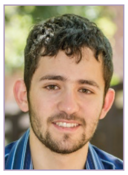
Full-strength 5-axis carbon fibre 3D printing revolutionizes aviation and space



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Carbon fibre is an incredible material but laminates are a "suboptimal structure", usually barely edging out metals. 3D printing this high-performance material will enable its true lightweighting potential, forever altering the trajectory of the aerospace sector.

A couple of years ago, an article in JEC Composites Magazine asked whether composites would remain competitive with metals in light of the faster pace of advancement in next-generation aluminium alloys and metal 3D printing. From a structural efficiency perspective, the answer could very well be no. Carbon fibres with roughly double the strength of initial carbon fibres from the 1960s are available today, yet the weight of composite parts has not halved. Weight is not an insignificant factor in the decision to use carbon fibre in aviation, but reduced corrosion, reduced fatigue, higher operating pressure, and increased flight comfort from better vibration damping have proven to be crucial additional benefits that permitted its implementation.

Aerospace regulations or micromechanics?

Composite experts will be quick to point out that many limitations in the lightweighting potential of carbon fibre composite laminates are due to the FAA or CMH-17 regulations that were originally written with metals in mind. These regulatory frameworks have made it challenging to implement fully bonded structures and the continued use of fasteners results in a much larger knockdown factor in composites than metals since composite laminates have poor bearing strength.

However, fasteners alone fail to account for the discrepancy between weight reduction in real systems and the ~10x higher specific strength and ~5x higher specific strength of a unidirectional laminate over 7075 aluminium. The need to orient the fibres in multiple directions and the higher process variability of composites do not explain the discrepancy either. So, why are carbon fibre structures not lighter given these vastly superior properties? The fundamental problem lies in the limitations inherent to parts and structures comprised of a composite laminate.

Composite laminates do not come close to the full fibre strength, which is only reached near 2% fibre strain. The failure of transverse or angle plies due to matrix cracking around 0.5% strain and other knockdown factors can bring it to about 0.3% strain, making it challenging to utilize more than about 20% of the full fibre strength in a laminate. Carbon fibers being a full order of magnitude stronger than aluminum alloys is the only reason composite laminates are viable given these reductions. Had these knockdown factors varied only slightly, the advantage of composites would disappear, and this is what might be happening now for aerospace fuselage skins due to 3rd (and 4th is coming) generation aluminium lithium alloys tipping the balance back in favour of metals. The only way to get around this limitation and reach the full potential of carbon fibre will be to use novel manufacturing methods that do not rely on the laminate substructure.

Mantis Composites' approach

5-axis continuous carbon fiber reinforced high temperature thermoplastics such as PEEK reinforced with continuous carbon fibres will enable the full performance of carbon fibre in end-use applications. Mantis Composites will be able to make complex geometries that were previously impossible to produce out of carbon fibre, and it will often be possible to build these intricate parts out of unidirectional substructures instead of a laminate.

With the strongest materials ever to be 3D printed and the structural efficiency this enables, using this technology will be the only way to reach the ultimate system performance in aerospace or automotive. The usual benefits of "3D printing" are just a bonus.
Markforged pioneered the use of carbon fibre to improve 3D printing with continuous T300 fibres in a nylon matrix, and other companies have used chopped or milled fibres with high-temperature thermoplastics. These are innovations that exist primarily within the prototype-centric 3D printing space. Additionally, improvements in geometric freedom for automated fibre placement or patch placement to enable lower production costs are innovations that exist within the framework of traditional composites — they cannot achieve the geometric advantage of true 3D printing.

The difference from a mechanical perspective is straightforward. Chopped fibres are about an order of magnitude weaker than continuous and sub-60% fibre strength translation in a nylon matrix is not an option for aerospace, even though it is fantastic for prototyping or other markets. These other technologies may be quite useful in aerospace and other industries, but none of them fundamentally changes aerospace parts manufacturing from a performance perspective.

In comparison, Mantis Composites can achieve a 90% fibre strength translation with a 30% fibre volume of high-strength carbon fibre in a high-temperature PEEK matrix (80% strength retention with 50% volume IM fibre), with a 5-axis printer that can make tight turns and orient fibres in nearly any direction in free space. This machine was designed for manufacturability with a high build-volume-to-footprint ratio to enable quick scaling for supplying parts to customers.

Fig. 1: 3D printed square grid — printing cellular structures enables high specific bending strength and stiffness

Fig. 2: 3D printed isogrid

Software drives scalability

The machine and the materials work, but three key software problems remain before production can be ramped up: 1) automated part design; 2) automated process analytics; and 3) non-destructive part analysis.

The company is currently developing one-off fibre paths for existing CAD models with small modifications as needed in collaboration with the customer. Over the next few years, it will transition to a generative design process where a user specifies loading requirements and a bounding box. Initially, this will operate with a "*building block*" approach where parts are formed from a set of substructural elements and attachment points that connect together, and it will eventually transition to full free-form generative design. In metal 3D printing, the shape fully determines the path, but with composites, both the shape and fibre path need to be determined based on performance requirements.

Fig. 3: True carbon fibre 3D printing combines material performance with optimized shapes

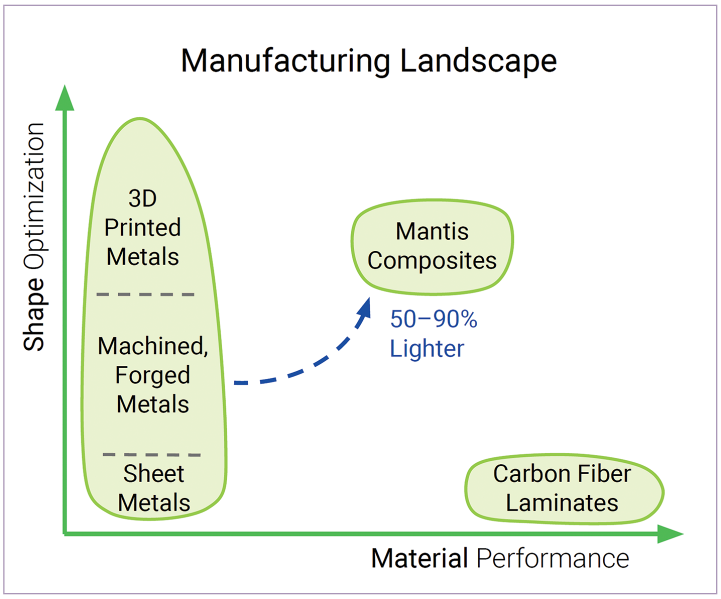

Fig. 4: Structural efficiency is a "product" of material performance and the shapes that can be fabricated

Next, the data logging capabilities of the printer need to be correlated with data from coupons and parts so that it can effectively improve over time and ensure consistency from part to part. Today, these capabilities are built into the machine so now it is only a matter of generating enough data to develop and train modelling algorithms. Finally, for the most critical applications, the parts will be micro-CT scanned for the highest possible performance and reliability on every part delivered.

Advanced materials and manufacturing landscape

3D printing of high-performance carbon fibre is more than just bringing the performance of carbon fibre to parts currently made using machined metals. Some parts or structures might work well with a simple sheet or laminate without additional stiffening structures that add weight. However, since buckling resistance grows with the cube of thickness, a shell structure will not always be the lightest. How can this comparison be abstracted to arbitrary part designs since the exact performance metrics must be narrowly defined? Structural efficiency can simply be thought of as a generalized performance metric derived from a "product" of material performance and the degree to which its shape is optimized.

The chart is based on shape alone, but the full geometric optimization that is possible for composites needs to consider their anisotropy. From a purely materials perspective, since 3D printing enables design elements that do not have the drawbacks of laminates, Mantis does not necessarily have lower performance on the X-axis than traditional composites for most parts. Since complex 3D-printed metal lattices and grids with two force members do not need much strength or stiffness in other directions, their geometric efficiency is not necessarily better than what the company can achieve with a simpler overall shape on the Y-axis.

Aerospace 2.0

Historically, technological manufacturing shifts have been represented by leaps in either the materials that can be manufactured or the shapes that are viable to manufacture out of known materials. What will the future of aerospace look like now that we have a substantial leap forward on both fronts simultaneously?

Many people have bemoaned a lack of innovation in the overall shape of airplanes, and the increased financing available for more efficient aircraft might finally enable a more dramatic shift such as a blended wing body plane. Since commercial and manned military aviation have longer design cycles and more regulations, these materials will most likely be utilized in UAVs, satellites, and race cars initially. Regardless of which markets implement high performance carbon fiber 3D printing first, one thing is clear: anyone involved in aerospace or motorsport structures has an exciting future to look forward to. □

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Focus

"The advantage of CFRP over aluminium in terms of stiffness trace (effective stiffness) would be 0.880/0.336 = 2.62. This is the penalty for the isotropy of aluminium grids." Stephen Tsai