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In collaboration with:



# MATERIALS GUIDE

Roboze PEEK, Roboze Carbon PEEK, Roboze Carbon PA PRO

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*ADDITIVE DESIGN LAB*

# Roboze PEEK

## TECHNICAL DATA SHEET

# Roboze PEEK



## Overview

Polyetheretherketone (PEEK) is a semi-crystalline, high-performance engineering thermoplastic. It belongs to polyketone family of polymers (PEK, PEEK, PEEKK, PEKK, PEKEKK) and amongst them, it is the most widely used and manufactured in large scale.

PEEK offers a unique combination of mechanical properties such as resistance to chemicals, wear, fatigue and creep, as well as exceptionally high-temperature resistance. It also has good resistance to combustion and good electrical performance.

The high thermal stability is provided by the diphenylene ketone groups, which impart high strength and high resistance to oxidation. Flexibility in the polymer backbone is provided by ether linkages. Due to the semi-crystalline nature of this polymer, its low tendency to creep, and its good sliding and wear, properties are retained over a wide temperature range.

PEEK is known for its excellent chemical resistance to many organic and inorganic chemicals and for its exceptionally good resistance to hydrolysis in hot water. For this reason, the polymer is often subjected to autoclave processes.

## Applications

PEEK finds application in a wide range of industrial sectors. Because of its good wear resistance, mechanical properties, and machinability, mechanical parts can be made of PEEK to replace steel in some applications.

Examples are high-speed rotors, intricate bearing shells, aircraft landing gear hubcaps, and aerospace P-clamps. Polyetherketones are usually not attacked by prolonged exposure to (sea) water or steam, which makes them ideal candidates for use in applications such as medical devices, subsea equipment and valve components.

## Design phase

The preparation of the samples and the execution of the individual tests followed the guidelines imposed by the associated regulations. Analyses on the relevant samples were carried out by an accredited, independent and impartial third party laboratory.<sup>1</sup>

<sup>1</sup>Although data measured in a controlled environment can provide an indication of the chemical/physical and mechanical properties of the material and thus enable comparison between different materials, the results of these tests may not be the same as those observed in the final component.

This phenomenon may be caused by the presence of geometric features or manufacturing conditions that may contribute to modifying the material behaviour. Furthermore, the properties of polymeric materials are a function of both temperature and environmental factors (solar radiation, humidity, etc.), which is why the effect of these variables should also be considered during the design phase, both in the case of short-term and long-term exposure.

In view of the above, it is recommended that a prototype be made in advance during the design phase to empirically verify its properties in the operating conditions required by the specific application.

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## Manufacturing Process

Specimens were manufactured on a Roboze ARGO 500 fed with a filament with a diameter of  $1.75 \pm 0.05$  mm. This thermoplastic filament was subsequently extruded through a 0.6 mm diameter nozzle. To minimize the concentration of water molecules adsorbed and absorbed by the filament due to exposure to the atmospheric environment, before starting the printing process, PEEK spools were subjected to a drying cycle at a temperature of 100°C for 12 hours in HT Dryer.

The temperature of the working chamber was set to 160°C. To allow isothermal conditions within the hot chamber, a 2 hour delay took place before starting the printing process.

Printing conditions for following data tables were:

- Chamber Temperature = 160°C
- Extrusion Temperature = 470°C
- Printing speed = 1200 mm/min
- Layer height = 0,2 mm
- Infill percentage= 100%
- 2 Shells

At the end of the printing process the samples are subjected to the phase of manual removal of the support structures.

The additive manufacturing technology produces intrinsically anisotropic components. As the orientation of the component on the printing plate changes, it will be possible to observe variations in terms of both the properties of the final article and the productivity of the printing process. Keeping in mind what has been written above, it is possible to identify three different orientations on the building plate that are named as follows:

- Flat (or XY)
- On Edge (or XZ)
- Upright (or ZX)

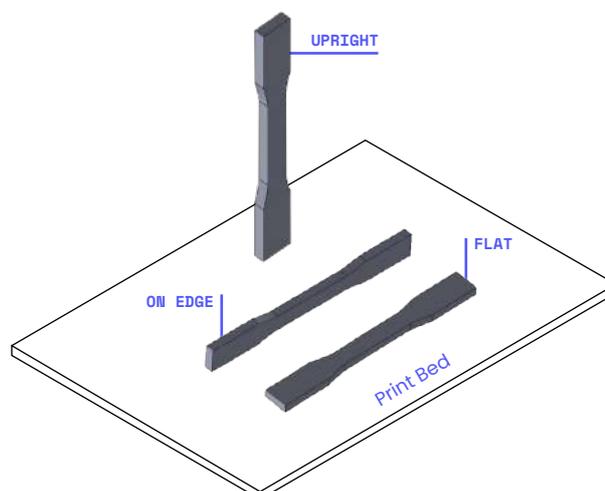


Figure 1 Example of On Edge, Upright and Flat orientation on the building plate

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## PEEK properties Summary

### MECHANICAL PROPERTIES

PROPERTY	OPERATING CONDITIONS	UNITS	ORIENTATION				TEST METHOD
			XZ	XY 0°	XY 45°	ZX	
Tensile Strength	25°C	MPa	95	89,9	87,4	53,0	ASTM D638
Young Modulus	25°C	GPa	3,5	3,5	3,4	3,3	ASTM D638
Elongation at Tensile Strength	25°C	%	4,8	4,7	4,5	1,9	ASTM D638
Tensile Strength	80°C	MPa			66,5		ASTM D638
Young Modulus	80°C	GPa			3,4		ASTM D638
Elongation at Tensile Strength	80°C	%			3,2		ASTM D638
Tensile Strength	120°C	MPa			56,9		ASTM D638
Young Modulus	120°C	GPa			3,3		ASTM D638
Elongation at Tensile Strength	120°C	%			3,0		ASTM D638
Tensile Strength	200°C	MPa			37,2	20,5	ASTM D638
Young Modulus	200°C	GPa			0,5	0,3	ASTM D638
Elongation at Tensile Strength	200°C	%			185	70	ASTM D638
Flexural strength	25°C	MPa			116,0		ASTM D790
Flexural modulus	25°C	GPa			2,8		ASTM D790
Compressive strength @ $\epsilon=1\%$	25°C	MPa				111,8	ASTM D695
Compressive strength @ $\epsilon=20\%$	25°C	MPa				135,0	ASTM D695
Compressive Modulus	25°C	GPa				4,0	ASTM D695
Shore Hardness	D scale				83,7		ASTM D2240
Coefficient of Friction	10 N				0,25		Pin on Disk

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## PEEK properties Summary

### PHYSICAL PROPERTIES

PROPERTY	OPERATING CONDITIONS	UNITS	ORIENTATION				TEST METHOD
			XZ	XY 0°	XY 45°	ZX	
Melting Temperature		°C	338				DSC
Glass transition temperature		°C	146				DSC
Heat Deflection Temperature	1.82 MPa	°C			161		DMTA
Coefficient of Thermal Expansion	20°C - 50°C	10 <sup>-6</sup> K <sup>-1</sup>	46				ASTM E228
Coefficient of Thermal Expansion	20°C - 100°C	10 <sup>-6</sup> K <sup>-1</sup>	48				ASTM E228
Coefficient of Thermal Expansion	20°C - 140°C	10 <sup>-6</sup> K <sup>-1</sup>	52				ASTM E228
Coefficient of Thermal Expansion	150°C - 200°C	10 <sup>-6</sup> K <sup>-1</sup>	127				ASTM E228
Thermal conductivity*	25°C	W/m-K			0,25		
Thermal conductivity	250°C	W/m-K			0,42		
T <sub>5</sub> %	Air	°C	569				TGA
T <sub>5</sub> %	N2	°C	569				TGA
Glow Wire Test – GWFI *	2mm thickness	°C	960				IEC 60695-2-12
Service Temperature*	During lifetime max 200h	°C	260°C				
Insulation Resistance Strip Electrode *	R25	Ω	>10 <sup>12</sup>				DIN IEC 60127 A
Surface Resistance *	ROB	Ω	>10 <sup>12</sup>				DIN IEC 60093
Dielectric Constant *	23°C 1 kHz		3,1				IEC 60250
Dielectric Constant *	23°C 50 Hz		3				IEC 60250

### GENERAL

PROPERTY	OPERATING CONDITIONS	UNITS	VALUE	TEST METHOD
Specific gravity		g/cm <sup>3</sup>	1,31	ISO 1183-3
Water Absorption	23°C/24h	%	<0.1	ISO 62
Melt Volume Rate		cm <sup>3</sup> /10min	22	ISO 1133
Melt Viscosity	400°C	Pa • s	350	ISO 11443
Color			Beige	

\* The information may come from the raw material, the semi-finished product or an estimate. Specific individual tests are recommended according to the application conditions required for the final implementation.

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## Mechanical Properties

### Tensile Properties

The tensile test is a destructive test useful to characterize the properties of materials when subjected to uniaxial tensile loads. A specimen of standard dimensions, having a "dogbone" geometry, is clamped by means of appropriate clamps to two crossbeams.

The movable crossbeam can move upwards, thus bringing the specimen into a tensile state. Once the displacement speed of the crossbar has been set, the load applied and the deformation undergone by the sample are monitored during the test.

In output the system is able to provide a Cartesian graph where on the ordinates is represented the stress ( $\sigma$ ), i.e. the ratio between the force applied to move the mobile crosshead at constant speed and the minimum section of the test specimen "dogbone", while on the abscissae is reported the strain ( $\epsilon$ ) i.e. the percentage ratio between the variation of length of the test specimen with respect to its initial dimensions ( $\Delta\ell$ ) and its nominal length before the start of the test ( $\ell_0$ ).

The stress-strain curve will be a function of the nature of the material. The characteristic parameters that can be derived from this curve are: tensile strength ( $\sigma_M$ ), Young's modulus (E) and strain at break ( $\epsilon_b$ ).

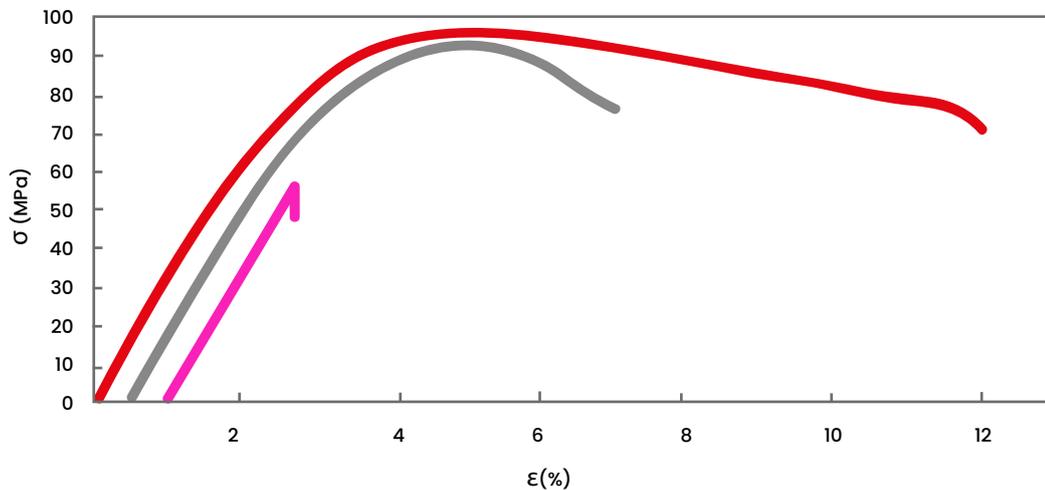


Figure 2 Comparison between tensile test behavior of PEEK samples built in different orientations

The initial section of the curve shows a region of linear elastic deformation. In this region (also called the Hookean region of the material), the material undergoes an instantaneous and reversible strain linearly dependent on the applied stress.

The angular coefficient of the tangent line to the linear elastic region is defined as Young's Modulus, which is the constant of proportionality between the strain undergone by the material and the applied stress. Young's modulus is generally measured from the stresses at 0.05% and 0.25% strain.

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Components manufactured by additive manufacturing have anisotropic mechanical properties. Since the aim of the additive manufacturing process is often to create parts of arbitrarily complex geometry, it is very difficult to align the sample in the direction that maximizes its mechanical properties.

Variations in spatial orientation lead not only to a change in the mechanical strength values of the component, but also affect the fracture mechanism: In the case of samples in XZ orientation, the specimen exhibits greater toughness, showing the phenomenon of necking before the fracture. In the case of specimens printed in ZX orientation, the fracture behavior is typical of a brittle material, since the fracture occurs along the linear elastic stretch of the  $\sigma$ - $\epsilon$  curve.

The standard followed to perform the characterization of the samples was ASTM D638. A speed of 1 mm/min was used to calculate the tensile modulus, thereafter, the speed was increased up to 50 mm/min until the specimen failed. It should be remembered that the results of the tensile test are a function of the set test speed, which is why for a proper comparison between different materials it is important to know in advance the speed at which the test was performed.

*Table 1 Tensile properties of PEEK measured at 25°C for different specimen orientations*

TENSILE TEST ASTM D638	UNIT OF MEASURE	ORIENTATION			
		XZ	XY 0°	XY ±45°	ZX
Tensile Strength	MPa	95	89,9	87,4	53,0
Elongation at Tensile Strength	%	4,8	4,7	4,5	1,9
Young Modulus	GPa	3,4	3,5	3,4	3,3

## Stress-Strain behavior at different temperature

Thermoplastic polymers, by their nature, undergo a progressive reduction of their viscosity with increasing temperature. This leads to a progressive softening of the material until it reaches complete melting.

Obviously, as it is possible to guess, the mechanical properties of the final product will depend on the working temperature: the higher the temperature, the lower the performance of the material. However, semi-crystalline thermoplastic polymers such as PEEK, thanks to the presence of crystalline domains, can maintain high mechanical properties even at temperatures above the glass transition temperature.

The variation of the mechanical properties as a function of temperature can be analyzed by performing tensile tests in a heated chamber at the desired temperature.

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Table 2 Tensile properties of PEEK measured at 80°C for XY ± 45° specimens

TENSILE TEST ASTM D638			
TEMPERATURE		UNIT OF MEASURE	XY ±45°
80°C	Tensile Strength	MPa	66,5
	Young Modulus	GPa	3,4
	Elongation at Tensile Strength	%	3,0

Table 3 Tensile properties of PEEK measured at 120°C for XY ± 45° specimens

TENSILE TEST ASTM D638			
TEMPERATURE		UNIT OF MEASURE	XY ±45°
120°C	Tensile Strength	MPa	56,9
	Young Modulus	GPa	3,3
	Elongation at Tensile Strength	%	3,0

Table 4 Tensile properties of PEEK measured at 200°C for XY ± 45° specimens

TENSILE TEST ASTM D638			
TEMPERATURE		UNIT OF MEASURE	XY ±45°
200°C	Tensile Strength	MPa	37,2
	Young Modulus	GPa	0,5
	Elongation at Tensile Strength	%	185

The variation of tensile strength as a function of temperature for XY ±45° specimens is plotted below.

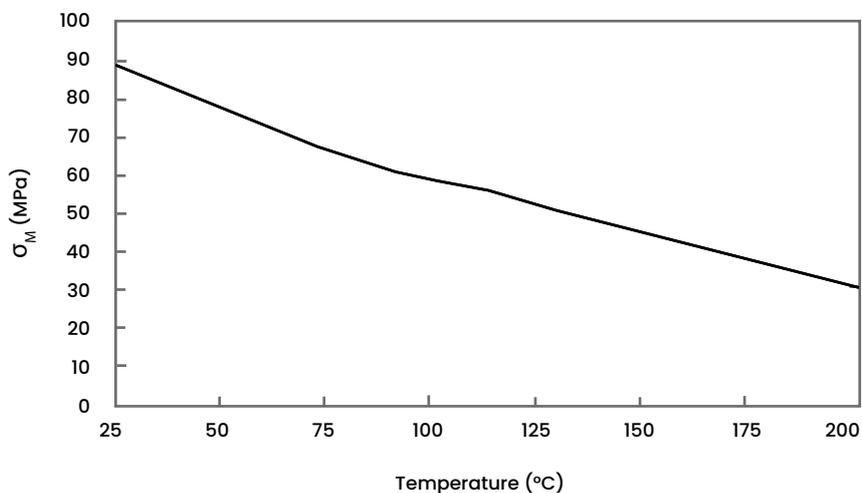


Figure 3 Variation of tensile strength as a function of temperature from 25°C to 200°C

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# Roboze PEEK

## Flexural Properties

During the design phase, the knowledge of the bending behavior of a material, results to be an essential key parameter for the correct structural dimensioning of the component.

Assuming to consider a bar of material supported at two points at the end and loaded with a load in a direction perpendicular to the center, it is possible to demonstrate how the stresses originating inside the body present an axial stress distribution of linear type: the stress  $\sigma$  reaches maximum values in modulus and opposite in sign at the extremes of the section and is zero at the neutral axis.

Reason for which the points below the neutral axis (and therefore the surface on which the applied load insists) will be in a state of compression, while the points above the neutral axis (and therefore belonging to the surface free from the action of the load) will present a state of traction.

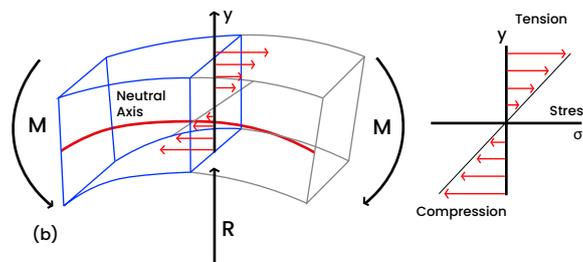


Figure 4 Stress variation along cross section of a beam subjected to flexural loads

The flexural behavior of PEEK was evaluated according to ASTM D790. The samples are bars with dimensions 12.7mm x 127mm x 3.2mm.

The testing speed was set to 1.35 mm/min and the support span was 50.8 mm. The strength is determined by the stress at break while the modulus is calculated by the tangent method.

Table 5 PEEK Flexural Properties

ORIENTATION	$E_f$ (MPa)	$\sigma_f$ (MPa)
XY $\pm 45^\circ$	2,8	116,0

## Compression Properties

Compressive stresses are inherently present in many engineering systems either due to the application of a compressive load directly on the component or due to the application of impact or bending loads. Another phenomenon directly related to compressive loads is buckling, which severely limits the efficiency of systems leading to an underutilization of the real properties of the material.

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The reference standard used for the determination of the compression properties of PEEK was ASTM D695. The specimens used are square-based prisms with different heights depending on whether you want to measure: the modulus or the stress.

The characteristic dimensions of the specimens are as follows:

- Compressive strength: (b) 12.7mm x (h) 12.7mm x (ℓ) 25.4mm
- Modulus of Compression: (b) 12.7mm x (h) 12.7mm x (ℓ) 50.8mm

For both tests, a testing speed of 13 mm/min was set.

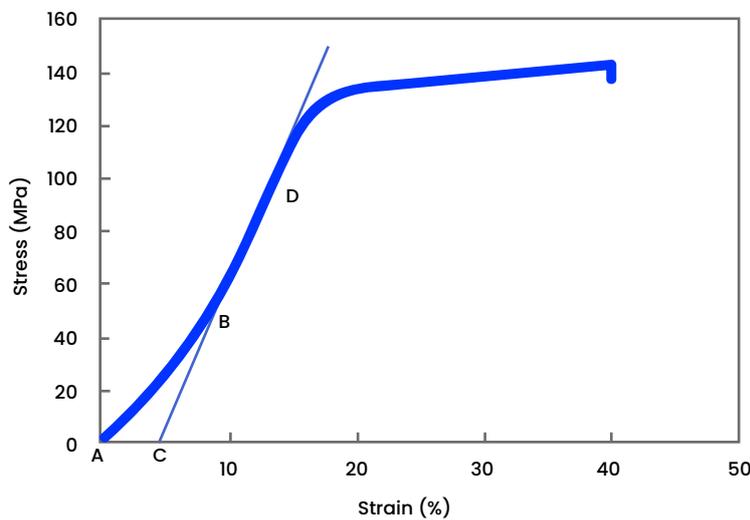


Figure 5 Stress strain curve for a PEEK sample subjected to compression test

Except for the initial toe region AC (typical measurement artifact not representing a property of the material), PEEK shows Hookeian (linear) behavior. The point of intersection (C) between the x-axis and the extension of the linear section (BD) is the corrected point of origin on the x-axis from which all strain were measured.

Table 6 Compressive strength and modulus values of PEEK at 25°C

$E_c$	$\sigma_c @ \epsilon=1\%$	$\sigma_c @ \epsilon=20\%$
4,0	111,8	135,0

The data reported in the table represent the average value of the values measured on samples placed in 15 different spatial coordinates inside the working chamber<sup>2</sup>.

<sup>2</sup> See <https://bit.ly/2ZFVM9v> for more details about the operating procedure.

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## Hardness Test

The hardness is a numerical value that indicates the characteristics of plastic deformability of a material and allow to determine the resistance offered by a material to be penetrated by another (penetrator). The test of hardness used to characterize the behavior of PEEK is the ASTM D2240 Shore D test method. In this test, the specimen is first placed on a hard flat surface. Then the indenter is pressed into the specimen making sure that it is parallel to the surface and finally the hardness is read within a certain amount of time of firm contact with the specimen.

Table 7 Shore D Hardness values of PEEK

SHORE D HARDNESS	ASTM D2240	83,7
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## Coefficient of friction

The debris that originates from the wear process generates a film at the interface between the surface of the sample under examination and the counterpart, which allows to reduce the friction coefficient and facilitate the sliding. Study on tribological properties of PEEK were performed on a pin-on-disc tribometer. The methodology of the test consists in fixing the PEEK disc on a rotating plate and the steel pin (counterpart) is pushed against the disc with 10 N load. The pin stays on the disc with two degrees of freedom: one vertical, which allows its direct contact with the surface of the disc, and the other horizontal, which is responsible for the friction contact. The counterpart is a 100Cr6 steel sphere with a diameter of 6 mm. Before each test, the sphere was washed with acetone to remove any residue and contamination. The test conditions were as follows:

- Applied load: 10 N
- Track radius: 15 mm
- Sliding speed: 20 cm/s
- Sliding distance: 1000 m

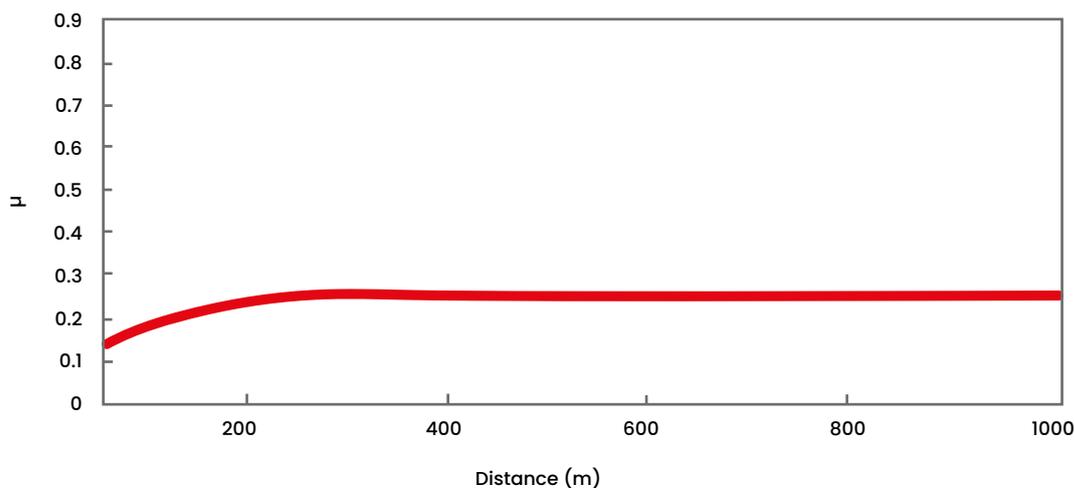


Figure 6 Variation in coefficient of friction as a function of sliding distance

The evolution of the friction coefficient can be observed. Initially, an increase in friction coefficient associated with the initial running-in period was observed then it stabilizes around values of 0,25.

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Table 8 Synthesis of experimental data for pin on disc test

PIN ON DISC TEST CONDITION	VALUE
<ul style="list-style-type: none"> <li>• Applied load: 10 N</li> <li>• Track radius: 15 mm</li> <li>• Speed: 20 cm/s</li> <li>• Distance: 500 m</li> <li>• Pin : Steel 100Cr6</li> </ul>	0,24

## Chemical Compatibility

PEEK is known for its excellent chemical resistance to many organic and inorganic chemicals and for its exceptionally good resistance to hydrolysis in hot water. The aryl rings in PEEK are linked via ketone and ether groups in “para” position (i.e. placed at opposite ends of the ring).

The resonance-stabilized chemical structure of PEEK results in delocalization of higher orbital electrons along the entire macromolecule, making it exceptionally unreactive and intrinsically resistant to chemical degradation.

CHART CODES
R - Resistant
LR - Limited Resistance
NR - Not Recommended
ND - No Data

CHEMICAL	RESISTANCE		
	20°C/68°F	60°C/140°F	100°C/212°F
Acetaldehyde	NR	NR	R
Acetone	R	R	R
Acetylene	R	R	R
Acid fumes	R	R	R
Alcohols	R	R	R
Aliphatic esters	R	R	R
Ammonia, aqueous	R	R	R
Aromatic solvents	R	R	R
Benzene	R	R	R
Carbonic acid	R	R	R
Caustic soda & potash	R	R	R
Chlorobenzene	R	R	R

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Copper salts (most)	R	R	R
Cyclohexane	R	R	R
Detergents, synthetic	R	R	R
Ether	R	R	R
Fatty acids (>C6)	R	R	R
Ferric chloride	R	R	R
Formaldehyde (40%)	R	R	R
Glycol, ethylene	R	R	R
Hydrochloric acid (10%)	R	R	R
Hydrochloric acid (conc.)	R	R	ND
Hydrocyanic acid	R	R	R
Hydrogen peroxide (30%)	R	R	R
Hydrogen peroxide (30 - 90%)	R	R	ND
Hydrogen sulphide	R	R	R
Hypochlorites (Na 12-14%)	NR	NR	NR
Lactic acid (90%)	R	R	R
Mercury	R	R	R
Methanol	R	R	R
Milk products	R	R	R
Moist air	R	R	R
Napthalene	R	R	R
Nickel salts	R	R	R
Nitric acid (<25%)	R	R	R
Nitric acid (50%)	R	R	R
Nitric acid (90%)	NR	NR	NR
Nitric acid (fuming)	NR	NR	NR
Oils, diesel	R	R	R
Oils, essential	R	R	R
Oils, mineral	R	R	R
Oils, vegetable and animal	R	R	R
Ozone	R	R	R
Phosphoric acid (20%)	R	R	R
Phosphoric acid (50%)	R	R	R
Phosphoric acid (95%)	R	R	R
Sea water	R	R	R
Silicone fluids	R	R	R
Silver nitrate	R	R	R
Sodium carbonate	R	R	R
Sulphates (Na, K, Mg, Ca)	R	R	R
Sulphites	R	R	R
Sulphuric acid (<50%)	R	ND	ND
Sulphuric acid (70%)	R	R	R
Sulphuric acid (95%)	NR	NR	NR
Urea (30%)	R	R	R
Water, distilled	R	R	R
Water, soft	R	R	R
Water, hard	R	R	R

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## Thermal Properties

### Glass Transition and melting temperature

Unlike thermosetting polymers, when heated, thermoplastic polymers undergo a progressive softening process until they reach complete melting. The energy supplied through heat irradiation can weaken and progressively break the Van der Waals bonds between the various polymer chains.

This phenomenon involves a reduction in the stiffness of the polymer, which ends behaving as an elastic solid and begins to assume the typical behavior of a viscoelastic material.

The higher the temperature, the greater the viscous component will be compared to the elastic one. Glass transition temperature ( $T_g$ ) is described as the temperature at which 30-50 carbon chains of the amorphous region start to move. As the temperature rises, the energy supplied to the system increases, allowing the progressive dissolution of the crystalline domains. The temperature at which this phenomenon occurs is called melting temperature ( $T_m$ ).

The technique that allows to determine the  $T_g$  and the  $T_m$  is the Differential scanning calorimetry (DSC).

DSC analyses were performed according to the following cycle: heating up from 80 to 400°C at 10°C/min, 3 min isothermal step at 400 C, cooling down to 80 C at 10 °C/min, 5 min isothermal step at 80 °C, final heating up from 80 to 400°C at 10 °C/min. Test was performed in nitrogen atmosphere.

The figure shows the DSC spectrum of the PEEK filament used for printing the samples. From the diagram it is possible to analyze the behavior of the material during the first heating cycle, the subsequent temperature-controlled cooling step and finally the second heating cycle (red, black, and green curve respectively). Such a temperature scan provides different information about the sample.

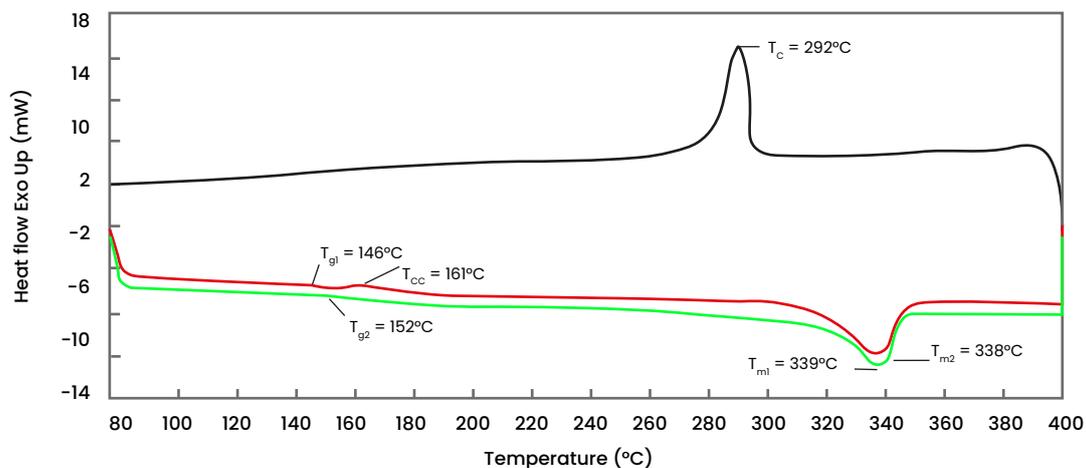


Figure 7 DSC spectrum of the sample representing the three thermal cycles

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Info about coefficient of thermal expansivity provides quantitative characterization of expansion properties, which is an important designing index of the composite structure. The smaller  $\alpha_T$  gives an advantage of stability during the printing phase or using process in high temperature environments.

Materials shows temperature dependence in their coefficient of thermal expansivity, especially above  $T_g$ . Therefore, a single reported number for CLTE will not accurately reflect the expansion behavior, except below  $T_g$  where a changes little. Nonetheless, it is customary to select a representative value of CLTE for comparison purposes.

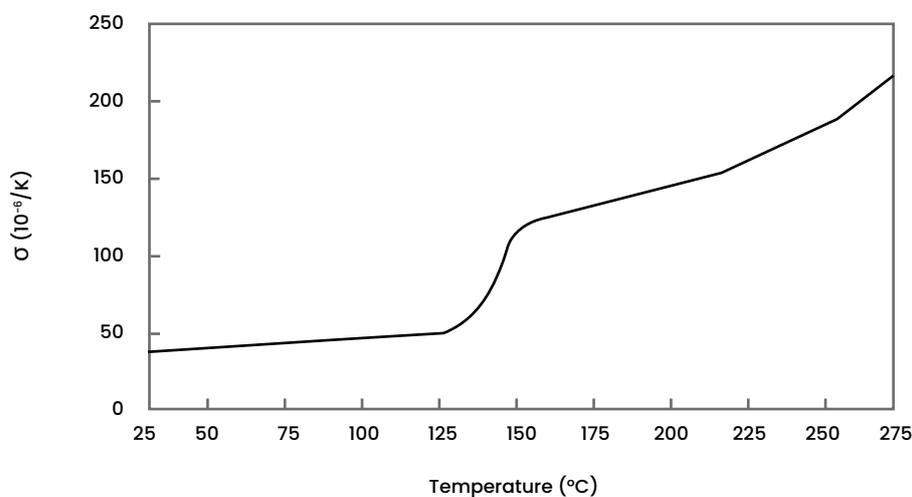


Figure 8 Variation of the linear thermal expansion coefficient with temperature

## Dynamic Mechanical Thermal Analysis (DMTA)

Dynamic mechanical thermal analysis (DMTA) was performed in a double cantilever configuration. A temperature range of 25 to 300°C, a heating rate of 3°C/min, a frequency of 1 Hz and 0.05% oscillation amplitude were set (the test was performed in strain controlled mode). DMTA measurements are used to assess the polymer stiffness and mobility of macromolecules under dynamic conditions. The dynamic mechanical behavior of PEEK samples has been studied and the following figure shows the variation of the storage ( $E'$ ) and loss ( $E''$ ) moduli with temperature.

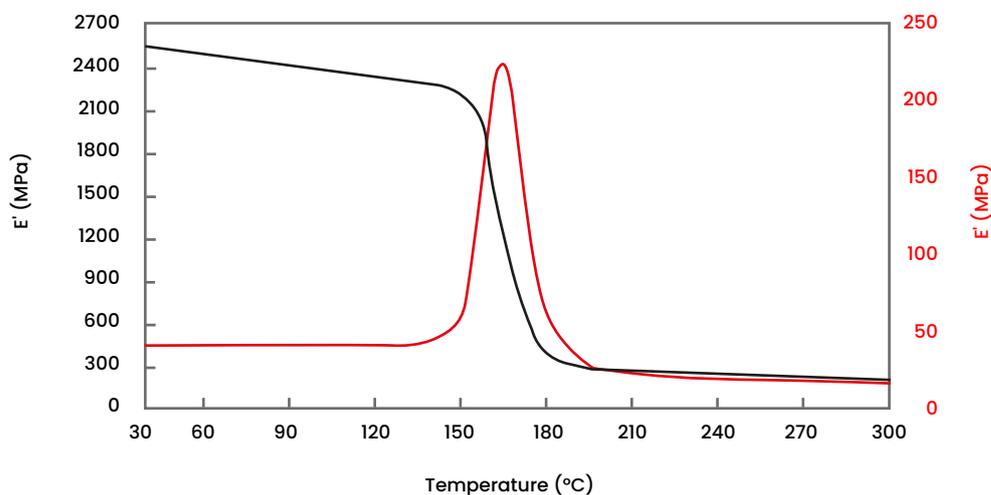


Figure 9 Development of storage ( $E'$ ) and loss module ( $E''$ ) as a function of temperature

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In the temperature range of 30-130°C, the material has a relatively high storage modulus and a low loss modulus. This results from the fact that in this temperature range the chains are locked in a rigid network.

In the range 130-200°C, there is a marked drop in the storage modulus, which is accompanied by a peak in the loss modulus; in this region the polymer chains acquire greater mobility, and the polymer undergoes a progressive phase transition from the condition of a rigid glassy material to that of a viscous fluid. Finally, in the range 200-300°C, a rubbery plateau can be observed in which both moduli remain constant. Here, the translational movements occurring in the liquid state are limited by the entanglements of the macromolecules acting as temporary crosslinks.

The Heat Deflection Temperature (HDT) was extrapolated from the storage module graph. The HDT at 1.82 MPa was determined as the temperature at which the storage module reaches 800 MPa in DMTA testing.

Table 10 Deflection Temperature

DEFLECTION TEMPERATURE AT 1.8 MPa	DMTA	°C	161
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## Thermal conductivity

Among the main thermophysical parameters to characterize the heat transfer properties of a material we find Thermal Conductivity.

To determine thermal conductivity, it is important to record thermal diffusivity and specific heat capacity. Thermal diffusivity was measured by laser flash method. Laser heat pulse was irradiated on the front side of cylindrical specimen (Ø12.5 × 3 mm), the heat is transmitted through the sample thickness direction and the resulting temperature rise at the sample's rear face is recorded as a function of time.

The higher the thermal diffusivity of the sample, the shorter the time needed to heat the opposite side of the sample.

Specific heat capacity was measured by differential scanning calorimeter. Thermal conductivity and can be obtained from following equation:

$$k = \alpha C_p \rho$$

where k is thermal conductivity,  $\alpha$  is thermal diffusivity,  $C_p$  is heat capacity and  $\rho$  is density.

The thermal conductivity of a semi-crystalline polymer can be described by means of the modified Maxwell model, which assumes that a semicrystalline polymer is made up of anisotropic spherical crystallites imbedded in an isotropic amorphous matrix. The thermal conductivity will therefore be a function not only of temperature but also of the percentage of crystallinity of the polymer.

Table 11 PEEK Thermal Conductivity at 250°C

THERMAL CONDUCTIVITY @ 250°C	W/m-K	0,25
THERMAL CONDUCTIVITY @ 250°C	W/m-K	0,42

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In fact, the first thermal cycle provides information on the product, thus considering the previous thermal history to which it was subjected prior to the analysis. The cooling cycle, on the other hand, makes it possible to analyze the behavior of the material during solidification. The slow and controlled cooling temperature allows the material to solidify in conditions that favor the rearrangement of the polymer chains in an ordered configuration. Finally, the second thermal cycle allows information to be obtained on the intrinsic properties of the material, since the influence of the thermal history of the product has been deleted during the melting that occurred at the end of the first cycle. From the graph the second heating cycle shows a similar trend to that shown for the first heating cycle, the melting peak has comparable amplitude and peak temperature between the two scans, however it was not possible to observe the cold crystallization peak in this case.

Looking at the cooling cycle, however thanks to the controlled cooling phase, the polymer chains of PEEK have sufficient time to organize themselves into ordered structures and thus generate crystalline domains. The crystallization peak is clearly visible in the cooling curve.

Focusing on the first heating cycle, an exothermic peak at 161 °C can be seen, which is attributable to the cold crystallization phenomenon. As the temperature increases, the polymer chains may become mobile enough to align themselves into further crystalline regions. When this happens, heat is released, and an exothermic peak is recorded by the instrument. From the graph, an endothermic peak is evident at 338°C, a peak caused by the melting of all the crystals in the sample. As would be expected, the endothermic peak is larger than the exothermic peak because the exothermic peak includes the combined energy to melt all the crystals formed, both during the previous thermal history of the material and during the DSC test. The percentage of crystallinity of the feed filament was found to be 36%.

Table 9 Summary of experimental data obtained through DSC analysis

T <sub>g</sub> (°C)	T <sub>m</sub> (°C)	ΔH <sub>m</sub> (J/g)	ΔH <sub>cc</sub> (J/g)	x <sub>c</sub> (%)
146	338	47,5	0,5	36%

## Coefficient of Thermal Expansion (αT)

When a material in the solid state is subjected to cooling and/or heating cycles it has a tendency to contract/dilate. The phenomenon of expansion of bodies is directly related to the atomic bond force. In fact, by supplying heat to the System, the increase of the vibration amplitude of the atomic bond is favored, thus causing the dilation of the body. The greater the bond force, the lesser the expansion of the material.

The linear coefficient of thermal expansivity (α<sub>T</sub>) is the length change for an infinitesimally narrow temperature range, at any temperature T, and is defined as follows:

$$\alpha_T = \frac{1}{L_0} \left( \frac{dL}{dT} \right)_T$$

Where L is the length of the sample, T its temperature, and L<sub>0</sub> its initial length. The coefficient of thermal expansion therefore represents the correlation coefficient between the deformation undergone by the material and the temperature variation.

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# Roboze PEEK

## Thermogravimetric analysis (TGA)

PEEK has flame retardant properties and high thermal stability. TGA is an efficient method of studying the thermal decomposition temperatures of a material using a few tens of milligrams of the sample itself. By heating the material in a controlled atmosphere (pyrolytic conditions), temperature is the only factor influencing the decomposition of the material. However, in a fire scenario, the influence of oxygen on decomposition and combustion behavior should also be considered. In this case, the material is subject to thermo-oxidative degradation. It is therefore equally important to determine the thermal stability of the material in air. Therefore, the sample was analyzed in both inert and oxidizing atmospheres.

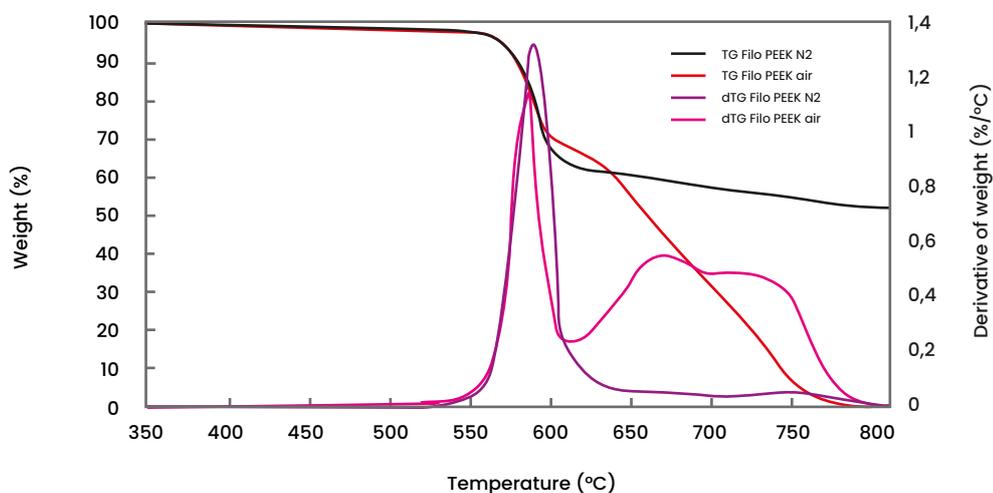


Table 10 TGA Spectrum of PEEK sample

In an inert atmosphere, the temperature of onset of thermal decomposition of PEEK ( $T_5\%$ ) was evaluated at 569°C and the maximum rate of mass loss (1.3%/°C) occurs at 583°C. At higher temperatures, the recorded mass loss is minimal. In fact, the final residual mass of PEEK at 800°C under nitrogen is 54%.

From this it can be deduced that the product formed during the pyrolysis of PEEK is quite stable in an inert atmosphere and at this temperature. It is known from the literature that PEEK is a polymer that tends to form carbon structures when subjected to pyrolysis. This suggests that during decomposition in nitrogen, the reaction that occurs leads to a thermodynamically stable carbonaceous structure.

When testing the sample in an oxidising atmosphere, the TG graph does not show any obvious temperature changes at the start of decomposition. This is evidenced by the temperature at which the sample records a 5% mass loss, which is similar to the previous case. From this, therefore, it can be deduced that the oxidative nature of the atmosphere in which PEEK is heated has little effect on the temperature at which it begins to decompose. This hypothesis is confirmed by looking at the temperature at which the peak mass loss occurs, which is similar to the previous case (582 °C).

However, the TG graphs also show that the presence of an oxidizing atmosphere modifies the decomposition mechanism which occurs at temperatures above 600°C. In fact, a non-zero DTG value is also observed at temperatures ranging from 605°C to 800°C .

This also suggests that the thermo-oxidative degradation of PEEK is at least a two-step process, one occurring at the beginning of decomposition, which involves the formation of a carbonaceous residue, followed by the slow oxidation of this carbonaceous residue at high temperatures.

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# Roboze PEEK

Furthermore, it is interesting to note that at 800°C, only the TG graph of PEEK in nitrogen shows a certain residual mass of almost half the initial mass of the material. This means that the carbonized structure formed during the initial phase of thermal decomposition in the presence of oxygen tends to be completely oxidized by passing into a volatile phase at oxygen concentrations of 22%.

## Glow Wire Test

Due to its excellent insulating properties and inherent flammability, PEEK is particularly used in the electronics industry. The Glow wire test is used to determine the ignition resistance of a polymer when it is brought into contact with an electrical resistor heated to a given temperature.

The highest temperature at which during three subsequent tests, flaming or glowing of the test specimen extinguishes within 30 seconds after removal of the glow wire without ignition of the indicator is called Glow wire flammability temperature (GWFI)

Table 12 Glow Wire Test of PEEK

PROPERTY	OPERATING CONDITIONS	UNIT OF MEASURE	VALUE	TEST METHOD
GLOW WIRE TEST – GWFI *	2mm THICKNESS	°C	960	IEC 60695-2-12

## Electrical Properties

### Surface Resistivity

Surface resistance is described as the ratio of a DC voltage to the current flowing between two electrodes that are in contact with the same surface of the specimen under test. The physical unit of surface resistance is Ohm ( $\Omega$ ). DIN IEC 60093 test method is used.

Table 13 Surface Resistance of PEEK

SURFACE RESISTANCE	DIN IEC 60093	>1012 $\Omega$
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### Dielectric Costant

Electrical permittivity, also known as the dielectric constant, is a physical quantity that quantifies the ability of a material to withstand the intensity of the electric field inside it. From a mathematical point of view, it is possible to define the dielectric constant as a ratio, where the denominator is the capacitance of a capacitor using the material in question as a dielectric species, and the denominator is the capacitance of a similar capacitor using a vacuum as a dielectric. The dielectric constant value is a function of various variables such as frequency, operating temperature, and humidity. IEC 60250 is the test used to check the dielectric constant of PEEK.

Table 14 Dielectric Costant of PEEK

PROPERTY	CONDITIONS	VALUE	TEST METHOD
DIELECTRIC CONSTANT	23°C 1 KHZ	3,1	IEC 60250
DIELECTRIC CONSTANT	23°C 50 HZ	3,0	IEC 60250

# Roboze Carbon PEEK

## TECHNICAL DATA SHEET

# Roboze Carbon PEEK



## Overview

Carbon PEEK is a composite material with a PEEK matrix reinforced with 20% chopped carbon fibers. These greatly improve the compressive strength, stiffness, and load capacity of the composite compared to virgin PEEK, vastly increasing the breadth of the applications possible.

Carbon PEEK has a higher thermal and electrical conductivity than neat PEEK and therefore reduces its rate of thermal expansion with a lower coefficient of linear thermal expansion (CLTE). Together with the chemical resistance typical of semi-crystalline polymers, it offers excellent mechanical properties and stability.

Thanks to the addition of carbon fibers, Carbon PEEK also offers a lower dry friction coefficient because of the higher thermal conductivity of the particles. It is very resistant to hydrolysis in boiling water and superheated steam, as well as to organics, acids, and bases. Carbon PEEK is considered among the strongest of all thermoplastics at room temperature thanks to its superlative properties that, together with its excellent wear and abrasion resistance, make it ideal for the substitution of metals in extreme environments.

## Applications

Carbon PEEK can be used both for functional prototypes and for end-use parts thanks to its very high mechanical properties.

It is used in a wide range of industries, from aerospace and defense to automotive, from oil and gas to manufacturing to motorsport. Its substantial durability makes it a common choice for demanding environments. Typical applications include bearing retainers, bushings, oil and gas processing equipment, seals, thrust washers, pump and compressor components, aircraft hardware and fasteners, aircraft mechanical components.

Thanks to its excellent property profile, which includes high toughness, continuous service temperature, and high melting point and glass transition temperature, it is the perfect candidate for metal replacement applications, which result in important weight savings, a fact that is particularly relevant in industries such as aerospace and defense.

## Design phase

The preparation of the samples and the execution of the individual tests followed the guidelines imposed by the associated regulations. Analyses on the relevant samples were carried out by an accredited, independent and impartial third-party laboratory.<sup>1</sup>

<sup>1</sup>Although data measured in a controlled environment can provide an indication of the chemical/physical and mechanical properties of the material and thus enable comparison between different materials, the results of these tests may not be the same as those observed in the final component.

This phenomenon may be caused by the presence of geometric features or manufacturing defects that may contribute to modifying the material behaviour. Thermal history, crystallinity variations, alteration of the distribution, dispersion, and orientation of the reinforcing phase are other factors that could induce the above phenomenon. Furthermore, the properties of polymeric materials are a function of both temperature and environmental factors (solar radiation, humidity, etc.), which is why the effect of these variables should also be considered during the design phase, both in the case of short-term and long-term exposure.

In view of the above, it is recommended that a prototype be made in advance during the design phase to empirically verify its properties in the operating conditions required by the specific application.

## TECHNICAL DATA SHEET

# Roboze Carbon PEEK

## Manufacturing Process

Specimens were manufactured on a Roboze ARGO 500 fed with a filament with a diameter of  $1.75 \pm 0.05$  mm. This thermoplastic filament was subsequently extruded through a 0.6 mm diameter nozzle. To minimize the concentration of water molecules adsorbed and absorbed by the filament due to exposure to the atmospheric environment, before starting the printing process, Carbon PEEK spools were subjected to a drying cycle at a temperature of 120 °C for 8 hours in HT Dryer.

The temperature of the working chamber was set to 160 °C. To allow isothermal conditions within the hot chamber, 2 hours was waited before starting the printing process.

Printing conditions for the data in the following tables were:

- Chamber Temperature = 160 °C
- Extrusion Temperature = 440 °C
- Printing speed = 2100 mm/min
- Layer height = 0.27 mm
- Infill percentage= 100%
- 2 Shells

At the end of the printing process the support structures were manually removed.

The additive manufacturing technology produces intrinsically anisotropic components. As the orientation of the component on the printing plate changes, so do both the properties of the final printed part and the productivity of the printing process. Keeping in mind what has been written above, it is possible to identify three different orientations on the building plate that are named as follows:

- Flat (or XY)
- On Edge (or XZ)
- Upright (or ZX)

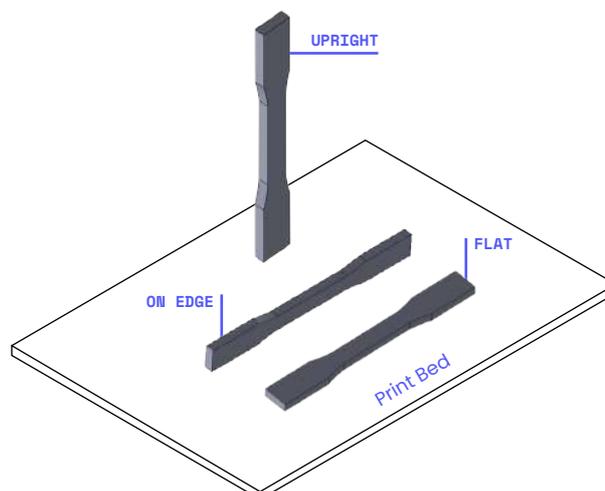


Figure 1 Example of On Edge, Upright and Flat orientation on the building plate

TECHNICAL DATA SHEET

# Roboze Carbon PEEK

## Carbon PEEK properties Summary

### MECHANICAL PROPERTIES

PROPERTY	OPERATING CONDITIONS	UNITS	ORIENTATION		TEST METHOD
			XZ	ZX	
Tensile Strength	25 °C	MPa	125	55	ASTM D638, type IV
Young's Modulus	25 °C	GPa	10.1	3.7	ASTM D638, type IV
Elongation at break	25 °C	%	2	2	ASTM D638, type IV

### PHYSICAL PROPERTIES

PROPERTY	OPERATING CONDITIONS	UNITS	VALUE	TEST METHOD
Specific gravity		g/cm <sup>3</sup>	1.41	ASTM D792
Glass transition temperature (T <sub>g</sub> )	20 °C/min heating and cooling rate, in air	°C	149	Differential Scanning Calorimetry (DSC)
Melting point (T <sub>m</sub> )	20 °C/min heating and cooling rate, in air	°C	341	Differential Scanning Calorimetry (DSC)
Reinforcing phase (carbon fibers)		% by weight	20	
Colour			Black opaque	

The information may come from the raw material, the semi-finished product, or an estimate.  
 Specific individual tests are recommended according to the conditions required for final implementation

TECHNICAL DATA SHEET

# Roboze Carbon PEEK

## Mechanical Properties

### Tensile Properties

The tensile test is a destructive test useful to characterize the properties of materials when subjected to uniaxial tensile loads. A specimen of standard dimensions, having a "dogbone" geometry, is clamped by means of appropriate clamps to two crossbeams.

The movable crossbeam can move upwards, thus bringing the specimen into a tensile state. Once the displacement speed of the crossbar has been set, the load applied, and the deformation undergone by the sample are monitored during the test.

In output the system is able to provide a Cartesian graph where on the ordinates is represented the stress ( $\sigma$ ), i.e. the ratio between the force applied to move the mobile crosshead at constant speed and the minimum section of the "dogbone" test specimen; while the abscissae report the strain ( $\epsilon$ ), i.e. the percentage ratio between the variation of length of the test specimen with respect to its initial dimensions ( $\Delta\ell$ ) and its nominal length before the start of the test ( $\ell_0$ ).

The stress-strain curve will be a function of the nature of the material. The characteristic parameters that can be derived from this curve are: tensile strength ( $\sigma_M$ ), Young's modulus (E) and elongation at break ( $\epsilon_0$ ).

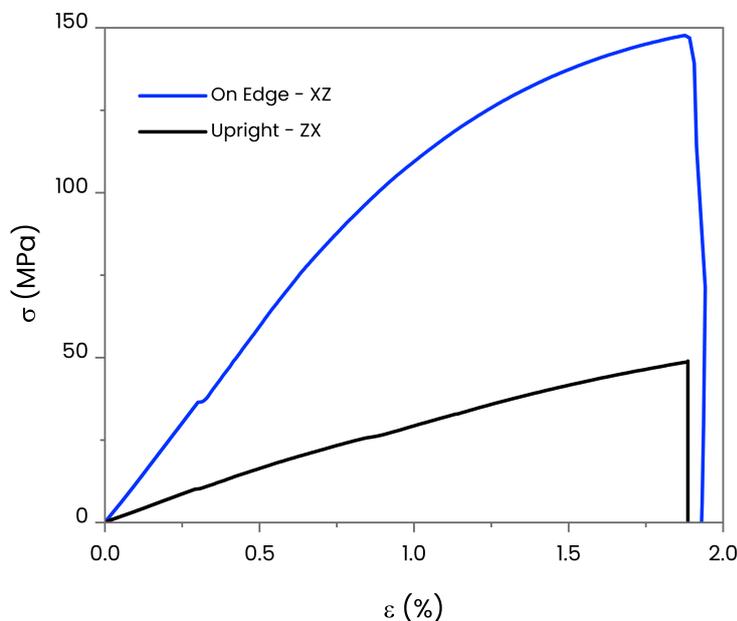


Figure 2: Comparison between tensile test behaviour of Carbon PEEK samples built in different orientations

TECHNICAL DATA SHEET

# Roboze Carbon PEEK

The initial section of the curve shows a region of linear elastic deformation. In this region (also called the Hookean region of the material), the material undergoes an instantaneous and reversible strain that is linearly dependent on the applied stress.

The angular coefficient of the tangent line to the linear elastic region is defined as Young's Modulus, which is the constant of proportionality between the strain undergone by the material and the applied stress. Young's modulus is generally measured from the stresses at 0.05 % and 0.25 % strain. It should be noted that components manufactured by additive manufacturing have anisotropic mechanical properties therefore, particularly with very complex geometries, it can be difficult to maximize the mechanical response. Typically the best practice is to identify the main load direction and orient the part in relation to this.

The samples were characterized using the ASTM D638 standard. ZX-oriented specimens were milled from a 120x3.2x60 mm plate to evaluate inter-layer adhesion properties with minimal interference from spurious phenomena. A speed of 1 mm/min was used to calculate the tensile modulus, thereafter the speed was increased up to 50 mm/min until the specimen failed. It should be noted that results of tensile testing are a function of test speed, therefore for a proper comparison between different materials it is important to know in advance the speed at which the test was performed.

*Table 1: Tensile properties of Carbon PEEK measured at 25°C for different specimen orientations*

PROPERTY	OPERATING CONDITIONS	UNITS	ORIENTATION		TEST METHOD
			XZ	ZX	
Tensile strength	25 °C	MPa	125	55	ASTM D638, type IV
Young's modulus	25 °C	GPa	10.1	3.7	ASTM D638, type IV
Elongation at break	25 °C	%	2	2	ASTM D638, type IV

# Roboze Carbon PA PRO

## TECHNICAL DATA SHEET

# Roboze Carbon PA PRO



## Overview

Polyamides (PA) are polymers characterized by repeating units (monomers) linked by amide bonds (CO-NH), on which many properties of this type of compound depend. PAs belong to the category of semi-crystalline polymers, i.e., polymers in which the macromolecular chains in the solid state tend to arrange themselves in crystalline regions known as "crystallites". The orderly distribution of the polymer chains is ensured by interactions between the amino group of one chain and the carboxyl group of the adjacent macromolecule.

Roboze's Carbon PA PRO is based on a PA 6 reinforced with carbon fibers (15 % by weight). The matrix has been engineered to minimize the melting temperature (234 °C) of the crystalline phase and thus reduce the extrusion temperature, enabling easier material processing. The addition of chopped carbon fibers results in a composite material with high mechanical strength, stiffness, and thermal resistance. Furthermore, the polyamide matrix offers high toughness at low temperatures as well as easy processing.

Carbon PA PRO has low moisture absorption rate, as well as low-warpage and high dimensional stability. In addition, it offers good resistance to a variety of hydrocarbons, such as gasoline, diesel, ethers, and esters.

Roboze's Carbon PA PRO is ideal for metal replacement applications thanks to its high tensile strength (Table 1). Significant weight reductions are also possible because of its low density (1.232 g/cm<sup>3</sup>) and it is possible to achieve an excellent surface smoothness and appearance. Using a spray plasticizer will waterproof parts printed with Carbon PA PRO, also decreasing surface roughness, and making components more resistant to UV light.

## Applications

Carbon PA PRO performs best in high mechanical stress applications such as motorsport where it has been successfully used in spoilers and other aerodynamic parts. Its outstanding properties also make it an excellent material for manufacturing structural components in aviation such as frames for drones. Furthermore, it finds many uses in the manufacturing industry, for example for support frames in robotic production lines and, particularly when combined with the design freedom of 3D printing, for the manufacturing of tooling such as centering devices and gripping fingers.

## Design phase

The preparation of the samples and the execution of the individual tests followed the guidelines imposed by the associated regulations. Analyses on the relevant samples were carried out by an accredited, independent and impartial third-party laboratory.<sup>1</sup>

<sup>1</sup>Although data measured in a controlled environment can provide an indication of the chemical/physical and mechanical properties of the material and thus enable comparison between different materials, the results of these tests may not be the same as those observed in the final component.

This phenomenon may be caused by the presence of geometric features or manufacturing conditions that may contribute to modifying the material behaviour. Furthermore, the properties of polymeric materials are a function of both temperature and environmental factors (solar radiation, humidity, etc.), which is why the effect of these variables should also be considered during the design phase, both in the case of short-term and long-term exposure. In view of the above, it is recommended that a prototype be made in advance during the design phase to empirically verify its properties in the operating conditions required by the specific application.

## TECHNICAL DATA SHEET

# Roboze Carbon PA PRO

## Manufacturing Process

Specimens were manufactured on a Roboze Plus PRO fed with a  $1.75 \pm 0.05$  mm diameter filament. This thermoplastic filament was subsequently extruded through a 0.6 mm diameter nozzle. Before starting the printing process, in order to minimize the amount of water molecules adsorbed and absorbed by the filament due to exposure to the atmospheric environment, Roboze Carbon PA PRO spools were subjected to a drying cycle at a temperature of 90 °C for 12 hours in HT Dryer

The temperature of the printing chamber was set to 90 °C. Before starting the printing process, 30 minutes of thermal equilibration were allowed.

The printing parameters for the following data are:

- Chamber Temperature = 90 °C
- Extrusion Temperature = 270 °C
- Printing speed = 3600 mm/min
- Layer height = 0.27 mm
- Infill percentage= 100%

At the end of the printing process the support structures were manually removed.

The additive manufacturing technology produces intrinsically anisotropic components. As the orientation of the component on the printing plate changes, so do both the properties of the final printed part and the productivity of the printing process. Keeping in mind what has been written above, it is possible to identify three different orientations on the building plate that are named as follows:

- Flat (or XY)
- On Edge (or XZ)
- Upright (or ZX)

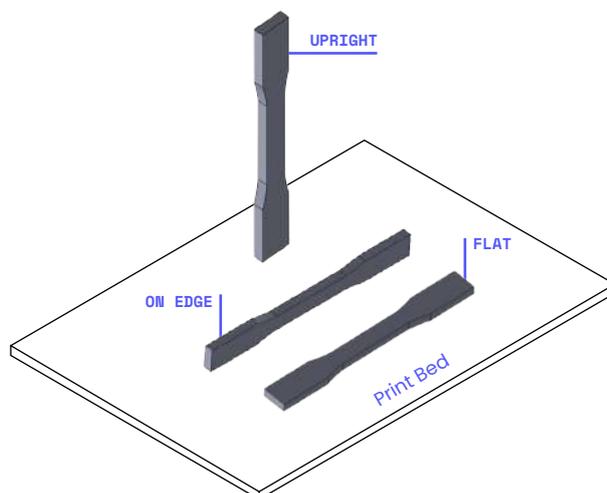


Figure 1 Example of On Edge, Upright and Flat orientation on the building plate

TECHNICAL DATA SHEET

# Roboze Carbon PA PRO

## Summary of Roboze Carbon PA PRO properties

### MECHANICAL PROPERTIES

PROPERTY	OPERATING CONDITIONS	UNITS	ORIENTATION			TEST METHOD
			XZ	XY ± 45°	ZX	
Tensile Strength	25 °C	MPa	171	141	32	ASTM D638, type IV
Young's Modulus	25 °C	GPa	13.1	8.8	2.6	ASTM D638, type IV
Elongation at break	25 °C	%	1.58	2	1.48	ASTM D638, type IV

### PHYSICAL PROPERTIES

PROPERTY	OPERATING CONDITIONS	UNITS	VALUE	TEST METHOD
Specific gravity		g/cm <sup>3</sup>	1.232	ISO 1183-1
Glass transition temperature (T <sub>g</sub> )	20 °C/min heating and cooling rate, in air	°C	70	ISO 11357-2 DSC
Crystallization temperature (T <sub>c</sub> )	20 °C/min heating and cooling rate, in air	°C	180	ISO 11357-3 DSC
Melting point (T <sub>m</sub> )	20 °C/min heating and cooling rate, in air	°C	234	ISO 11357-3 DSC
Melt volume flow rate	275 °C, 5 kg	cm <sup>3</sup> /10 min	42.2	ISO 1133
Reinforcing phase (carbon fibers)		% by weight	15	
Colour			Black	

The information may come from the raw material, the semi-finished product, or an estimate.  
Specific individual tests are recommended according to the conditions required for final implementation

TECHNICAL DATA SHEET

# Roboze Carbon PA PRO

## Mechanical Properties

### Tensile Properties

The tensile test is a destructive test useful to characterize the properties of materials when subjected to uniaxial tensile loads. A specimen of standard dimensions, having a "dogbone" geometry, is clamped by means of appropriate clamps to two crossbeams.

The movable crossbeam can move upwards, thus bringing the specimen into a tensile state. Once the displacement speed of the crossbar has been set, the load applied, and the deformation undergone by the sample are monitored during the test.

In output the system is able to provide a Cartesian graph where on the ordinates is represented the stress ( $\sigma$ ), i.e. the ratio between the force applied to move the mobile crosshead at constant speed and the minimum section of the "dogbone" test specimen; while the abscissae report the strain ( $\epsilon$ ), i.e. the percentage ratio between the variation of length of the test specimen with respect to its initial dimensions ( $\Delta\ell$ ) and its nominal length before the start of the test ( $\ell_0$ ).

The stress-strain curve will be a function of the nature of the material. The characteristic parameters that can be derived from this curve are: tensile strength ( $\sigma_M$ ), Young's modulus (E) and elongation at break ( $\epsilon_0$ ).

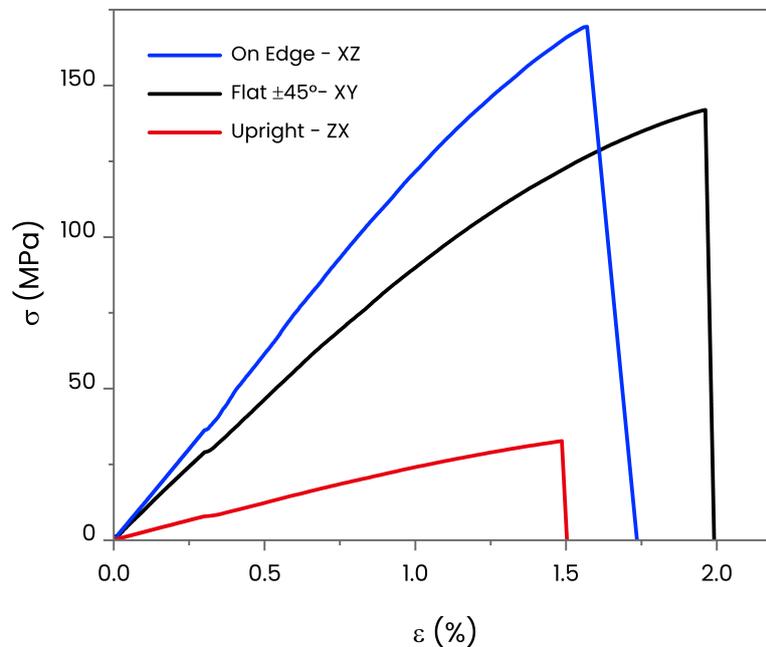


Figure 2: Comparison between tensile test behavior of Carbon PA PRO samples built in different orientations

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# Roboze Carbon PA PRO PRO

The initial section of the curve shows a region of linear elastic deformation. In this region (also called the Hookean region of the material), the material undergoes an instantaneous and reversible strain that is linearly dependent on the applied stress.

The angular coefficient of the tangent line to the linear elastic region is defined as Young's Modulus, which is the constant of proportionality between the strain undergone by the material and the applied stress. Young's modulus is generally measured from the stresses at 0.05 % and 0.25 % strain. It should be noted that components manufactured by additive manufacturing have anisotropic mechanical properties therefore, particularly with very complex geometries, it can be difficult to maximize the mechanical response. Typically the best practice is to identify the main load direction and orient the part in relation to this.

After drying in oven at 90 °C, the samples were tested using the ASTM D638 standard (Type IV). ZX-oriented specimens were milled from a 120x3.2x60 mm plate to evaluate inter-layer adhesion properties with minimal interference from spurious phenomena. A speed of 1 mm/min was used to calculate the tensile modulus, thereafter the speed was increased up to 50 mm/min until the specimen failed. It should be noted that results of tensile testing are a function of test speed, therefore for a proper comparison between different materials it is important to know in advance the speed at which the test was performed.

*Table 1: Tensile properties of Roboze Carbon PA PRO measured at 25 °C for different specimen orientations*

PROPERTY	OPERATING CONDITIONS	UNITS	ORIENTATION			TEST METHOD
			XZ	XY ±45°	ZX	
Tensile Strength	25 °C	MPa	171	141	32	ASTM D638, type IV
Young's modulus	25 °C	GPa	13.1	8.8	2.6	ASTM D638, type IV
Elongation at break	25 °C	%	1.58	2	1.48	ASTM D638, type IV

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# Roboze Carbon PA PRO

## Physical properties

### Water and moisture absorption

Carbon PA PRO filament should be stored at 15 – 25 °C in its originally sealed package in a clean and dry environment. If the recommended storage conditions are observed the products will have a minimum shelf life of 12 months. Since residual moisture in the filament can lead to several problems during the printing process, it is recommended to dry it for at least 4 hours (and a maximum of 16 hours) at 90 °C before printing. The water molecules adsorbed and absorbed by the material may trigger hydrolysis phenomena during extrusion due to the high temperature of the process. Moreover, it is good practice to keep the printed parts in a dry environment. The reason being that since water behaves as a plasticizer with PAs, technically relevant mechanical parameters (e.g., Young’s modulus) of printed parts can be negatively affected by absorbed moisture.

### Melting and glass transition temperatures

Unlike thermosets, when heated thermoplastic polymers undergo a progressive softening process until they reach complete melting. The energy supplied through heat irradiation can weaken and progressively break the van der Waals bonds between the various polymer chains.

This phenomenon involves a reduction in the stiffness of the polymer, which stops behaving as an elastic solid and begins to assume the typical behavior of a viscoelastic material. The higher the temperature, the greater the viscous component will be compared to the elastic one.

As the temperature rises, the energy supplied to the system increases, causing the carbon chains to start moving. This changes the material from a hard and relatively brittle “glassy” state into a viscous or “rubbery” one, this happens at a temperature known as the glass transition temperature ( $T_g$ ). Further heating allows the progressive dissolution of the crystalline domains, which happens at the melting temperature ( $T_m$ ). The crystalline domains are generated during the cooling of the material, and this happens to a temperature known as crystallization temperature ( $T_c$ ). The characteristic temperatures of Carbon PA PRO are given in the following table.

Table 2: Glass transition temperature ( $T_g$ ), melting temperature ( $T_m$ ), and crystallization temperature ( $T_c$ ) of Carbon PA PRO

PROPERTY	UNIT	VALUE	TEST METHOD
GLASS TRANSITION TEMPERATURE ( $T_g$ )	°C	70	DSC
CRYSTALLIZATION TEMPERATURE ( $T_c$ )	°C	180	DSC
MELTING POINT ( $T_m$ )	°C	234	DSC

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