FEATURE

Current achievements and future outlook for composites in 3D printing

Michael Chapiro

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

E-mail address: mchapiro@mantiscomposites.com.

0034-3617/ http://dx.doi.org/10.1016/j.repl.2016.10.002

Please cite this article in press as: M. Chapiro, Reinf. Plast. (2016), http://dx.doi.org/10.1016/j.repl.2016.10.002

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.

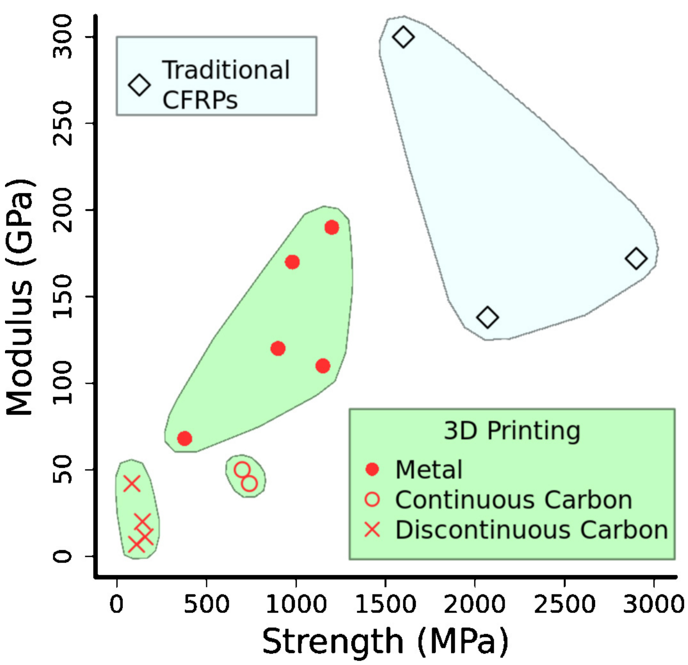

FIGURE 2
Strength and stiffness of traditional composites compared to 3D printing.

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.

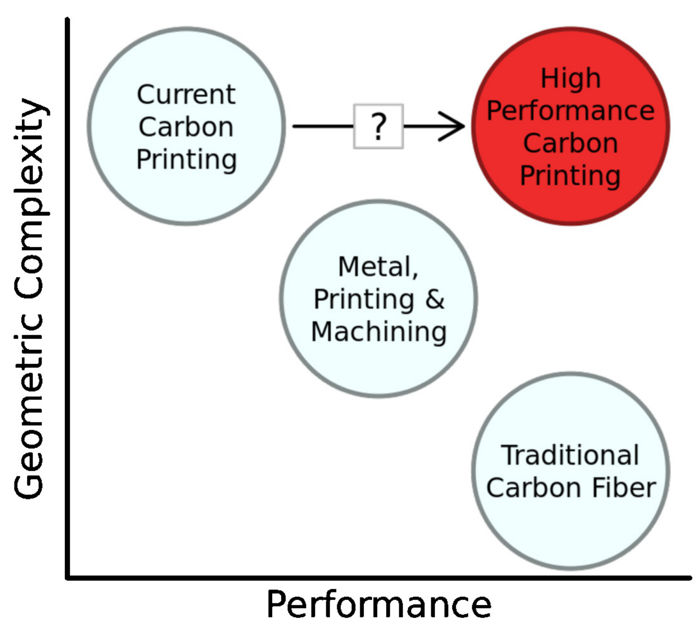

FIGURE 3
Carbon fiber 3D printing could bring high performance and complexity.

Please cite this article in press as: M. Chapiro, Reinf. Plast. (2016), http://dx.doi.org/10.1016/j.repl.2016.10.002