RAISE3D

Fiber-Reinforced Thermoplastic 3D Printing

White Paper

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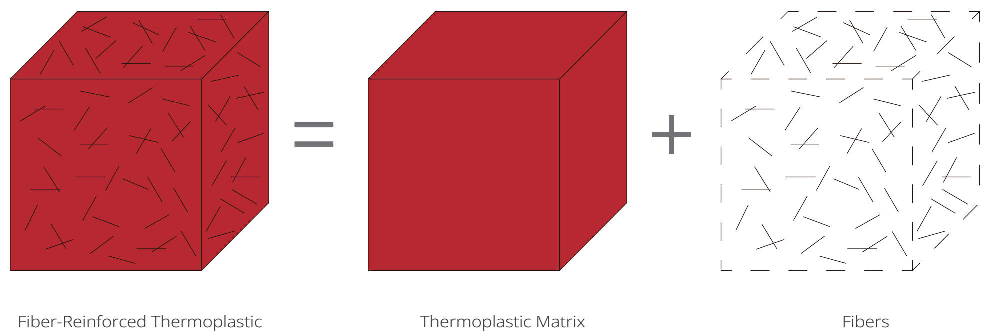
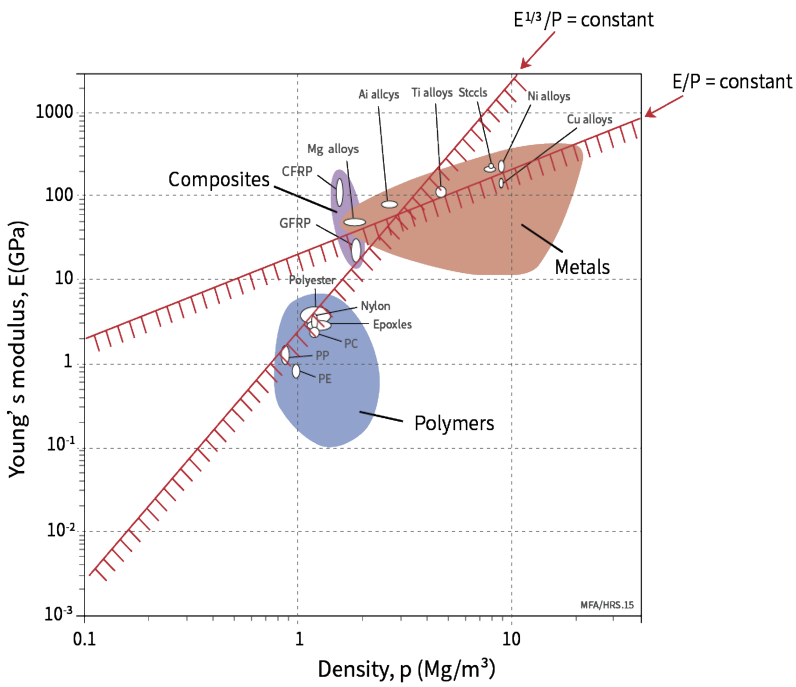
1 Background of Fiber-Reinforced Thermoplastic

- Fiber-reinforced thermoplastic is an emerging industrial material category with high-performance properties, making it a valuable solution for high-end industrial application. It is typically created by adding chopped fibers to the thermoplastic. Most popular reinforce fiber types such as carbon fiber, fiberglass, and Kevlar fiber have superior strength-to-weight ratio. Embedded fibers provide strength and stiffness along the direction they laid on while the thermoplastic matrix maintains the cohesion of these fibers and allows them to take loads. Thermoplastics exhibit much lower stiffness and strength than fiber materials like carbon fiber. Therefore, the infilled fibers can withstand extra loads and stress, boost the properties of the neat matrix materials.



- The general purpose of composite is *to achieve **a high performance** while **remaining lightweight**, especially compared to metal, both fibers and plastic components are much lighter.* Evenly and randomly distributed fibers can enhance the thermoplastic component's strength in all directions. Therefore, when a reinforced part is loaded with stress along the fibers' direction, the fiber can strengthen itself as much as metal.



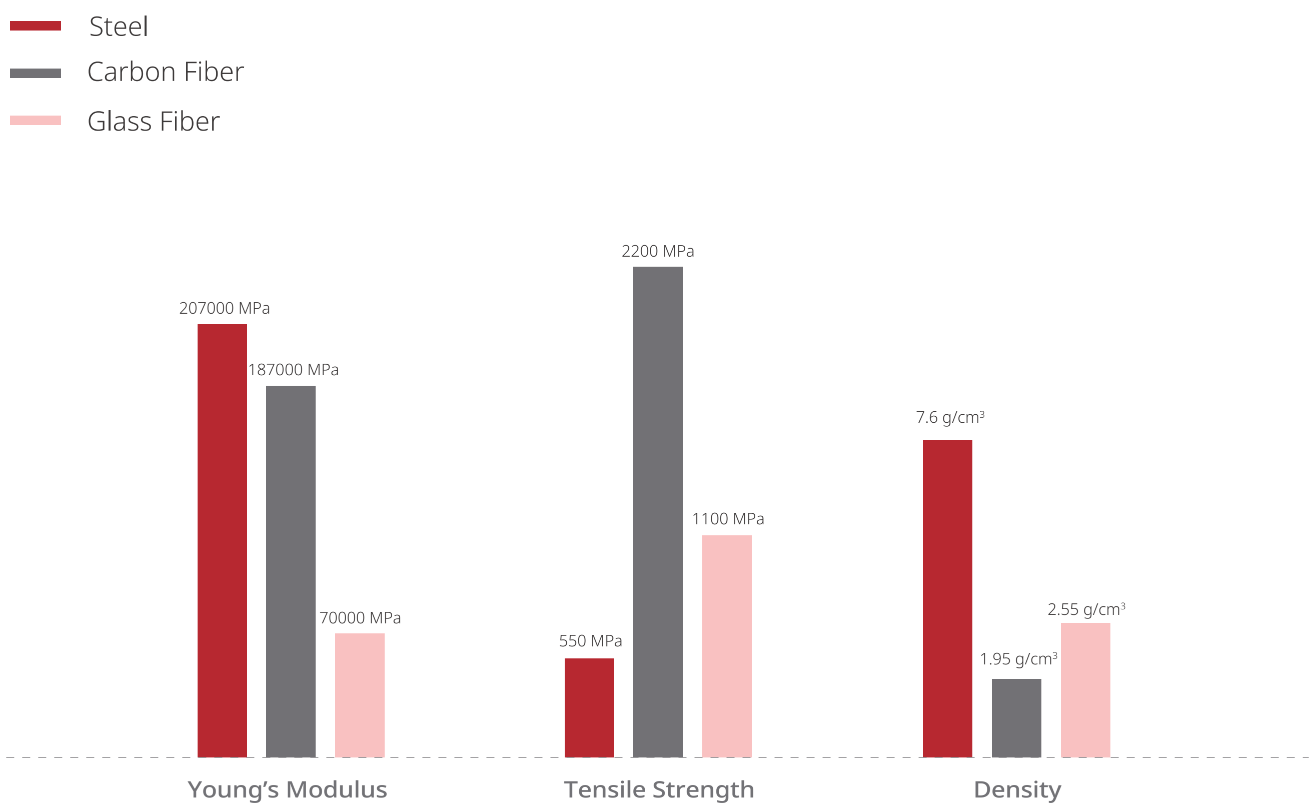
The Performance-Density Ratio Positioning of Different Materials Class.
Data Source: *Introduction to Aerospace Materials*, 2012, Pages 569-600

2 3D Printing with Fiber Reinforced Thermoplastics

- FFF 3D printing enables an additive manufacturing (AM) process to fabricate fiber-reinforced thermoplastic parts. For the last decade, thanks to the excellent flow ability of thermoplastic as matrix, fiber-reinforced thermoplastics can be easily shaped into continuous filament that can be applied by an FFF 3D printer. Almost all 3D printing thermoplastics, such as ABS, PC, PP, PA, and PPS, can be reinforced with fiber. With 3D printing technology, it becomes easy to fabricate thermoplastic parts in any shape with fibers evenly distributed inside.

Carbon fiber infilled in filament in microscopic view.
Source: *https://www.3dnatives.com/*

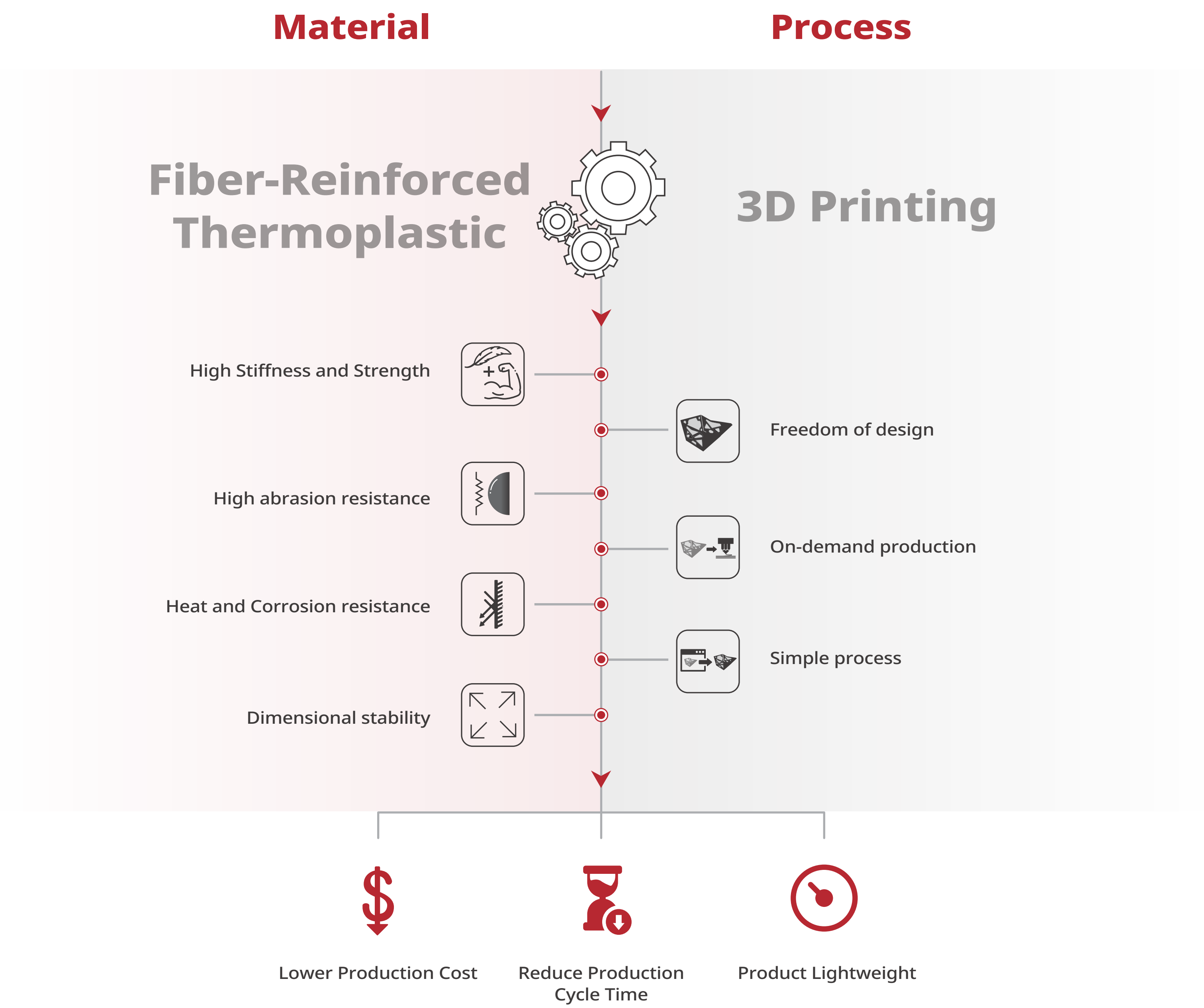
- Currently, carbon fiber and glass fiber are two of the most popular fibers for FFF printing filaments. *They both have a superior strength-to-weight ratio compared to polymer and metal.* Carbon fiber is five times stronger than steel and twice as stiff but remaining five times lighter. For example, a bicycle frame made of carbon fiber-reinforced resin has the same strength and stiffness but five times less weight compared to one made by steel. By comparison, it has the highest strength-to-weight ratio and Young's Modulus in the current material portfolio. Thus, it is extremely valuable in lightweight product and industry. Glass fiber has a relative lower strength and Young's Modulus than carbon fiber. However, this makes it much more flexible and durable than carbon fiber so that it can undergo more deformation before breaking.



Ashby, M and Jones, D, (2006) Engineering Material 2. 3rd Edn, Oxford: Elsevier

	Steel	Carbon Fiber	Glass Fiber
Young's Modulus	207000 MPa	187000 MPa	70000 MPa
Tensile Strength	550 MPa	2200 MPa	1100 MPa
Density	7.6 g/cm^3	1.95 g/cm^3	2.55 g/cm^3
Strength-Weight Ratio	78.5 kNm/kg	862.7 kNm/kg	709.7 kNm/kg

3 Potential Application of Fiber-Reinforced Thermoplastics in Industry



- Producing high-performance components with fiber-reinforced thermoplastics has been a sign on the growing demand for manufacturing. With a balance of shape giving and process flexibility, FFF printing using fiber-reinforced thermoplastics is promising to lower production costs, reduce life-cycle and optimize component structure at any time. Manufacturing sectors, especially automotive and aerospace, can find enormous value with composite filament and FFF technology, as they highly prize lightweight properties for their products. Moreover, lower energy consumption, higher productivity and reliability are also relevant advantages of FFF.

Structural Components

Carbon fiber thermoplastics have a comparable stiffness to metal yet are still lightweight, making them an excellent alternative for metal structural components. Examples of large metal structural components can be found in cars or airplanes. Since these large-scale parts are manufactured in metal, they are significantly heavier, meaning automotive and aerospace manufacturers will greatly benefit from lightweight parts. This is the reason that leading automotive manufacturers are applying carbon fiber to reinforce cars' monocoque chassis and replace sheet metal such as aluminum. Usually, such a replacement can result in a 10-30% reduction in total weight, which equals to around 100 kg.

Such components need certain capabilities from FFF printers to deliver large parts in one piece efficiently and to reduce assembly time.

Heavy Duty Components

Manufacturers have recognized opportunities in their business operations for replacing current materials with fiber-reinforced thermoplastic to utilize its high-performance capabilities in heavy-duty roles. These heavy-duty roles include components and industries in a harsh environment that usually encounter high temperatures, frequent impact, vibration, and abrasion. A common use for fiber-reinforced thermoplastic is to apply carbon fiber reinforced thermoplastics in making vacuum pumps. Carbon fiber reinforced thermoplastic's abrasion resistance and creep resistance provides enough durability and dimensional stability against continuous rotating impacts from inside.

By using FFF printing to produce fiber-reinforced thermoplastic parts, manufacturers have the flexibility to replace all product lines with fiber-reinforced thermoplastics without having to renew the corresponding production lines.

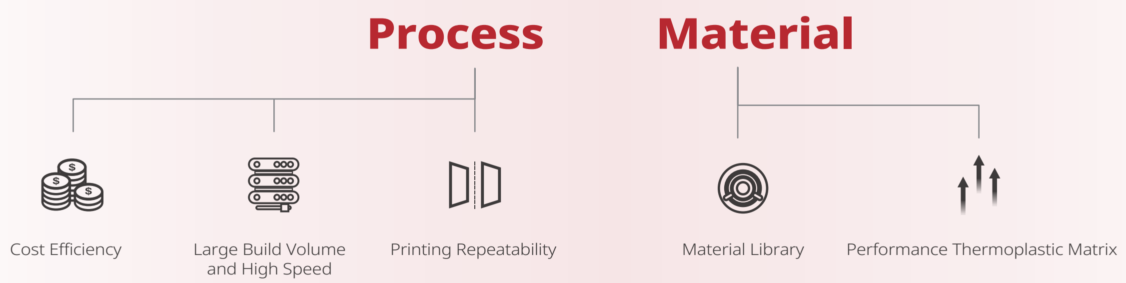
Jigs and Fixtures

Jigs and fixtures made with carbon fiber thermoplastics are favored on the production line. Fiber thermoplastic parts are lightweight, making them easier to operate than metal parts. Generally, there is an occasional demand for jigs and fixtures with varying requirements due to changes in the production line. A better solution for jigs and fixtures would enable manufacturers to produce small quantities of customized parts, which makes 3D printing an excellent solution for this since parts can be produced as needed using 3D printing, according to specific instructions in a design file.

A desktop FFF 3D printer specializing in carbon fiber filament printing is a great solution to manufacture jigs and fixtures. Its design-build volume can fulfil the most requirements and has the advantage of being compact enough to easily deploy in any setting. Its printing speed of around 100 mm/s can respond to any tight-time situations.

4 Valuable Capability for FFF Printing using Fiber-Reinforced Thermoplastics

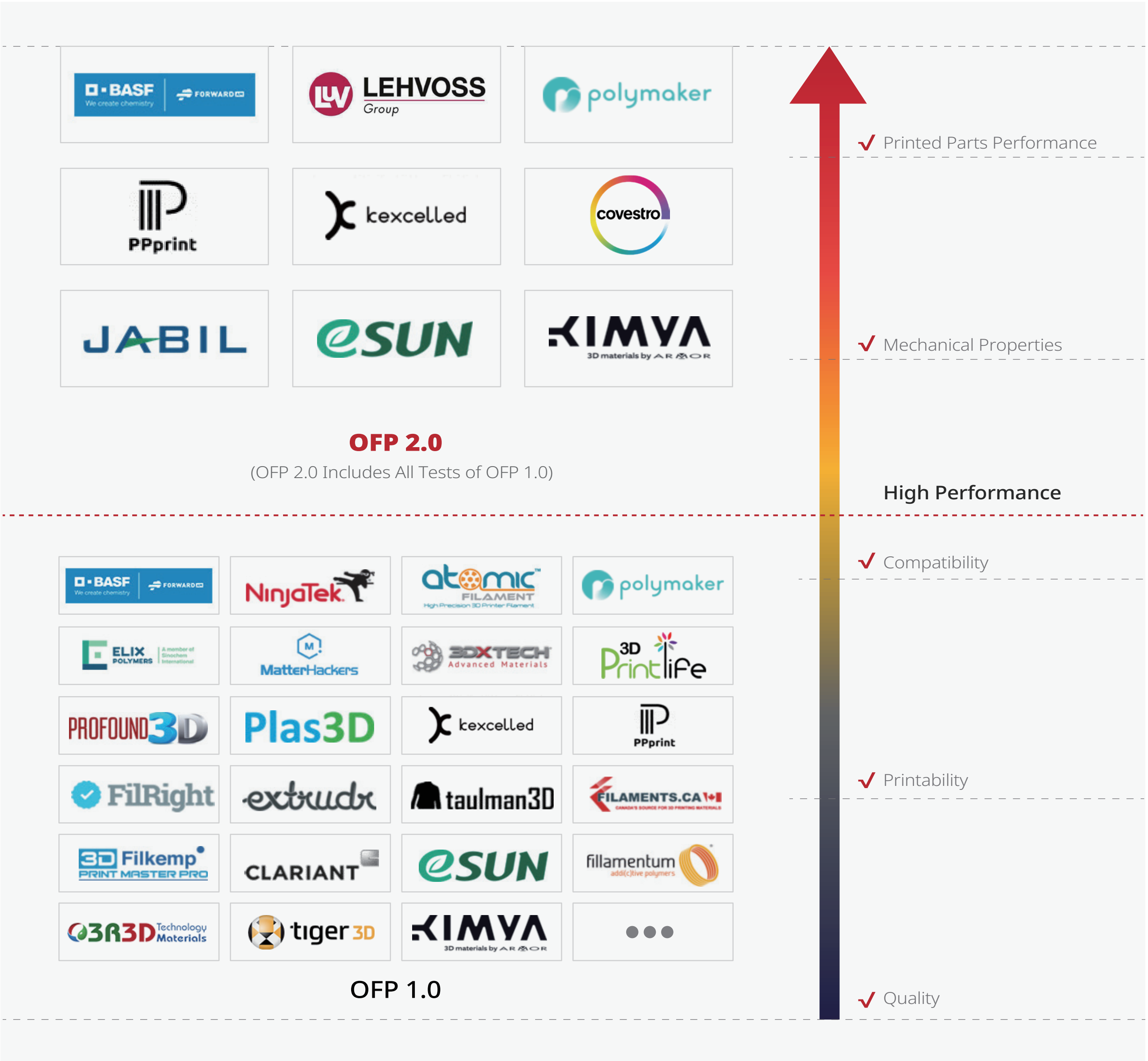
- *The purpose of fiber-reinforced thermoplastic FFF 3D printing is to deliver high-performing end-use parts for an industrial manufacturing scenario.* As a result, fiber-reinforced thermoplastic FFF 3D printing differs from FFF printing technology for general thermoplastics such as ABS, PETG, PC, and ASA. Fiber-reinforced thermoplastics FFF printing technology must possess a much higher capability in both the material and the 3D printing technology itself. Raise3D has devised this technology by creating industrial-purposed filaments and redesigning the FFF printing mechanism. Raise3D has designed the RMF500 and E2CF, the first two models of its composite thermoplastics' printer family, for large and small-scale manufacturing respectively.



Raise3D Fiber-Reinforced Thermoplastic 3D Printing Solutions

Material Library

When manufacturers are looking for an FFF printing solution, it should be ensured that their project implementation via FFF could be supported by a wide availability of reliable and performance-driven filaments. *Fiber-reinforced filament is expected to expand quickly because it brings benefits by adding chopped fiber into thermoplastic.* When made these fiber filled thermoplastic into filament, there are numerous candidates from the thermoplastic family. For example, Raise3D provides engineering and performance grade thermoplastics, including PA12 (Polyamide 12), PET (Polyethylene Terephthalate), PPA (Polyphthalamide), and PPS (Polyphenylene Sulfide) as part of the Open Filament Program. Apart from these, Raise3D will select and certify top-performance fiber composite filament from a third party manufacturer. Standardized tests will be carried out to verify the quality and performance of the filament and its printing settings. Users can find optimized filament printing profiles for each printer type from ideaMaker Library and apply them directly by utilizing Raise3D's slicing software, ideaMaker.

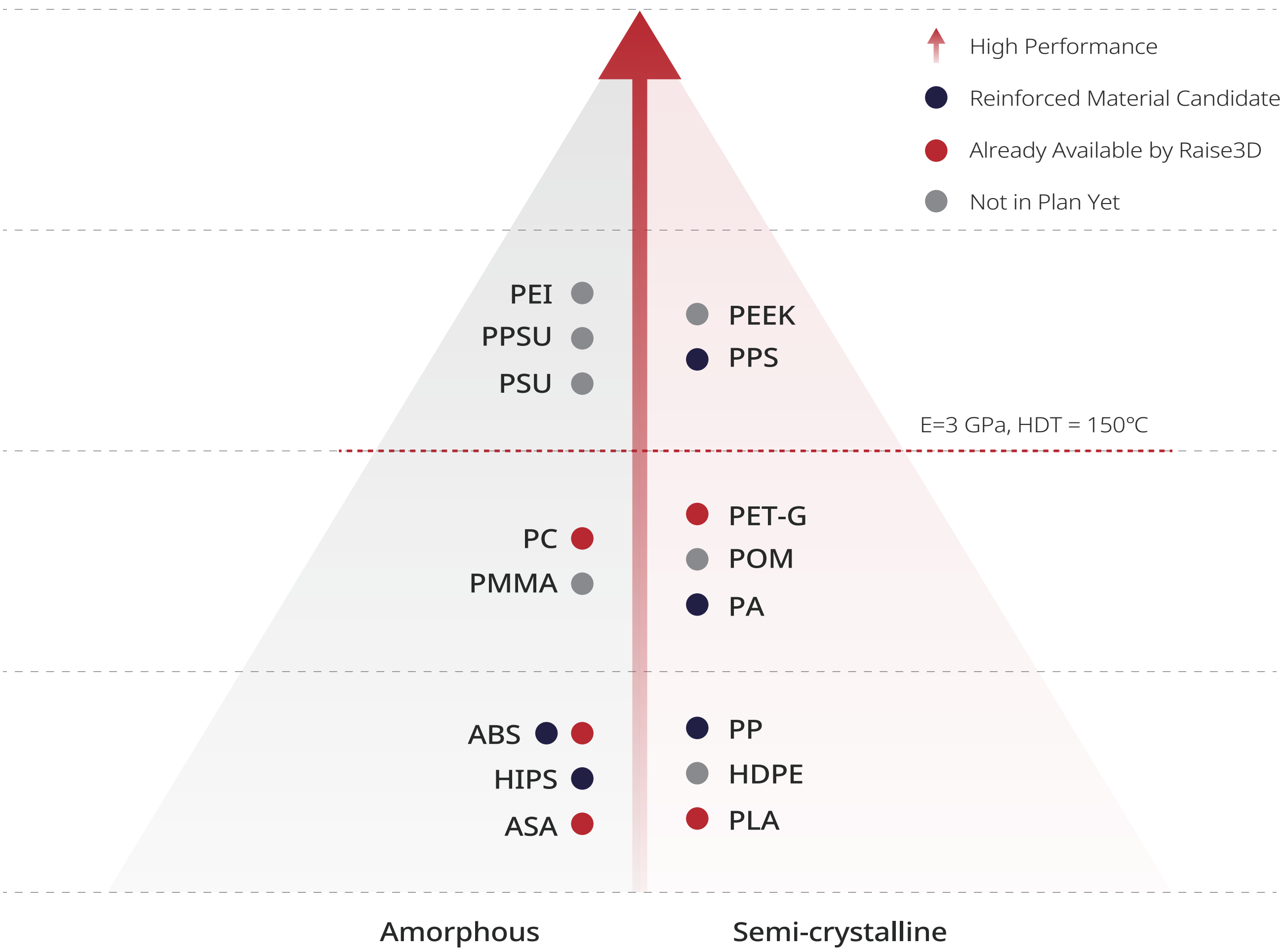


Raise3D's OFP Expansion to Industrial Materials

Performance Thermoplastic Matrix

An industrial customer orientated FFF 3D printer should support and cover high-performance thermoplastics which have the most outstanding stiffness and heat resistance. *For some engineering and industrial applications, appropriate materials usually feature Young's modulus of over 3 GPa and heating deflection temperature (HDT) over 150°C.* Typical 3D printing thermoplastic, such as PETG, PA and ABS, have low Young's modulus and they do not have enough heat resistance for long term service over 150°C.

Raise3D's High Performance Candidate for Reinforced Material



However, by reinforcing engineering and performance thermoplastic with fibers, Raise3D achieves composite filament with significantly improved thermal and mechanical properties. This category includes PET CF (Carbon Fiber Reinforced Polyethylene Terephthalate), PA12 CF (Carbon Fiber Reinforced Polyamide 12), PPA GF (Glass Fiber Reinforced Polyphthalamide), PPA CF (Carbon Fiber Reinforced Polyphthalamide), and PPS CF (Carbon Fiber Reinforced Polyphenylene Sulfide), which have Young's Modulus from 3.3 to 13 GPa and HDT from 100 to 220°C. By comparison, by printing with composite filament, the printed part can withstand loading of over 80 MPa, while most unfilled thermoplastics have a limit of around 40-50 MPa. Moreover, Raise3D's composite filaments are designed with a unique performance enhancement by post-treatment. For example, PA12 CF will have an overall performance improvement of around 40-50% after annealing. (One practical annealing method is to place freshly printed piece into an oven set with 80°C for least 8 hours. It will be helpful to press printed piece with heavy weight on top to prevent warping during annealing.)

Raise3D PA12 Carbon Fiber Filament		
0.4 mm Nozzle	As Printed	100°C Annealed
Tensile Strength (MPa)	44	**72**
Young's Modulus (MPa)	1918	**3304**
Elongation at Break (%)	34	4
Bending Strength (MPa)	48	**110**
Bending Modulus (MPa)	2012	**3535**
Notched Charpy Impact (KJ/m^2)	18	13
HDT @ 0.45 MPa	90°C	**131°C**
HDT @ 1.8 MPa	/	105°C

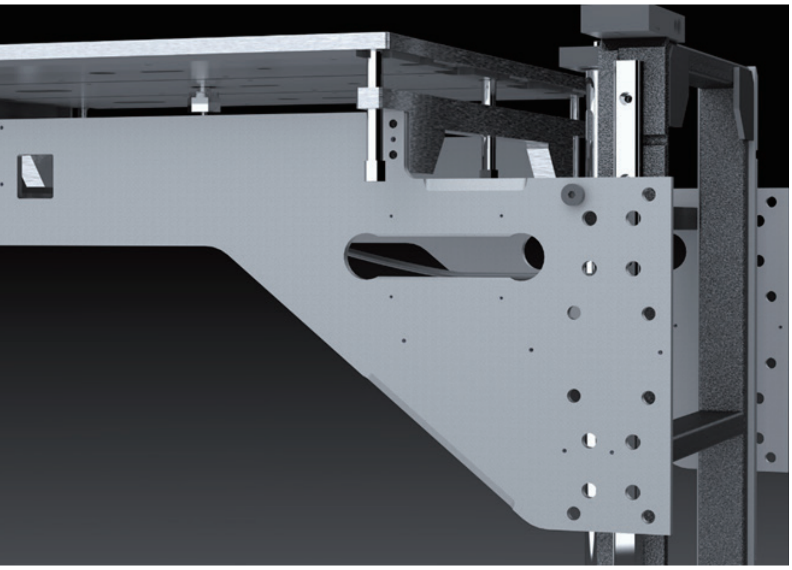
Technical Sheet of PA12 Carbon Fiber Filament before and after Annealing

Cost Efficiency

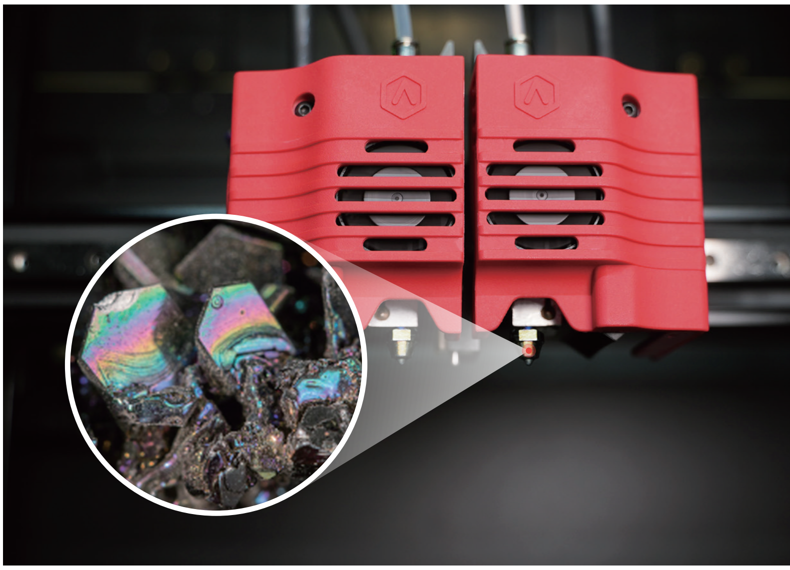
Printing with fiber-reinforced filaments has a different set of technical hardware requirements due to distinct material characteristics. Based on material science, especially for fiber filled material, there is lots of free space for hardware optimization by redefining the FFF printer. *Doing so will result in great printing quality, higher speed, and better cost-efficiency.* For example, with specifically-developed fiber-reinforced filament such as PA12 CF, Raise3D's RMF 500 can maintain warp-free printing quality without the heating chamber and 70% lower energy consumption compared to other industrial printers. The crystallization behavior of composite is also optimized for FFF processing. In addition, the reduction of heating chamber module decreases the total cost of the machine itself.

Printing Repeatability and Reliability

Repeatability and reliability are essential for mass production in industrial manufacturing. *In large-batch printing, the delivered print quality should be consistent for each piece all the time.* This raises the standard for overall mechanical engineering performance to a new level when compared to traditional FFF printing. For the RMF500 3D printer, which is specifically designed for mass production, such high standard is critical. The RMF500 features a full highly stiff steel structure and 1μm closed-loop drive system to guarantee a precise print. Both the E2CF and the RMF500 feature hardened nozzles (Silicon Carbide) of over 60 HRC hardness to resist abrasion from the carbon fiber filled filaments, which are more abrasive than other materials.

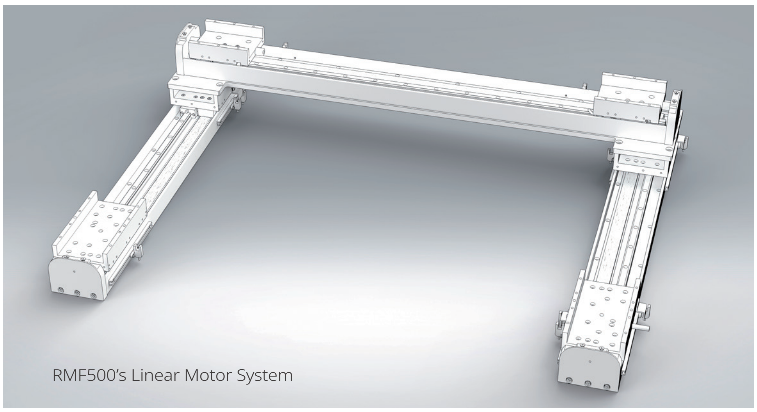


RMF500's Steel Frame



E2CF's Hardened Nozzle Made by Silicon Carbide.
Source: *https://nanografi.com/blog/silicon-carbide-sic-micron-and-nano-powder/*

Large Build Volume and High Speed



RMF500's Linear Motor System

Fiber-reinforced thermoplastic is valuable in the creation of large parts such as structural components, which also generates its own set of challenges when FFF printing. *It is a critical capability for a manufacturer to be able to deliver large-format prints with fiber-reinforced thermoplastics in a short time frame.* The RMF500 has a build volume of up to 500 x 500 x 500 mm and a maximum speed reaching up to 300 mm/s, allowing it to produce large 3D printed parts quickly. Its linear motor system has a faster printing speed compared to the belt and screw system adapted by traditional FFF printers.

Appropriate Return on Investment

Industrial manufacturers also have occasional and variable demand for fiber-reinforced thermoplastics such as jigs and fixtures. *A backup compact printer with limited productivity and build volume, but still reliable as industrial printer is suitable for such scenario.* E2CF is a desktop FFF printer which provides on-demand fabrication with PA12 CF. It can print parts with any geometry smoothly at a speed of 100 mm/s inside build volume of 330 x 240 x 240 mm. E2CF is a very handy production tool for production and customer service teams to fabricate jigs and fixtures in-house, as frequently as needed.

5 Conclusion

FFF 3D printing opens up a new range of applications for fiber-reinforced thermoplastics equipped with the most outstanding properties via additive manufacturing. In addition, the awareness of traditional polymer manufactures also accelerates 3D printing R&D and enlarges the existing availability and diversity of composite filaments. As part of a growing trend, the development of FFF printing solutions for fiber-reinforced thermoplastics is expected to evolve with cost-efficiency, performance and material-driven DNAs. In summary, fiber-reinforced thermoplastic FFF printing enables:

- Industrial grade strength parts and components
- Lighter weight components vs. metal and solid polymer components
- Highly desirable properties for automotive and aerospace industries

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