TECHNICAL DATA SHEET

Roboze Carbon PA

Overview

Carbon Polyamide (PA 6/66) was developed for Roboze customers and is based on a polyamide matrix reinforced with 10% by weight of carbon fibers.

Polyamides (PA) are macromolecules characterized by the CO-NH amide group, 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 be arranged in regular structures, forming 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 Carbon PA's matrix has been engineered to minimize the melting temperature (200°C) of the crystalline phase and thus reduce the extrusion temperature, enabling easier processing of the material.

The addition of 10 % by weight of chopped carbon fibers makes it possible to obtain 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 has low water (9 % - ISO 62) and moisture (2,6 % - ISO 62) absorption. It also exhibits low-warpage and high dimensional stability despite the semi-crystalline nature of the polymer. In addition, Carbon PA offers good resistance to a variety of hydrocarbons, such as: gasoline and diesel fuels, ethers and esters.
Roboze's Carbon PA provides the answer to all industrial needs such as: high-end mechanical applications, thanks to its high tensile strength (XY: 88 MPa and XZ: 93 MPa, ZX:69 MPa), weight reduction (density: 1.16 g/cm^3), metal replacement, and excellent surface appearance. Carbon PA is still a hygroscopic material: it may tend to deform over time due to its tendency to absorb water. One way to resolve this problem is using a spray plasticizer that will waterproof the part, decrease its surface rugosity, and make the component resistant to UV light.

Applications

Carbon PA has excellent mechanical properties comparable to aluminum AA1050A, hence this material best performs for high mechanical stress applications such as motorsport. For instance, it is successfully used in spoilers for F1 cars, and functional parts such as pedals and brake levers for motorcycles.

Design phase

The preparation of the samples and the execution of the individual tests followed the guidelines imposed by the associated regulations.[1]

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[1] 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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TECHNICAL DATA SHEET

Roboze Carbon PA

Manufacturing Process

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

The temperature of the heated deposition chamber was set to 100°C. Before starting the printing process, two hours of thermal equilibration were allowed.

The printing parameters for the following data are:

- Chamber Temperature = 100°C
- Extrusion Temperature = 280°C
- Printing Speed = 1600 mm/min
- Layer Height = 0.1 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 supports.

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)

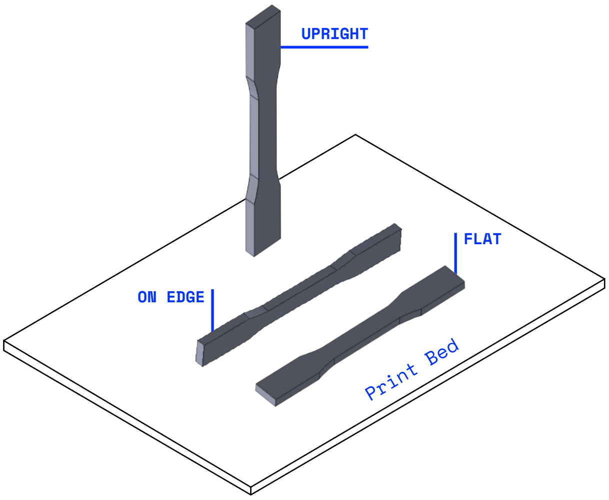

Figure 1 Example of On Edge, Upright and Flat orientation on the building plate

TECHNICAL DATA SHEET

Roboze Carbon PA

Summary of the Carbon PA properties

MECHANICAL PROPERTIES

PROPERTY	OPERATING CONDITIONS	UNITS	ORIENTATION			TEST METHOD
			XZ	XY ±45°	ZX	
Tensile Strength	25°C	MPa	93	88	69	ASTM D638
Young Modulus	25°C	GPa	4.9	3.9	2.7	ASTM D638
Elongation at Tensile Strength	25°C	%	4.1	4.5	3.9	ASTM D638
Flexural strength	25°C	MPa	85	64	65	ASTM D695
Flexural modulus	25°C	GPa	4.2	3.0	2.8	ASTM D695
Compressive strength	25°C	MPa	102		148	ASTM D790
Charpy Impact Strength	25°C	kJ/m^2		60		ISO 179/1eU

PHYSICAL PROPERTIES

PROPERTY	OPERATING CONDITIONS	UNITS	ORIENTATION	TEST METHOD
Specific gravity		g/cm^3	1.16	ISO 1183-3
Water Absorption 23°C	2 mm	%	9	ISO 62
Moisture Absorption 23°C – 50% RH	2 mm	%	2.6	ISO 62
Melting Temperature		°C	200	DSC
Crystallization temperature		°C	162	DSC
Heat Deflection Temperature*	1.8 MPa	°C	88	ISO 75-2
Color			Black	

*Value referred to sample manufactured by injection molding

TECHNICAL DATA SHEET

Roboze Carbon PA

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 the ordinates represent the stress (σ), 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 (ε), 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 (ℓ_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 (σ_M), Young's modulus (E) and strain at tensile strength (ε_M).

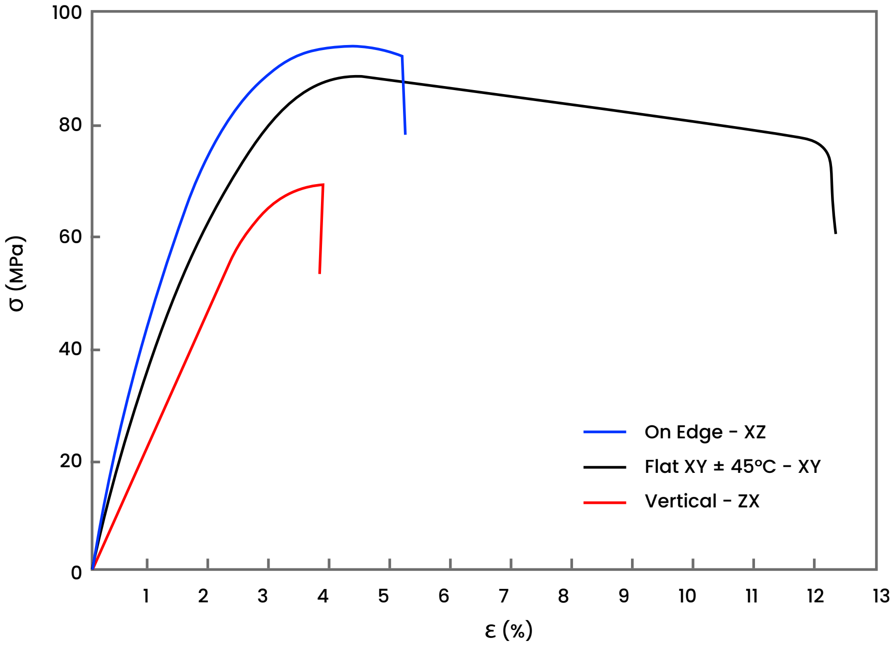

Figure 2 Comparison between tensile test behaviour of Carbon PA samples built in different orientations

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.

Components manufactured by additive manufacturing show 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.

In this case study, the variation of the mechanical properties was less than 30% between the configuration with the highest performance (XZ) and the sample with the lowest mechanical properties (ZX), thus indicating a good degree of isotropy of the FFF part. In additions, specimens printed with XY orientation and ± 45° infill angle also show two and three times higher fracture toughness when compared to specimens printed in XZ and ZX orientations respectively.

The ASTM D638 standard was followed to perform the characterization of the samples. 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 Carbon PA measured at 25°C for different specimen orientations

TENSILE TEST ASTM D638		ORIENTATION		
	UNITS	XZ	XY ±45°	ZX
Tensile Strength	MPa	93	88	69
Elongation at maximum stress	%	4.1	4.5	3.9
Young's Modulus	GPa	4.9	3.9	2.7

Flexural Properties

During the design phase, the knowledge of the bending behaviour of a material, results to be a key parameter for the correct structural dimensioning of the component.
As shown in Figure 3, considering a bar of material fixed at both ends, and with a vertical load applied to its middle point, it is possible to demonstrate how the stresses originating inside the body present a linear axial distribution: the stress σ reaches maximum absolute values , although opposite in sign, at the extremes of the section, while it is zero at the neutral axis.

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

TECHNICAL DATA SHEET

Roboze Carbon PA

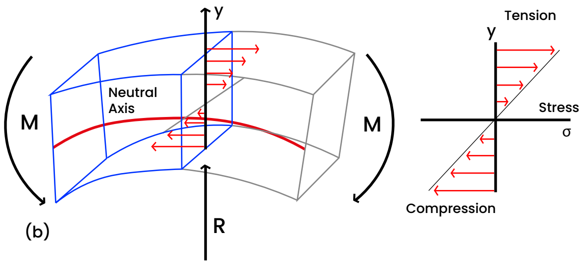

Figure 3 Stress variation along the cross section of a beam subjected to flexural loads

The flexural behavior of Carbon PA 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.

Table 2 Carbon PA Flexural Properties

ORIENTATION	E_F (MPa)	σ_F(MPa)
XZ	4.2	85
XY ±45°	3.0	64
ZX	2.8	65

The stress-strain curve for the three different printing orientations is shown below.

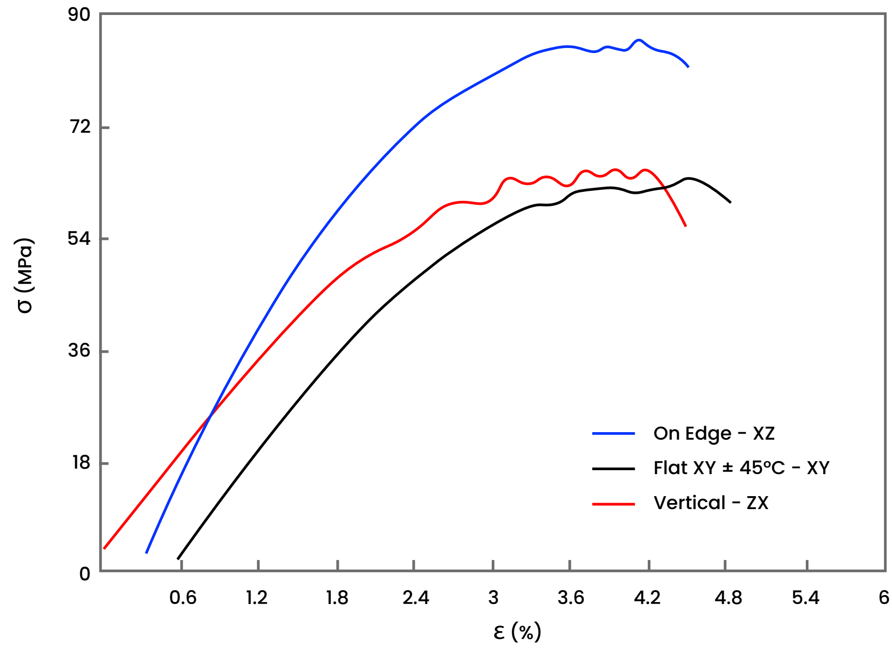

Figure 4 Stress-strain curves for Carbon PA subjected to bending tests

TECHNICAL DATA SHEET

Roboze Carbon PA

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.

The ASTM D695 standard was used for the determination of the compression properties of Carbon PA. Dimensions of cylindrical specimens are as follows:

- Diameter: 12.7mm
- Height: 25.4mm

The testing speed was set at 1.3 mm/min

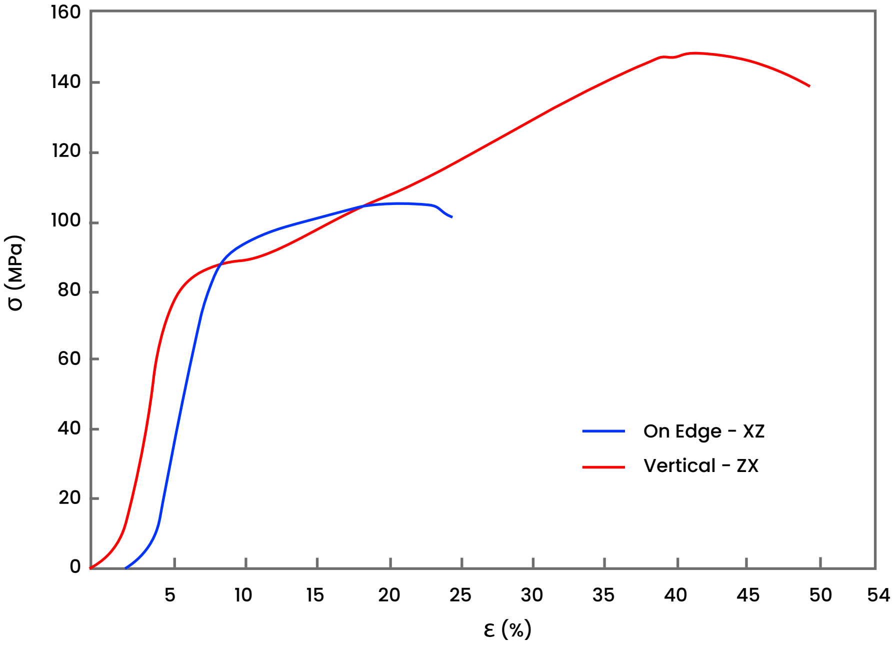

Figure 5 Stress strain curve for Carbon PA samples subjected to compression test

Except for the initial toe region (typical measurement artifact not representing a property of the material), Carbon PA show Hookean (linear) behavior. Subsequently, a deviation from linear behavior can be noticed until the maximum strength value is reached. The compressive strength values for two different spatial orientations are summarized in the following table:

Table 3 Compressive strength values of Carbon PA at 25°C

ORIENTATION	σ_M(MPa)
XZ	148
ZX	102

TECHNICAL DATA SHEET

Roboze Carbon PA

Impact Test

The Charpy impact test measures the energy absorbed by a standard specimen while breaking under an impact load. ISO 179/1eU specifies a procedure for defining the Charpy impact strength of polymers. Charpy Impact test can be applied for valuing the brittleness or toughness of different materials when subjected to impulsive forces.

This test consists of striking with a hammer on a pendulum arm a suitable specimen consisting of a notched horizontal beam supported by its ends. The hammer strikes the specimen and the energy absorbed by the sample is evaluated by the reduction in motion of the pendulum arm.

Table 4 Impact strength values of Carbon PA at 25°C

ORIENTATION	TEST TEMPERATURE	TEST METHOD	IMPACT STRENGTH (kJ/m^2)
XY ± 45°	23°C	ISO 179/1eU	60

Chemical Compatibility

Carbon PA is a polyamide (PA) matrix composite material reinforced with chopped carbon fibers. PA is known for good resistance to many hydrocarbons, such as oils and fuels. This makes polyamides ideal for automotive and motorsport applications.

A list of some of the most common industrial solvents to which Carbon PA shows chemical inertia is summarized in the following table:

CHEMICAL	RESISTANCE	
	VERY RESISTANT	RESISTANT
Brake Fluids	X	
Cooling Liquids	X	
Detergents	X	
Esters		X
Ethers		X
Gasoline and diesel fuel		X
Halogenated Compounds		X
Hydrocarbons and aromatics		X
Oils	X	

Physical Properties

Melting Temperature

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

Roboze Carbon PA

This phenomenon involves a reduction in the stiffness of the polymer, that stops behaving as an elastic solid and begins to assume the typical behaviour 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, 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 Tm is the Differential Scanning Calorimetry (DSC). The characteristic temperature of Carbon PA are given in the following table:

Table 5 Summary table of melting and crystallisation temperatures of Carbon PA

PROPERTIES	TEMPERATURE (°C)	TEST METHOD
Melting Temperature	200	DSC
Crystallization temperature	162	DSC

Water and moisture absorption

Residual moisture in the filament can lead to several problems during the printing process. The water molecules adsorbed and absorbed by the material may trigger hydrolysis phenomena during the extrusion, due to the high temperature of the process. This may cause reduction of the molecular weight and mechanical properties of the polymer.

Information about the hygroscopic properties of the material is therefore of particular interest for an efficient printing process.

ISO 62 defines a method for verifying the moisture absorption properties in solid polymers. It also describes procedures for determining the amount of water absorbed by plastic specimens, when immersed in water or when subjected to humid air. The diffusion coefficient is determined supposing Fickian diffusion behaviour. This model is applicable both for homogeneous materials and for composites tested below their glass transition temperature.

During the test the specimens are immersed in distilled water at 23 °C, or exposed to 50% relative humidity at given temperatures, for given periods. The percentage of water absorbed by each test specimen is determined by measuring the difference of the specimen mass before and after exposure to water.

Table 6 Moisture and water absorption properties of Carbon PA

PROPERTY	OPERATING CONDITIONS	UNITS	VALUE	TEST METHOD
Water Absorption 23°C	2 mm	%	9	ISO 62
Moisture Absorption 23°C – 50% RH	2 mm	%	2.6	ISO 62