Lightweight Composite Materials and Manufacturing

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Point of View Paper
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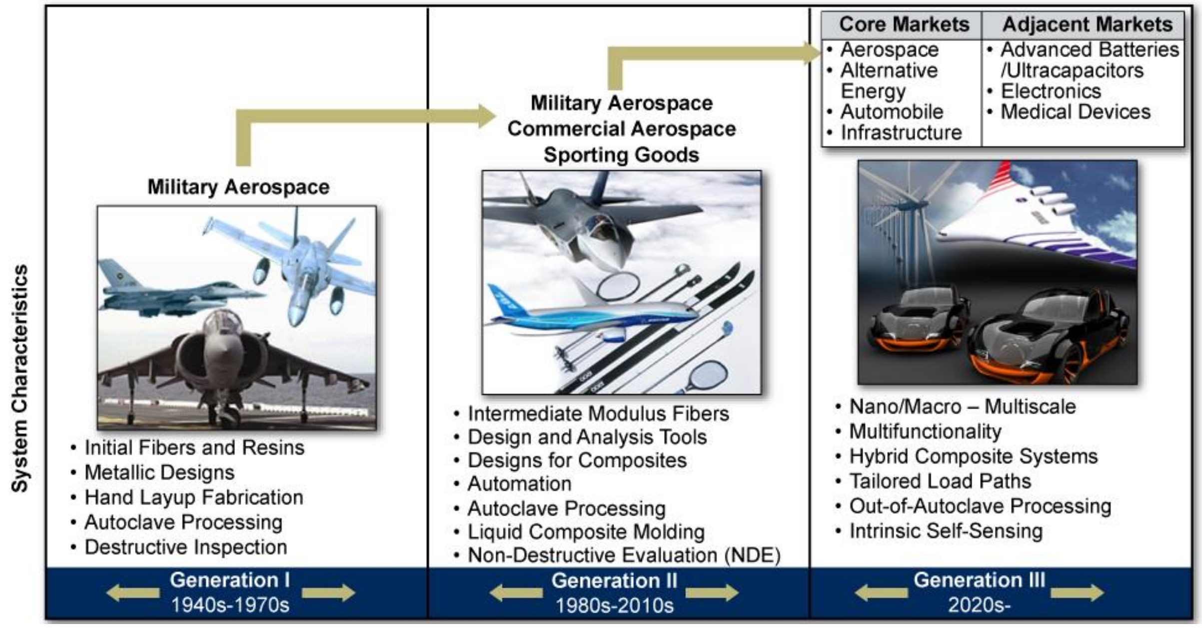
Advanced Composite Industry

Lightweight, high-strength, fiber-reinforced composites represent a fast growing industry that is vital to the economic future and national security of the U.S. In 2005, the composites industry employed nearly 300,000 people and contributed more than $45 billion to the U.S. economy. A $110 billion market is predicted over the next decade.

As shown in the following figure, Generation I composites, made with fiberglass and early carbon fibers, served as metal replacements in secondary, non-load-bearing aircraft parts in the 1940's – 1970's. The Generation I success spurred the development and massive use of modern carbon fibers in load-bearing structures that replaced metals. State-of-the-art, or Generation II, composites brought about a broader use in selected structures.



The 1970's-80's saw major investments being made in constituent materials (reinforcement fibers and matrices), processes, design guidelines and property analysis tools. Advancements in the 1980's and 1990's resulted in innovative uses of composites in commercial aerospace, auto, marine, space and sporting goods. These advancements also expanded applications for the military, due to the materials' unparalleled ability to solve seemingly contradictory requirements, such as reducing weight while increasing mechanical properties. These significant developments catapulted the relatively small composite market into a $45 billion industry.

Over the past 30 years, however, the growth of composites use has been slower than predicted in commercial markets due to the lack of compelling system-level performance/cost benefits. If the engineering mindset continues to focus on metal substitution, compared to aluminum, carbon fiber will never be able to make a strong business case, which would be a huge lost opportunity for America. The system-level performance and life-cycle cost benefits of advanced composites have not been fully realized due to a conservative design approach, as well as a relatively higher unit cost of carbon fiber than for metals.

Major Gaps

Treated as a metal replacement, total performance improvement at the systems level has largely been incremental since the 1960's, despite a tremendous body of knowledge gained in materials science and through impressive engineering developments. If we continue this incremental "metal substitutions" trend and extrapolate into the out-years, composites cannot meet the more stringent requirements for tomorrow's lightweight engineered systems, characterized by unprecedented performance, energy efficiency, safety, environmental compatibility and life cycle affordability. A disruptive technological and business model that drastically increases the "total systems value" of composites is needed.

To this end, the author has hosted a number of large-scale discussion forums, including a National Science Foundation (NSF) Workshop on Multifunctional Composites in March 2011 and a Defense Production Act Committee (DPAC) Workshop on Lightweighting in June 2012. The findings from these workshops are consistent and present a recurring theme – that integrated structural and functional composite structures are the best approach to achieving high-energy efficiency, low emission vehicles of the future.

Although the "substitutions" practice spurred tremendous developments in materials (i.e., fibers and resins), overall carbon fiber composites are still being used today just as they were in the 1960's. Known as "black aluminum," carbon fiber/epoxy composites replace their heavier metal counterparts in structures for weight. This "metal substitutions" practice has three major problems:

1. Developments in composite material science have not propagated to the systems level. Systems must be designed to take full advantage of the value of composites. In most cases, substitutions are done incrementally (e.g., one metal transmission link replaced by one composite link, or consolidation of a few metal parts with one composite). The optimal deployment strategy should be system/function driven, not component substitution.
2. Currently, composites are laminate-based. They have better in-plane (two dimensional or x-axis and y-axis) mechanical properties than metals, but poor out-of-plane (or z-axis) performance. The lack of understanding and control of composite laminates' out-of-plane behavior is a major reason for industrial conservative designs characterized by a relatively large safety factor. *The true value of composites has yet to be realized*.
3. Current and future engineered systems are actually "systems of subsystems," which offer functions such as electromagnetic interference (EMI) shielding, de-icing, lightning strike protection, electro-optics, and heat dissipation. Generations I & II design procedures start by replacing a major metal structure with a lighter composite counterpart. Then, parasitic components are secondarily bonded or embedded to obtain these functions. Industry parasitic components include copper meshes for lightning strike protection of composite aircraft, aluminum foils for EMI shielding, copper cables as heat pipes and strain gages for sensing. In addition to added weight, these parasitic parts are made from materials inherently incompatible with composite constituent materials, leading to issues such as manufacturing difficulties, delaminations, premature failures and high maintenance cost. The engineered system (structures and functions) is not viewed as an integrated whole, but is treated as separate pieces; parasitic parts are after-thought add-ons, which is a major limitation of current composite systems.

Besides the absence of a system-focused mindset, the current "structure first/parasitic function second" paradigm is primarily due to a lack of materials that are intrinsically multifunctional. For example, polyacrylonitrile (PAN) based carbon fibers are mechanically strong but have poor thermal conductivity, whereas pitch-based carbon fibers are known to have metal-like thermal conductivity, yet they are brittle.

What Is Different Now?

The potential of nanomaterials is being demonstrated now at small scales in laboratory settings (TRL 3). Now is the time to harness the tremendous potential of these emerging and future developments for system-level benefits. These benefits will only come from system requirement-guided designs (i.e., functions driven by systems requirements and built into constituent materials without parasitic parts). By analogy, nature provides excellent examples of multifunctional composite systems. One such example is bones. In addition to providing lightweight structural support, bones store chemical energy in marrow, produce blood cells, and serve as attachment points for muscles.

The natural synergy of advanced composites and nanotechnology presents a path forward for developing Gen III composite systems. Nanomaterials (e.g., nanotubes, nanofibers, graphene and nanoclays) possess unprecedented intrinsic mechanical and functional properties. Emerging nanomaterials, combined with an ability to manipulate them at the nano-level, provide an opportunity to design and build composites from the molecular level up, a realization of "materials by design" with a systems focus. Designed-in and integrated intrinsic multifunctionalities will offer unprecedented design freedom and major performance improvements, leaving a profound and lasting mark.

What Are Generation III Lightweight Composite Systems?

The following table compares the characteristics of the current Gen II composites to Gen III composites and how government funding programs such as the National Network for Manufacturing Innovation (NNMI) will impact the transformation from a monolithic design mindset of lightweight, anisotropic, passive materials used to "replace" metals, to a new class of lightweight, integrated engineered systems.

Transformative advances in composites in Year 2015 and beyond

Today (Gen II composites)	2015 and beyond (Gen III composites)
• Part level design and analysis • Material development for reduced structural weight	• Development of system level design and analysis tools • System focus to achieve performance, safety, fuel efficiency and environmental compatibility • Multifunctionality-driven design
• Single attribute – design as metal replacement • Parasitic components – additional functions increase in complexity, weight and cost	• Intrinsic multifunctionalities – materials with tailored functions • Eliminates parasitic components – system simplification leads to affordability and reliability
• Acceptable in-plane strength • Little z-axis electrical/thermal conductivity	• Dramatically enhanced out-of-plane properties • Efficient three-axis electrical/thermal conductivity paths
• Destructive or non-destructive testing	• Intrinsic self-sensing and health monitoring
• High life cycle costs	• Low life-cycle ownership cost and reliability

Lightweight Composite Materials and Manufacturing Innovation Program Goals

To achieve the vision of making intrinsically multifunctional composites - the design choice for high-performance engineered systems - a lightweight composite materials and manufacturing innovation consortium must meet the following goals:

1. Demonstrate that multiple functions can co-exist symbiotically in lightweight, cost effective, engineered systems without the use of parasitic components;
2. Develop technology demonstration test beds that will allow industrial partners – large OEMs and small and medium-size companies – to participate in scaling up and transitioning these technologies to U.S. industry through creative IP & licensing agreements and new start-ups;
3. Create new, innovative education and training programs with technical colleges and leverage on-going activities, e.g., NIST MEP, to develop a skilled workforce for advanced composite materials and manufacturing innovation; and
4. Become the innovation leader in future ultra-lightweight systems through integrated design, prototyping, and commercialization and a robust domestic supplier base.

Working with a large number of industrial, university and government partners spanning the entire composites supply chain, the lightweight composite materials and manufacturing innovation consortium should create crucial engineering and educational infrastructures. Small, innovative firms can work closely with the consortia on projects such as SBIR/STTR and NIST MEP to augment these innovation programs.

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Georgia Tech Manufacturing Institute

Taking a holistic approach to re-energizing U.S. manufacturing and shepherding new technologies across the valley of death, the Georgia Tech Manufacturing Institute (GTMI) catalyzes collaborations of industry/government with many units across the Georgia Tech campus - from engineering to science to business to policy. In addition to working closely with academic faculty and students, GTMI personnel collaborate with the Georgia Tech Research Institute, Georgia Manufacturing Extension Partnership and Georgia Tech's technology transfer functionaries and business incubators on advanced composites and nanomaterials, scalable nanomanufacturing, and supply chain realignment.

For more information on lightweight composite materials, contact the author below. For more information on GTMI, visit http://www.manufacturing.gatech.edu

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