FEATURE

Current achievements and future outlook for composites in 3D printing

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The composites industry has a tendency to get caught off-guard by metals as they make progress into more applications. 3D printing is an area where metals have taken the lead, but a number of developing technologies could put composites back on top.

Composites are often heralded as the materials of the future. Their strength properties offer an incredible advantage over any other material. With the Boeing 787, Airbus A350, and BMW i-series, composites are well on their way to establishing a stronghold in mainstream manufacturing. However, the metal industry is still very much a threat to the continued success and growth of the composites industry. Alcoa's 3rd generation of aluminum–lithium alloys has led many companies to move away from composites, and these alloys are slated for various new aerospace projects. Considering that it was only in the past few years that composites became viable in a large-scale performance production line, these forward leaps in metals could pose a threat to the increasing market penetration of composites.

FIGURE 1
As-printed and post-machined part by Norsk Titanium.

Metal 3D printing

3D printing is another area where metals compete with composites. Metal 3D printing already works fairly well for a variety of alloys, but by virtually any metric, there is currently no 3D printing technology for composites that is comparable in performance to the best that metal 3D printing has to offer, let alone something comparable to tape laying. Research in metal 3D printing has been ongoing for the past decade, leading to multiple advances with applications in aerospace and other industries such as high-performance automotive. Titanium 3D printers can currently achieve comparable properties to machined titanium when using a solid rod feedstock, and although these parts require some degree of post-machining, they are proving effective for intricate, high-strength parts. Selective laser sintering (SLS) printers use a powdered input material that eliminates this machining step, making them precise enough to use in components such as fuel nozzles in CFM's LEAP engine, but the powder process has other drawbacks such as porosity.

A fully functional carbon fiber 3D printer should be able to produce intricate, detailed, and strong parts greatly surpassing the capabilities of machined aluminum and 3D printed metal at a cost that falls in between the two, all while allowing users to tailor their properties with entirely new CFRP (Carbon Fiber Reinforced Polymer) structures. Composite feedstocks are less expensive than the precisely powdered alloys used in some metal 3D printers, and the energy required to heat a thermoplastic or reactive polymer is much lower than the energy required to fuse metal. This potential of composites has not yet been achieved due to limited investment in this area and engineering challenges, rather than because of any inherent physical limitations.

Significant disadvantages

Several startups have developed various systems to 3D print composite materials over the past few years, but all the current approaches demonstrate significant disadvantages when

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compared to machined aluminum, especially for industrial applications. As a result, these startups tend to focus on either consumer 3D printing or merely provide geometric prototypes.

The material feedstock presents one of the major limitations. Markforged, the maker of the first carbon fiber 3D printer, is the only company currently offering a continuous fiber process. Their printer has brought higher performance 3D printing to businesses in need of small prototypes, as well as the maker movement. However, researchers have shown that their filament has large voids and contains many resin-rich areas, resulting in substantially lower properties than the rule of mixture would allow—their unidirectional coupons just barely surpass 6061 aluminum in tensile strength. Plus, the combination of porosity and printing parallel layers rather than multiaxial printing results in poor shear and fatigue properties leading to delamination and matrix cracking. Markforged has effectively targeted their product to the consumer and prototyping market, offering a safer and more manageable alternative to CNC machining aluminum at home, but this solution (especially when considering the $500/lb+ price point for their filament) is difficult to justify outside of the home, workshop, or makerspace.

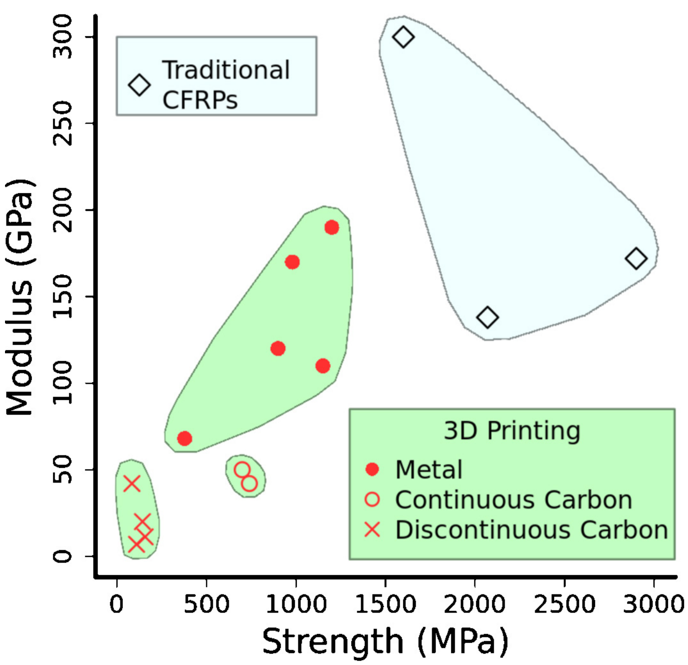

FIGURE 2
Strength and stiffness of traditional composites compared to 3D printing.

An invalid comparison

Metals are isotropic, meaning their properties are uniform in all directions, allowing their elastic state to be fully captured with two properties: Young's Modulus and Poisson's ratio. Composites on the other hand are anisotropic and require a greater number of constants to describe their elastic behavior. For instance, a unidirectional composite laminate is a transversely isotropic material with five independent elastic constants and a special orthotropic composite laminate with multiple ply-angles has nine elastic constants. Given the largely consumer focus of the 3D printing market, it is not unexpected that companies would provide the single most impressive metric, the unidirectional Young's modulus, but this is insufficient to fully understand the achievable performance.

The comparison becomes even more questionable if one suggests that a 3D printed material is 'stronger than metal' (a common benchmark) when it barely edges out some particular aluminum alloy in a unidirectional tensile test. A metal will have similar compressive and tensile strength, whereas the compressive strength of a composite is much lower than its tensile strength. The anisotropy of composites is also relevant for a variety of other static strength properties that involve a combination of tension, compression, and shear loads.

The durability and fatigue properties of commonly used metals are well-understood, but composite materials are brittle and were prone to catastrophic failure before the advances of toughened thermoset resins. 3D printing of composites could have the advantage here since it typically involves intrinsically tougher thermoplastics. However, the failure to approach the theoretical rule-of-mixtures property limits, along with substantial porosity, indicates that these parts could not be used reliably in most engineering applications.

The large performance gap between metals (machined or 3D printed) that composites have yet to close, despite claims of comparable or superior properties (particularly specific properties), can be reconciled by considering the laminated structure by which composite parts are made. Depending on the fiber, a unidirectional carbon fiber composite can have anywhere from 4 to 8 times the tensile strength of 6061 aluminum, which works out to as high as 16 times higher specific strength. So why is that in reality a carbon fiber part replacing an aluminum one only results in a 30–40% weight reduction? Even ignoring the fact that many structures are stiffness rather than strength driven, and the higher safety factors used with composites, the fibers need to go in multiple directions. Adding a lamina at ninety degrees nearly halves strength in the primary direction. A few forty-fives for shear and it goes lower still. However, the geometric limitations of current carbon fiber part designs are also a factor. Therefore, an effective carbon fiber 3D printer would have the potential to optimize the external topology of a part to achieve substantially higher weight savings if it could combine comparable unidirectional strength and stiffness of traditional composites with internally optimized fiber paths.

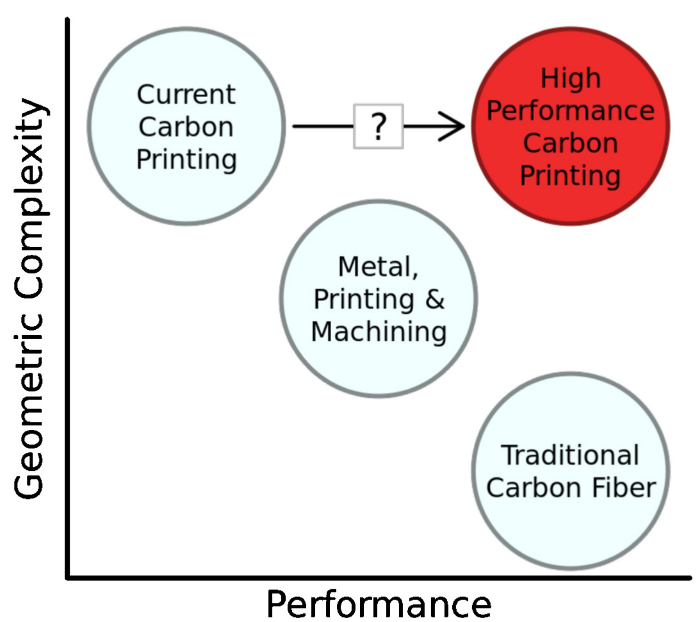

FIGURE 3
Carbon fiber 3D printing could bring high performance and complexity.

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3D printing discontinuous fibers

The current attempts to 3D print continuous carbon fibers still require significant improvements and innovation before reaching viability, and unsurprisingly, mechanical performance only gets lower with other morphologies. Enter discontinuous carbon fiber 3D printing, a process that currently yields low properties, since the fibers are so short they pull out of the matrix rather than reinforcing up to fiber failure. The minimum length to have the fiber rupture rather than slip is known as the critical fiber length. Although chopped carbon fiber feedstock is available for SLS applications from companies such as CRP Technology, the powder structure limits fiber length. Impossible Objects has developed a process that involves stacking layers of carbon fiber tissue-paper-like material, and pressing those together. Both of these technologies realize the benefits of more uniform properties due to the somewhat random fiber orientation in the SLS powder and the random fiber orientations within the plane for Impossible Objects. However, this can also be a drawback since it defeats the ability to optimize the fiber orientations and only the external geometry can be optimized. Plus, the fiber length limitations result in properties on the order of those seen in neat high-temperature thermoplastics, and there is no obvious route to increasing fiber length with either of these two printing processes.

Fused deposition modeling (FDM) printing could theoretically achieve longer fiber lengths, but in absolute terms, all current solutions have fiber lengths about an order of magnitude lower than the critical length. Regardless, it is still an interesting area that some companies are pursuing. Arevo Labs is a startup company currently offering fiber-reinforced FDM with high-temperature thermoplastics. The current processes for making FDM filament are adapted from the same sort of screw-extruders that are used for injection molding, and this process breaks down carbon fibers well below their critical length. Therefore, when Arevo adapted this process to the intrinsically stronger PEEK, they did obtain some improvement over carbon fiber reinforced ABS, but not enough to bring the full strength of composites to their parts. Arevo's parts have roughly double the tensile strength and 4 times the tensile modulus of neat PEEK. While this may be close to the performance of injection-molded carbon fiber reinforced PEEK, Cytec's ACP-2 PEEK (intermediate modulus), a prepreg composite material commonly used for automated tape laying, has 30x the tensile strength and 40x the tensile modulus of neat PEEK. That is a large performance gap. Arevo uses a multi-axis robotic arm instead of a simple 3-axis printer, which allows them to develop parts more tailored to the strength needs of their customers, but higher mechanical properties are needed to achieve the full value of that system. Besides, their high cost (higher than Markforged) further detracts from use in a production setting.

Potential methods

While the current outlook may seem bleak from a high-performance composites perspective, there are still potential methods for higher performance 3D printing with short fibers. Given how short all the fibers are in these processes, any company that could develop a filament for FDM with high-temperature thermoplastics and carbon fibers with an average length closer to or preferably above the critical length could achieve substantially higher properties at a reasonable cost, opening up many new opportunities.

FIGURE 4
Nylon 3D printed parts with Kevlar reinforcement by MarkForged.

Despite the current limitations, it is important that efforts are being made toward making carbon fiber 3D printing work. Large amounts of money are being invested into proven metal 3D printing technologies, but far less money is going toward developing the so far unproven concept of a fully functional carbon fiber 3D printer. With metal 3D printing, well established companies are focusing on developing cutting edge technology, whereas composite 3D printing advancements are largely coming from smaller startups, with disjointed approaches. Some of the approaches show paths toward improvement—short fibers can be made longer, multi-axis printing machines can be developed that target a low cost per print time for parallel manufacturing, and continuous fibers need to be wet-out effectively, and oriented along expected stress lines (Figs. 1–4).

A research team at the Tokyo University of Science has developed a co-extrusion method for 3D printing continuous carbon fiber where a tow of carbon fiber is passed through the thermoplastic melt pool inside a modified nozzle. They were able to demonstrate much higher relative properties as a percentage of rule-of-mixtures using PLA with carbon fiber as well as with jute fibers. However, this team was only using a 7% fiber volume fraction in comparison to the 34% in Markforged's carbon filament layers (note that the Markforged printing process involves combining composite layers with layers of pure plastic, so the effective fiber volume is usually lower). The researchers suggested that their process would work with a much larger fiber volume percentage, but effectively wetting a much larger bundle of fibers in such a short distance, with a high viscosity thermoplastic, would be challenging to say the least.

Texas based startup, Cosine Additive, is confronting the problem of length reduction of carbon fibers in the filament production process with an interesting approach. Cosine Additive focuses on large-scale FDM printing and they are interested in developing a BAAM (Big Area Additive Manufacturing) style printer that uses pellets as feedstock instead of a filament. Cosine Additive is focused on industries such as tooling where short fibers are acceptable rather than aerospace, which has much higher performance requirements. Cosine Additive has recently partnered with Oak Ridge National Lab to increase their

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production rate 10 lbs/h, but speed is not their only innovation. They are also interested in the possibility of a pellet-based extruder that does not use a traditional screw-extrusion process in order to preserve the length of the carbon fibers and achieve higher properties.

Sporadic effort

Despite the strides and innovations of various companies, it's not just incremental improvements that allowed the metal industry to develop their current 3D printing technology. The metal industry made significant investments into a technology with the potential to be a game-changer. Alcoa's yearly revenue is roughly the same as the entire carbon fiber composites market, and their investment is focused, whereas the composite industry often makes sporadic efforts toward short-term objectives that do not usually span the entire industry. The model of playing catch-up works in some areas, but why not gain a definitive edge and maintain the lead? This can be achieved, to the benefit of the composites industry and its customers, by systematically engaging and pursuing new technologies, even if those technologies are not being developed in-house, and still need maturation.

Stratasys recently released an FDM printing process that is similar to Arevo Labs (if they are using high-temperature thermoplastics rather than ABS or Nylon), but with additional mechanical axes to allow not only printing in any direction, but also from any angle, and with a much larger build volume. This is certainly an impressive accomplishment, but strapping existing FDM nozzles to ever-larger commercially available robotic arms will only push progress so far. The composites industry has the most to gain from improving the performance of 3D printing technologies so that they can meet the needs of high performance industries—and this is not the focus of the 3D printing industry that has grown within consumer and low-performance business markets so far. Composites may very well be the material of the future, but 3D printing is the manufacturing method of the future, and until the two are combined in an effective, inexpensive, and scalable method, the ease of use and performance of metal, both in 3D printing and machining, will continue to prevail.

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