0	7.0
	Unnotched, 23°C	ISO 179/1U		no break	no break	no break	no break
Izod Impact Strength	Notched, 23°C	ISO 180/A	kJ/m^2	4.5	5.0	6.5	7.5
	Unnotched, 23°C	ISO 180/U		no break	no break	no break	no break
Thermal Properties							
Melting Point		ISO 3146	°C	343	343	343	343
Glass Transition (T_g)	Onset	ISO 3146	°C	143	143	143	143
Coefficient of Thermal Expansion	Along flow <T_g	ISO 11359	ppm/°C	45	45	45	45
	Average <T_g			55	55	55	55
	Along flow >T_g			120	120	120	120
	Average >T_g			140	140	140	140
Heat Deflection Temperature	1.8MPa	ISO 75A-f	°C	156	156	152	152
Thermal Conductivity	23°C	ASTM C177	W/m°C	0.29	0.29	0.29	0.29
RTI	Electrical	UL 746B	°C		260	260	260
	Mechanical without impact				240	240	240
	Mechanical with impact				180	180	180
Flow properties							
Melt Viscosity	400°C	ISO 11443	Pa.s	90	130	300	350
	420°C						
Other Properties							
Density	23°C	ISO 1183	g/cm^3	1.30	1.30	1.30	1.30
Electrical Properties							
Dielectric Strength	2.5mm thickness	IEC 60243-1	kV/mm	16	16	16	16
Comparative Tracking Index	23°C	IEC 60112	V	150	150	150	150
Loss Tangent	23°C, 1MHz	IEC 60250	n/a	0.003	0.003	0.003	0.003
Dielectric Constant	23°C, 1kHz	IEC 60250	n/a	3.3	3.3	3.2	2.8
Volume Resistivity	23°C	IEC 60093	Ωcm	10^{16}	10^{16}	10^{16}	10^{16}
Recommended processing conditions							
Temperature settings	hopper – nozzle		°C	350-365	350-365	350-370	355-375
Mould Temperature (max 250°C)			°C	160-200	160-200	170-200	170-200
Nozzle Temperature			°C	365	365	370	375
Tool Temperature			°C	160	160	170	180
Spiral flow	1mm wall thickness		mm	245	220	130	110
	3mm wall thickness						
Mould Shrinkage	Along flow	ISO 294-4	%	1.0	1.0	1.0	1.0
	Across flow		%	1.3	1.3	1.3	1.3

		Glass fibre reinforced					Carbon fibre reinforced			
HT G22	ST G45	PEEK 90GL30	PEEK 150GL30	PEEK 450GL30	HT 22GL30	ST 45GL30	PEEK 90CA30	PEEK 150CA30	PEEK 450CA30	HT 22CA30
115	115									
		190	190	180	200	200	260	260	260	260
		130	115	115	125	130	180	150	160	170
		80	70	60	75	80	110	95	85	110
		45	40	35	55	50	65	55	50	70
20	20	2.3	2.5	2.7	2.8	2.5	1.3	1.5	1.7	1.6
3.7	4.3	12.0	12.0	11.8	12.0	12.0	27	26	25	26
185	180	290	280	270	300	300	360	360	380	370
110	110	190	190	190	210	200	250	250	250	240
32	36	80	80	80	120	125	120	120	120	170
16	21	50	50	50	85	75	60	60	60	90
4.2	4.1	12.0	11.5	11.3	11.0	11.0	24	23	23	23
140	145	250	250	250	290	290	300	300	300	300
90	90	160	160	160	180	190	200	200	200	210
30	35	55	55	55	75	75	70	70	70	95
					50	50				65
3.8	4.0	7.5	7.5	8.0	9.0	9.5	6.0	6.0	7.0	6.5
no break	no break	45	55	55	70	70	45	45	45	45
5.0	6.0	8.5	9.0	10	11	11	6.0	7.5	9.5	8.5
no break	no break	40	50	60	70	70	40	40	45	45
373	387	343	343	343	373	387	343	343	343	373
152	162	143	143	143	152	162	143	143	143	152
45	45	20	20	18	20	21	5	5	5	5
55	55	45	45	45	45	40	40	40	40	35
75	105	20	20	18	25	23	5	6	6	5
130	125	110	110	110	110	100	90	100	100	90
163	172	335	335	328	360	380	342	339	336	368
0.29	0.29	0.30	0.30	0.30	0.30	0.30	0.95	0.95	0.95	0.95
			240	240						
			240	240				240	240	
			220	220				200	200	
190		220	280	560	500		260	320	675	550
	220					550				
1.30	1.30	1.52	1.52	1.51	1.53	1.53	1.40	1.40	1.40	1.41
17	21	17	17	20	16	19				
150	150	150	150	150	150	150				
0.0035	0.004	0.004	0.004	0.005	0.005	0.004				
	3.0	3.3	3.3	3.2	3.2	3.3				
10^{16}	10^{16}	10^{16}	10^{16}	10^{16}	10^{16}	10^{16}	10^{5}	10^{5}	10^{5}	10^{5}
375-395	375-395	355-370	360-380	360-385	375-395	385-410	360-380	365-385	375-395	380-405
190-215	200-220	170-200	170-200	180-200	190-215	200-220	170-200	180-210	180-210	190-215
395	395	370	380	385	395	410	380	385	395	405
200	200	180	180	190	200	210	190	200	200	200
200	160	185	150	85	105	100	130	140	75	80
	680			410		440			330	
1.0	1.1	0.3	0.3	0.3	0.3	0.3	0.1	0.1	0.1	0.1
1.2	1.2	0.9	0.9	0.9	0.9	0.9	0.5	0.5	0.5	0.7

			Friction and Wear grades				Special Products		
ST 45CA30	PEEK 90HMF20	PEEK 90HMF40	PEEK 150FC30	PEEK 450FC30	PEEK 150FW30	PEEK 450FE20	WG101	WG102	ESD101
270	280	330	150	140	180	78	180	190	120
180	190	220	100	95			125	130	
120	120	145	65	55			85	85	
70	80	85	35	35			55	55	
1.7	1.9	1.2	2.0	2.2	1.8	25	1.9	1.9	1.5
25	22	45	12.5	12.5	15	2.9	19	19	11.5
380	400	480	220	230	270	125	280	290	190
290	290	350					220	220	
190	180	220					140	145	
100	100	120					70	75	
22	20	37	11.5	11.5	14.5	3.2	17	17	10.5
310	270	310	170	170		105	220	250	
210	200	250	110	110		65	160	175	
95	90	120					65	80	
65							45	55	
7.0	7.5	8.0	4.0	5.0			5.0	5.0	
50	60	60	30	35			35	35	
9.0	9.5	10.5	5.0	6.0	5.0	7.5	5.5	6.0	3.5
50	60	60	30	35	35	no break	35	35	25
387	343	343	343	343	343	343	343	373	343
162	143	143	143	143	143	143	143	152	143
10	5.5	3.0	12	15	9	40	9	9	25
40	40	35	45	45	45	60	35	35	40
13	3.0	1.0	15	20	9	120	10	10	70
95	100	80	110	115	110	140	90	90	125
383	347	349	315	315			343	367	
0.95			0.87	0.87			1.30	1.30	
			240	240					
			180	180					
	200	330	290	550	260	340	350	600	275
560									
1.41	1.37	1.45	1.45	1.45	1.43	1.40	1.44	1.44	1.65
						21			
						0.004			
						2.8			
10^5	10^5	10^5	10^8	10^{10}	10^7	10^{15}	10^6	10^7	10^8
390-415	365-385	365-385	360-380	365-385	365-385	355-375	370-390	390-410	365-385
200-230	180-200	190-200	170-200	170-200	170-200	170-200	180-210	190-215	180-220
415	385	380	380	385	385	375	390	410	385
210	190	190	180	200	180	180	200	190	180
90	180	100	130	80	165	130	135	85	140
410				380				360	
0.1	0.0	0.0	0.2	0.3	0.1	1.2	0.0	0.1	0.4
0.7	0.6	0.4	0.7	0.7	0.6	1.7	0.5	0.6	0.5

NOTES

Based in the UK, Victrex is an innovative and world leading global provider of high-performance polymer solutions for the aerospace, automotive, electronics, energy and medical industries. Every day, millions of people rely on products and applications containing our polymers – from smart phones, aircraft and cars all the way to medical devices and oil and gas installations. With over 35 years' experience, we provide cutting-edge technological solutions that shape future performance for our customers and markets and drive value for our shareholders.

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