

07 WHITE PAPER

Essential guide on fiber-filled materials for FFF 3D printing

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01

Filled Materials

With the consolidation of the FFF technology, the filament fusion and deposition process has become highly controlled. For this reason, we can now print a great number of different materials with a whole range of properties and look. Not only a wide variety of colours are now common, but also filaments with a high level of additives and fillers have started to be accessible.

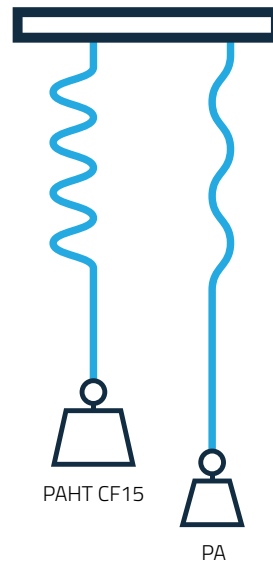


Figure 1: Photo of PA and PAHT CF15 under load.

Fillers have been used in the plastic industry since its beginning: the main purpose of fillers was initially to reduce the amount of costly polymer matrix in a blend, and so increase the economic yield of the manufacturing process. Inorganic solids such as calcium carbonate, talc, clay and carbon black are still in use as cheap fillers, and can make up to 90% of some commodity thermoplastic formulations.

Depending on the chosen combination of filler and polymer matrix, the consequent filled material can acquire much better properties, compared to the original polymer alone.

The addition of filler is known to impart one or more of the following benefits:

- Reduction of cost
- Improved mechanical properties (e.g. stiffness, hardness, impact resistance)
- Improved thermal resistance and thermal conductivity
- Reduce thermal expansion
- Fire retardancy

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Some of the properties of fillers derive from the shape of the particles they are composed of. The value of **aspect ratio** is used to describe the shape and regularity of filler particle: it is calculated dividing the longest dimension for the shortest. For example, glass microspheres are perfectly spherical (aspect ratio = 1, *Figure 2a*) and so equally respond to mechanical stress coming from any direction. They are especially used for increasing stiffness, compression strength and hardness. Platelets (*Figure 2b*) develop as a thin and planar structure and are typical of clay fillers. Rods can be considered as short cylinders of solid material, with intermediate geometry between a sphere and a fibre (*Figure 2c*).

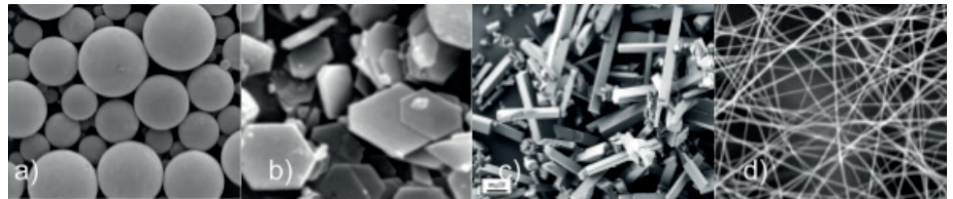
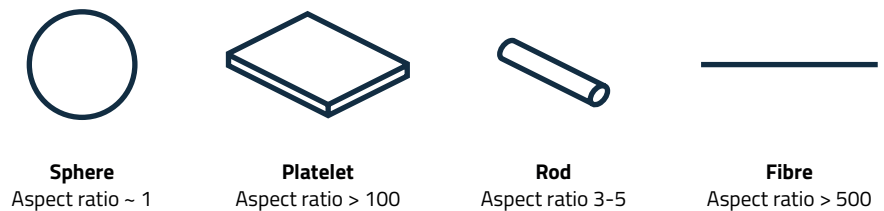


Figure 2: Fillers can be characterised by their size, shape and aspect ratio.



A special class of fillers is represented by **fibres**: contrary to spherical or irregular particles, fibres have a high aspect ratio (i.e. they develop along one dimension, *Figure 2d*). The combination of an ordered structure and high intrinsic strength makes fibres ideal for those applications where the strain is applied from a preferential direction. Indeed, if properly aligned in the same direction, fibres have the potential to greatly increase the mechanical properties of the material they are dispersed in. As an example, tensile strength and modulus are properties that are normally enhanced by the addition of a fibre filler. The most common fibre fillers are glass fibre (cheap and stiff), carbon fibre (strong and heat resistant), aramid fibre (impact and heat resistant), acrylic (cheap and low density).

Polyamides such as PA 6 and PA 6/6 are commonly blended with carbon fibres: the two materials are exceptionally compatible, and in the right proportion result in a very stiff and sturdy blend, with a strength comparable to that of a weak aluminium alloy, but for half the weight.¹ Carbon fibre-filled polyamides largely find applications in the automotive industry, for parts in contact with oils and subject to loads in aggressive environment such as the engine bay of a car.

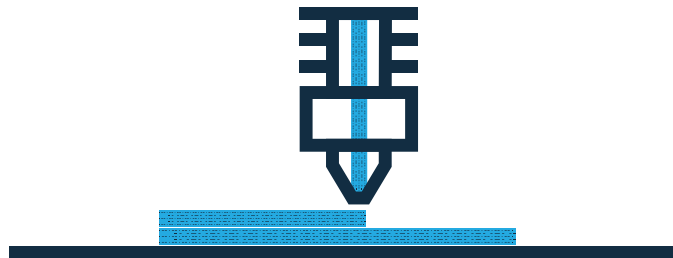
¹ PAHT-CF15 = 1.24 g/cm³; Al = 2.7 g/cm³

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During the FFF process, due to their high aspect ratio, the dispersed fibres align with the direction of the fused filament flow, creating a highly homogeneous structure, with parallel fibres running along the direction of the nozzle path (*Figure 3*).²

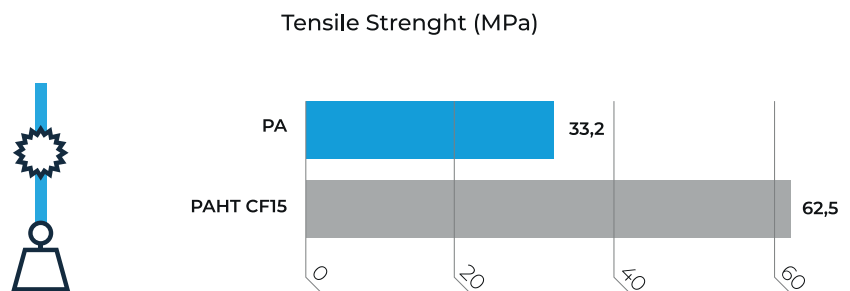
Where this allows for higher mechanical properties along the orientation axis of the fibres, the material's anisotropy is more pronounced, so there will be a "strong" and a "weak" direction. Typically, parts are much weaker along the z-axis: this effect can be dampened by a careful optimisation of the printing parameters, to ensure the highest interlayer adhesion.

Figure 3: Self-alignment of short-cut fibres during FFF processing.



To better show the effect of the addition of carbon fibres to a polyamide matrix, we compared the properties of our two filaments PA (polyamide) and PAHT-CF15 (polyamide, 15% carbon fibre-filled), taking into account that each of them is a complex formulation and they only share the chemical nature of the polymer matrix. PA is characterised by being a flexible and durable material, ideal for moving parts, when sudden hits or falls are expected. The addition of 15% carbon fibre completely transforms the polyamide blend into a very stiff material, capable of withstanding heavy loads without flexing, even at high temperature.

Figure 4: Comparison of tensile strength for non-filled and carbon fibre-filled polyamide.



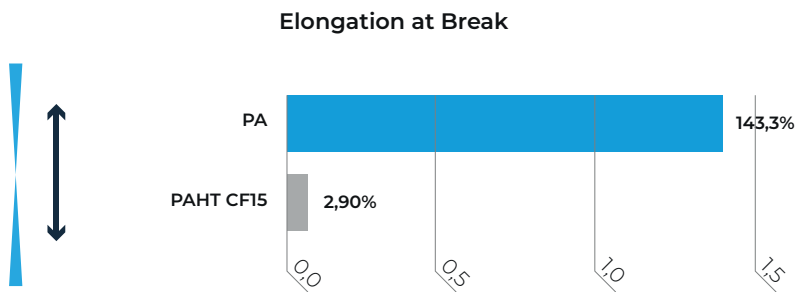
Tensile strength is the measure of the maximum weight that a bar of material can support before breaking. The presence of 15% carbon fibre almost doubles the tensile strength of base polyamide, thanks to the high level of alignment achieved during the FFF process (+88% tensile strength, *Figure 4*).

² 1. Tekinalp, H. L. et al. Highly oriented carbon fiber-polymer composites via additive manufacturing. *Compos. Sci. Technol.* **105**, 144–150 (2014).

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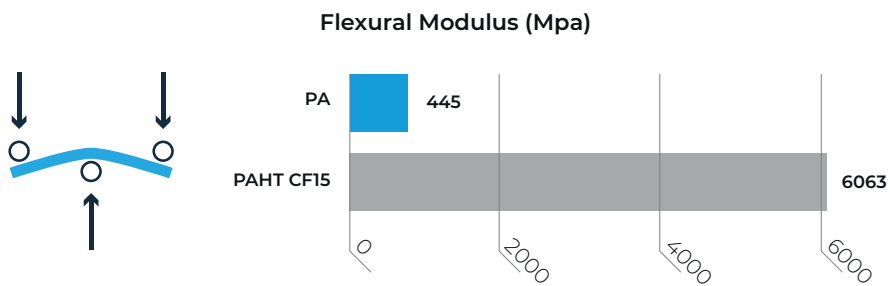
All this extra strength comes with a price: the filled material is much more stiff and can only be stretched to 2.9% its original length before breaking. This is a common drawback of all highly filled and rigid materials. On the contrary, non-filled PA is highly ductile, which means that can be stretched up to one and a half times its original length before breaking (*Figure 5*).

Figure 5: Comparison of elongation at break for non-filled and carbon fibre-filled polyamide.



Stiffness can be measured as a value of flexural modulus, which indicates the resistance of an object to a bending deformation. According to this evaluation, PAHT-CF15 is 14 times stiffer than unfilled PA, with a modulus of 6063 MPa versus 445 MPa for PA (*Figure 6*). This effect comes from the presence of rigid carbon fibres that lock the polymeric chains in position, preventing them from moving freely and so resisting elastic deformation.

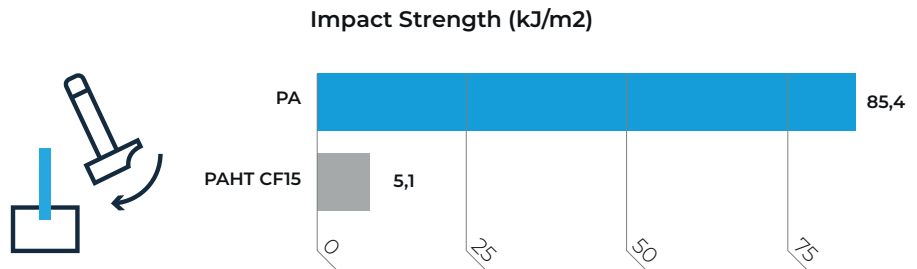
Figure 6: Comparison of flexural modulus for non-filled and carbon fibre-filled polyamide.



Filled Materials

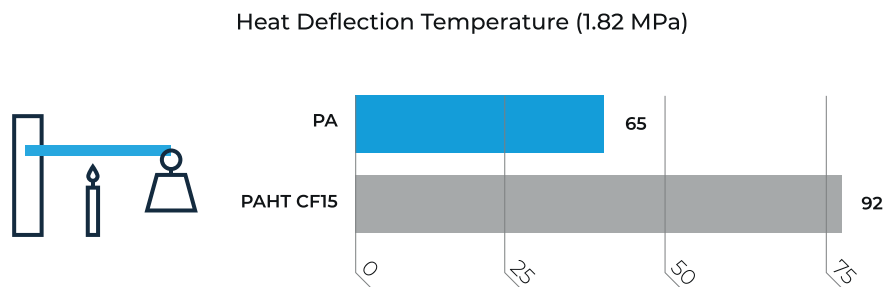
As previously discussed, rigid materials are inherently weaker when subject to a sudden and localised impact. Impact strength measures the maximum energy that an object can absorb and dissipate as a consequence of a hit with a hammer. Unfilled polyamide PA outperforms PAHT-CF15 with an impact strength of 85.4 kJ/m², 17 times higher than that of the filled filament (5.10 kJ/m², Figure 7).

Figure 7: Comparison of impact strength for non-filled and carbon fibre-filled polyamide



An important advantage of the addition of fibres to thermoplastic is a generally improved thermal resistance, which is normally translated into better dimensional stability in hot environment, such as car engine bays, electric panels and in proximity of moving parts. Heat deflection temperature measures the maximum temperature at which a bar of material can bear a fixed load without bending, and depends not only on the glass transition temperature of the polymer matrix, but also on the flexural modulus and length of the fibres, in reinforced materials. PAHT-CF15 withstands temperatures 42% higher than what tolerated by unfilled PA (Figure 8). This makes PAHT-CF15 an ideal material for structural and supports element, designed to work in hot environments.

Figure 8: Comparison of heat deflection temperature for non-filled and carbon fibre-filled polyamide.



The addition of fibres in 3D printing filaments also affects the printability properties of the material. For example, in the molten state, the presence of rigid, solid particles greatly increases the melt viscosity of the blend, thus requiring higher printing temperatures to ensure an optimal flow. Because of this physical limitation, not all hot ends are suited to printing highly filled materials.

Another aspect to take into consideration is the abrasive effect of solid particles/fibres. The use of carbon and (especially) glass fibres can result in a considerable wear of the classical brass nozzle over a relatively short period of time. For this reason, when working with fibre-filled materials, to ensure consistent printing performances a special hardened nozzle such as BCN3D Hotend X is highly recommended.

An important advantage provided by the addition of carbon and inorganic fibres is a lower coefficient of linear thermal expansion (CLTE), which allows for a lower tendency to warp, phenomenon particularly evident at the base and thin walls of a printed part. It is still recommended the use of specific build plate adhesives such as Magigoo PPGF or Magigoo PA.

02

BCN3D Filaments

Our range of BCN3D Filaments include carbon and glass fibre-filled materials for the most demanding and technical applications. These filaments feature the mechanical benefits provided by fibre reinforcement, while maintaining a consistently good printability and surface finish.

Our range includes PAHT-CF15 (polyamide, 15% carbon fibre-reinforced) which we have extensively discussed and PP-GF30 (polypropylene, 30% glass fibre-reinforced).

PAHT-CF15 combines high temperature and chemical resistance with extreme mechanical properties. It allows to print parts able to withstand high temperatures (150 °C for a prolonged period, peak temperatures of 180 °C). In comparison with standard PA, the addition of 15% carbon fiber makes the final composite material stronger and stiffer thus introducing new possibilities of application for FFF 3D printing.

PP-GF30 is a high-solid composite filament, filled with glass fibre for chemically resistant, lightweight and dimensionally stable parts. It is amongst the most used filled materials in the automotive industry, characterised by a long service life and able to resist to all weather conditions.



Figure 9: Picture of fibre filled BCN3D Filaments, packaging and spools.

“There is no such a thing as a perfect material, but there is always a material that perfectly fits each application”

Fibre-filled filaments for 3D printing represent an invaluable advancement, pushing the limits of FFF technology towards stronger materials, which withstand high levels of mechanical and thermal stress and can therefore be used to substitute metals in some applications. However, we must not forget that strength and stiffness are often synonyms of brittleness, and filled materials are no exception. Therefore, in the design phase of an object or technical component, we will be careful while choosing the proper material for a specific application: not always the strongest means the best fit, since one has also to consider environmental factors such as use temperature, humidity, presence of vibrations, aggressive chemicals or light. A scrupulous consideration of all these factors will lead to the optimal choice of material and will ensure the best performances and longest product life.

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