Composite Materials: Enabling APL to Meet Complex Requirements for Critical Systems

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ABSTRACT

With their proven performance, unique properties, and manufacturability, composite materials lend themselves to many applications. The Johns Hopkins University Applied Physics Laboratory (APL) uses composite materials for advanced prototypes and flight-worthy assemblies in support of a variety of systems and missions, from spacecraft components and instruments, to ground- and air-based communication hardware, to uncrewed aerial vehicles of all shapes and sizes. APL designers and engineers typically use thermoset polymer resins reinforced with a variety of fiber types and architectures to create high-performing composite structures. Leveraging its expertise in several composite molding techniques, APL is able to manufacture parts that meet complex requirements and perform as intended to ensure mission success. This article describes APL's composite fabrication capabilities and contributions.

INTRODUCTION

Composite materials—created when materials with different physical, chemical, and mechanical properties are combined to maximize the desired qualities of each material for a specific application—have been used for thousands of years (Figure 1). For example, a mud brick, one of the world's oldest construction materials, combines mud or a mud-like material with a filler such as straw, resulting in a material that is resilient to squeezing, tearing, and bending and is therefore strong enough to be used in walls, buildings, and other structures. Concrete and fiberglass are examples of modern composites. As the state of the art continues to advance with the formulation of new materials, processes, and manufacturing technologies, not only do composite materials remain important in many traditional applications, but they also have the potential to revolutionize capabilities in contemporary and future applications.

For example, composite materials for spacecraft, aircraft, underwater vehicles, infrastructure, and ground-based structures continue to be in demand. Boeing is building an aircraft that is 80% composite by volume and 50% by weight.[1] NASA is flying a helicopter on Mars with composite rotor blades.[2] Composite bridges are replacing aging steel and concrete,[3] and robots are fabricating composite structures for critical applications.[4] Material suppliers continue to formulate new polymer chemistries that will drive new applications and opportunities for advanced manufacturing.

APL is no stranger to composite materials. In the 1980s, APL engineers were tasked to redesign a center

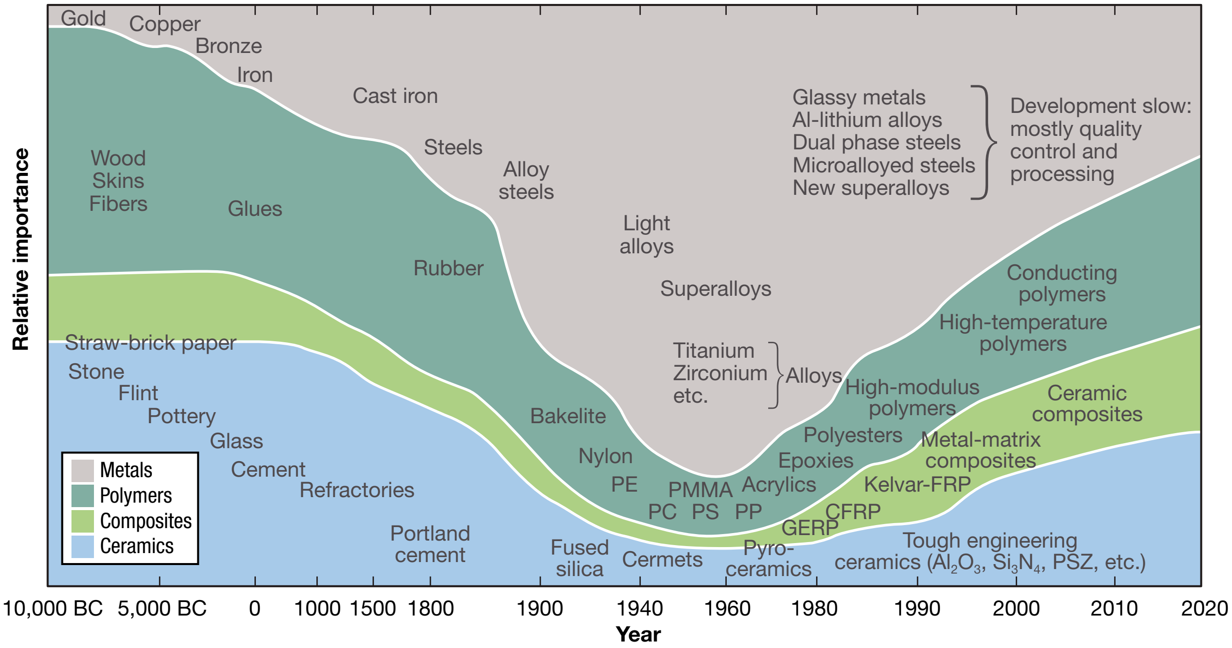

Figure 1. Evolution of engineered materials, including composites. (Modified from Ashby,[5] with permission from Elsevier.)

support structure for the POLAR BEAR satellite using graphite/epoxy composite.[6] In the 1990s and 2000s, APL engineers were involved with composite structures—for example, with the high-temperature solar panels for MESSENGER (MErcury Surface, Space ENvironment, GEochemistry, and Ranging)[7] and the Seeman Composites Resin Infusion Molding Process (SCRIMP), which has been applied to great advantage in the Advanced Natural Gas Vehicle Integrated Storage System Program and for the submarine sensor fairings used on SCAMP.[8] The Lab has been manufacturing composite structures for 35 years. This work started in prefabricated sheet-metal buildings on APL's campus where staff members used a 1 × 1 × 3-ft "Mini-Bonder" autoclave to cure the composite materials. Parts were size limited, ply patterns were manually designed, and molds were fabricated from aluminum using three-axis computer numerical control (CNC) machining. Fast-forward to today: APL experts work in a modern facility that includes a 625-ft^2 cleanroom and is home to a 4 × 8-ft autoclave and a 5 × 5 × 6-ft walk-in oven to cure larger parts. They use flattening software to generate ply patterns, an automated ply cutter to cut them, and additively manufactured molds to support low-cost rapid tooling. And they have a large five-axis CNC router to machine molds and composite parts to size.

In addition to designing, analyzing, and manufacturing composite structures in-house, APL often collaborates with external vendors to supply prototype and fully configured composite hardware for flight when parts are too big to cure using in-house equipment or have other unique requirements. In these cases, during all phases of fabrication, APL subject-matter experts maintain technical oversight of both critical and noncritical composite structures built outside of the Lab. They participate in formal reviews, write material and process specifications, travel to contractor sites to witness fabrication and acceptance operations, and provide input on any nonconformance or fabrication issues.

This article outlines APL's current composite fabrication capabilities, some of the challenges associated with composite structures exposed to extreme environments, and how the Laboratory is using composites in critical systems that explore our solar system, monitor deep space, and fly through the atmosphere to support our nation's defense. It also discusses the future of composites manufacturing at APL.

OVERVIEW OF COMPOSITES AT APL

Materials and Process

The current state of the art for composite fabrication at APL is a manual hand layup of fiber-reinforced thermoset polymer prepreg material. *Prepreg* refers to reinforcement (unidirectional, woven, or braided) that is impregnated with a semi-cured, or "B-stage," resin. Plies of prepreg are stacked on top of one another at specific fiber angles over a mold and then vacuum bagged and cured in an oven or autoclave at an elevated temperature to achieve a full degree of cure and cross-linking. After curing is completed, the parts are trimmed and drilled to their final shape for assembly. Prepreg is the material of choice at APL because it is engineered to a resin content that yields a cured laminate with a specific fiber volume fraction and ply thickness. Fiber volume is important for composite structures because the fiber is what contributes to the overall mechanical performance.

Two other composite fabrication processes used at APL are wet layup and vacuum-assisted resin transfer molding (VaRTM).[9] During wet layup, dry reinforcement is applied over a mold and impregnated with resin using a squeegee or a similar tool, and this progression is repeated for subsequent plies. This age-old process was used to build some of the earliest composite structures. It is still used today, particularly for commercial fiberglass parts and for repair of advanced composites. The drawbacks to the wet layup process are that it is messy and it is hard to achieve a laminate with a low void percentage, consistent resin content, and specific fiber volume fraction. With the VaRTM process, dry reinforcement is applied to a mold as a full stack (or preform) and vacuum bagged. Resin is drawn through the entire preform until it is fully impregnated, and then it is cured at room temperature or in an oven, depending on the resin system.

Popular fiber reinforcements in use at APL include carbon fiber, fiberglass, quartz, and Kevlar. Each of these fibers has distinct properties and is chosen based on the application of the hardware. Much like the reinforcement, the resin is also chosen based on the environment the hardware will be subjected to. The resins used most at APL are epoxies and cyanate esters. Epoxies make up roughly 70% of the resins APL uses to build composite hardware, with cyanate esters making up 20% and a combination of phenolic and vinyl esters making up the last 10%. Cyanate esters are very stable in space and are often used for spaceflight hardware, such as solar array substrates or tubes used for magnetometer booms and struts. Certain cyanate esters also have the ability to be post-cured at higher temperatures than most epoxies to achieve a very high glass transition temperature. Composite laminates, depending on the reinforcement and polymer resin, can be any of the following: strong, stiff, lightweight, damage tolerant, thermally and electrically conductive, insulated, or radio frequency (RF) transparent. Composite materials have a wide array of applications and continue to be realized for new applications.

Additive Molds to Enable Rapid Prototyping of Unique Designs

To successfully build composite hardware, the mold design, fabrication, and use are critical to avoid fabrication and fit-up issues in later assembly steps. Typical molds for composites are made from machined metal ranging from Invar (a nickel–iron alloy) to aluminum or even from composite materials themselves. Although APL teams sometimes use machined aluminum molds, more often they use additively built molds to rapidly create prototypes. The additive molds are built via fused filament fabrication (FFF), a process that combines thermoplastic model and support filament to build a part. APL's additive molds are built using polycarbonate or ULTEM 1010 because these materials have high-temperature capability for 250°F or 350°F cure cycles. While the coefficient of thermal expansion (CTE) is greater for these additive materials than for standard aluminum or other low-CTE materials, the molds can be scaled appropriately to generate the required part shape. Figure 2 shows an example mold that was additively manufactured for composite layup using ULTEM 1010.

In addition to using polycarbonate and ULTEM 1010 filament to fabricate composite molds, APL has used soluble additive support filament material to build molds for layup. The support material used for polycarbonate can be used as a mold for elevated-temperature cures and then dissolved in a bath of mostly hot water and alkaline solution to separate the part from the mold. Soluble molds enable composite parts to be fabricated with geometries that would otherwise prevent the tool from separating from the part. An example is the work that an APL team did for a project called CRACUNS (Corrosion Resistant Aerial Covert Unmanned Nautical System).[10] For CRACUNS, a soluble additive mold

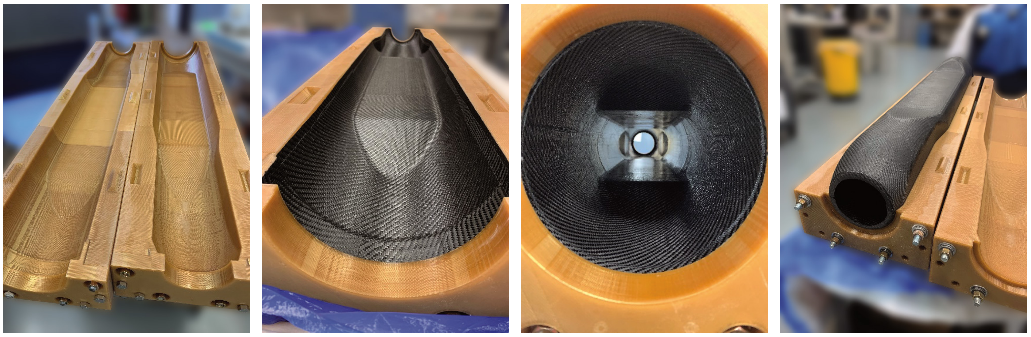

Figure 2. An fused deposition modeling additively manufactured layup mold for composite fabrication using ULTEM 1010. This two-part clamshell mold was used to manufacture a composite fuselage for a drone aircraft prototype. Each mold half had carbon prepreg material applied to it, and when the molds were stacked, the material was joined on the inside to make the continuous barrel.

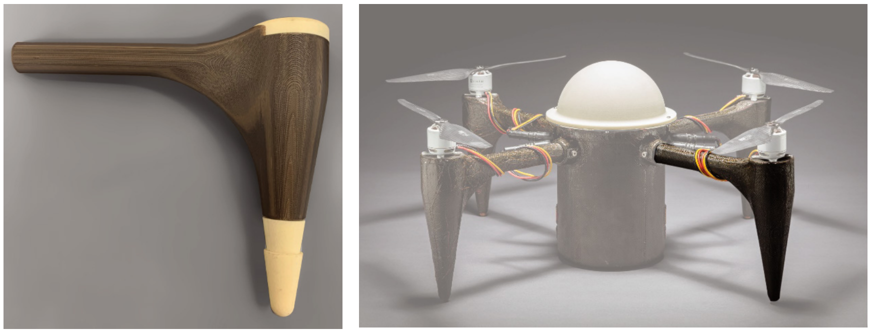

Figure 3. Mold and finished product for the CRACUNS aircraft. Left, Additively manufactured layup mold using soluble support material (brown) and glass-filled nylon inserts (cream color). Right, Assembled CRACUNS aircraft showing the composite leg assemblies.

with additively built glass-filled nylon feet and caps was used to build out the legs of the aircraft (Figure 3). Carbon fabric prepreg was wrapped around the mold and co-cured to the glass-filled nylon parts. After it was cured, the soluble mold was dissolved away, leaving a hollow co-cured composite assembly. Because of the geometry of the leg and co-cured assembly, a soluble tool was required to enable this design.

Composites Manufactured outside of APL

As mentioned earlier, when parts are too big to cure using in-house equipment or have other unique requirements, APL collaborates with external vendors. Two great examples of this kind of collaboration, discussed below, were for the Europa Clipper spacecraft that will explore one of Jupiter's moons. Instead of being constructed at APL, Europa Clipper's 3-m high-gain antenna and extremely large solar arrays are being built by external vendors because of their large size and complexity. In both cases, APL composites experts worked to test potential materials and select the materials that will best meet the application's requirements, and then they oversaw the fabrication work. There are also many examples of APL composites experts assisting with and overseeing fabrication work for major Department of Defense programs as part of the Lab's trusted agent role. This work has been performed for a variety of applications, including tactical rocket motor cases, shipboard radomes, and Navy aircraft.

EXAMPLES

Europa Clipper Composite Structures

The Europa Clipper mission[11] is being developed by NASA's Jet Propulsion Laboratory and APL. The spacecraft (Figure 4, left), scheduled to launch in late 2024, uses composite materials on the two main systems required for communication and power: the solar array panels and the high-gain antenna. The massive five-panel solar array assemblies on each side of the propulsion module, once deployed, will span roughly 100 ft (30 m). Each solar array panel is 8.2 × 13.5 ft (2.5 × 4.1 m) in size and consists of a composite sandwich laminate that provides the substrate for the solar cells. The sandwich laminates consist of thin high-modulus carbon fiber/epoxy face sheets bonded to an aluminum honeycomb core. The high-gain antenna attached to the main spacecraft bus contains a 9-ft (3-m) composite main reflector, backing structure, strut tubes, and sub-reflector (Figure 4, right). The main reflector, the sub-reflector, and the backing structure for the main reflector are sandwich laminates that use thin high-modulus carbon/cyanate ester face sheets bonded to carbon composite honeycomb core. The carbon composite honeycomb core is used for applications that require dimensionally stable structures during changing temperatures. The reflector is a fully carbon composite structure to avoid RF receiving and transmitting issues due to thermal distortion at temperature extremes. If aluminum honeycomb core were used for the reflector, the CTE mismatch between the aluminum core and composite skins at temperature

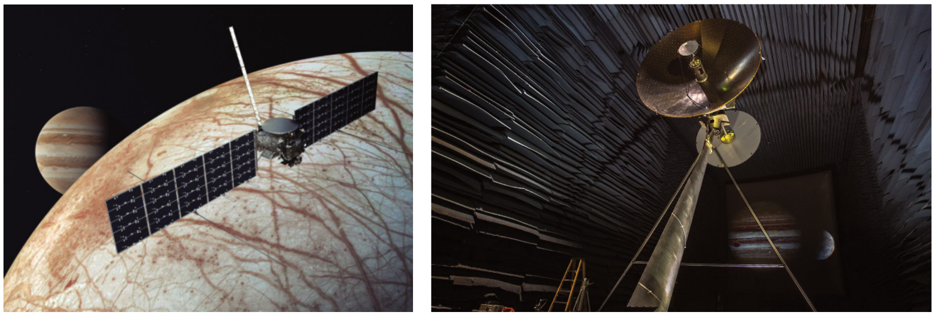

Figure 4. Composite structures on Europa Clipper. Left, Artist's rendering of the Europa Clipper spacecraft orbiting Europa. The high-gain antenna and massive solar arrays are shown, both of which are constructed with composite materials. (Photo credit: NASA/JPL-CalTech, https://europa.nasa.gov/resources/182/2021-europa-clipper-spacecraft-artists-concept/.) Right, The full-scale prototype of the Europa Clipper's high-gain antenna being tested at NASA Langley. The all-composite main reflector, strut tubes, and sub-reflector are visible. (Photo credit: NASA/Langley, https://www.jpl.nasa.gov/news/europa-clipper-high-gain-antenna-undergoes-testing.)

extremes could result in a change in the reflector shape that would adversely affect its function. While the flat solar array substrates can afford to use aluminum core, the high-gain antenna benefits from using composite core because of its shape stability requirements.

A Substrate Design and Investigation for Cryogenic Temperatures

During the initial design phase for the Europa Clipper solar array substrates at APL, prototype substrate coupons failed testing during conditioning intended to simulate the Europa environment and qualify the substrate design. Clipper will experience periods of extremely cold, cryogenic temperatures in addition to periods of high radiation. The initial substrate design that was tested leveraged designs from previous APL-designed spacecraft; however, the effect of the cold temperature and radiation exposure on the composite substrate was unknown since those past substrate designs were never qualified to these extremes.

Initial testing of the substrates revealed large disbonds between the skin and honeycomb core (Figure 5). During thermal cycling between –238°C and –120°C, the change in temperature caused the composite skins to disbond from the aluminum honeycomb core. There was no question that thermal strain from CTE mismatch contributed to the issue, but it was not the only contributor. Two other confirmed causes were the residual stress in the nonsymmetric layup of the composite skins and the dense honeycomb core (8.1 pcf). Other identified possible causes were residual stress at the fiber–resin matrix interface, the surface preparation method, inconsistent application and insufficient volume of film adhesive, fiber sizing issues, and issues with consolidation pressure during bonding of the skins to the core.

The team generated a design of experiment to test a number of material, layup, and process variables. These variables included changes in the prepreg (same fiber, different resin), areal weight of the unidirectional fibers, film adhesive (areal weight, number of plies, and reticulation versus non-reticulated), and face sheet layup configuration. Multiple test panels were built using different configurations, conditioned, and tested in flatwise tension. Then large test panels were built using different layups, and after each environmental exposure, test coupons were removed from the panels and tested. Test coupons are small sections of the large panel that are machined into a specific size depending on the mechanical test. Conditioning cycles prior to testing included a room temperature baseline, cycling between –178°C and +120°C for seven cycles, –238°C to –120°C for seven cycles, irradiation at 63 Mrad, and another –238°C to –120°C thermal cycle for seven cycles. After each conditioning cycle, the large test panels were nondestructively inspected using both ultrasonic and laser shearography to detect any disbonds or delaminations that occurred from conditioning. Half the substrates conditioned at the cold cycle (–238°C to –120°C) completed testing with no signs of damage. Those test coupons were irradiated, thermally cycled between –238°C to –120°C, and tested. The sandwich laminate chosen presented the tightest data set of all the variations tested and exceeded the flatwise tensile strength requirement of 600 psi after each conditioning run. Table 1 outlines the specifications of the chosen versus the original panel configuration.

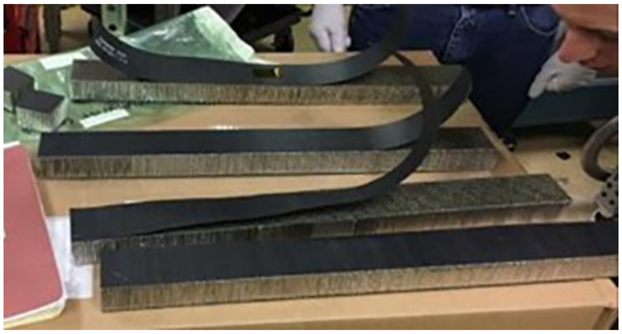

Figure 5. The initial sandwich laminate design for the Europa Clipper solar array substrates. The test coupons exhibited skin-to-core disbonds after thermal cycling down to –238°C.

Because delaminations and disbonds were avoided, the team acknowledged this design as a solution for the Europa Clipper composite solar array substrate. The density of the core, lower cure temperature of the prepreg, laminate layup, adhesive application, and surface preparation all played significant roles, resulting in a

Table 1. Differences between the initially designed solar array substrate for Europa Clipper and the design that passed all testing without failure

	Original Debonded Coupon Configuration	Non-Debonded Coupon Configuration
Core density	8.1 pcf, 1/8-in. cell, 0.002-in. foil	6.1 pcf, 1/8-in. cell, 0.0015-in. foil
Prepreg	M55J/cyanate ester, 0.002-in. cured ply thickness (CPT)	M55J/cyanate ester, 0.0017-in. CPT
Facesheet	Asymmetric, [0/+45/90/–45], 0.015-in, thickness, 350°F cure temperature	Symmetric, $[0/+60/-60]_s$, 0.010-in. thickness, 250°F cure temperature
Film adhesive	FM-300-2U 0.015 psf, 0.030 psf, reticulated, beyond shelf life	FM-300-2U 0.030 psf, nonreticulated, within shelf life
Surface preparation	Light abrasion	Heavy abrasion

composite substrate that would survive the harsh Europa environment and carry out its role as the backbone for the solar cells that power the spacecraft.

A Composite Radome for Deep-Space Radar

Damage tolerance and service temperature are two important characteristics of composites. In the case of a thin, composite ground-based radome for a high-power antenna, it is critical to understand how the material will behave when the system heats up or suffers potential damage—for example, from a hail strike. For a deep-space monitoring initiative, an APL team developed an array of ground-based transmit and receive antennas to support radar installations to monitor, identify, detect, and evaluate objects in orbits far from Earth. A very powerful antenna is required for these tasks, and the radome assembly is one critical part the team had to develop.

Material Identification, Modeling, and Down-selection

The team identified five materials, along with their respective fabrication processes, as potential candidates for building the radome: fiberglass/epoxy composite, quartz/cyanate ester composite, polycarbonate, high-density polyethylene (HDPE), and fluorinated ethylene propylene (FEP). These materials were selected because of their low dielectric constant and loss tangent, allowing for a nearly RF transparent radome. A material with a low dielectric constant has poor electrical conductivity (i.e., an insulator) and less tendency to store an electrical charge, which could disrupt the signal. A material with a low loss tangent is able to provide a clear signal transmission and return. The team then built a computer model based on a hemispherical shell design and input the electrical properties of each material to simulate the radome's performance. Dissipated power was calculated at eight stations along the radome surface (Figure 6, left). Those power values were fed into the thermal model (Figure 6, right) so that the team could understand how the radome would heat up during operation and identify any potential thermal concerns. Thermoset and thermoplastic polymers require thermal considerations because their amorphous or semi-crystalline molecular structure will break down or melt and start to degrade at certain temperatures. A radome must be able to keep its shape, maintain its transparency, and protect the transmit/receive elements inside, so understanding the material's thermal properties and behaviors is paramount. Once the thermal modeling was complete, the team established the peak temperature for each radome simulation using the five materials and calculated the thermal margins between peak temperature and service temperature.

Only three of the five materials and processes considered for manufacturing the radome had positive thermal margins: quartz/cyanate ester composite, polycarbonate, and injection-molded FEP. Of these, the team chose quartz/cyanate ester composite because of its high thermal margin and manufacturability.

Using a machined aluminum mold, three plies of 4581 quartz/cyanate ester prepreg were applied to the mold, bagged, autoclave cured, and oven post-cured. The particular cyanate ester resin used for the radome has the ability to be post-cured at a higher temperature than the initial 350°F cure to develop and increase the laminate's glass transition temperature. After post-cure, the radome could experience temperatures upward of 450°F and remain intact without softening or losing shape, ensuring it would withstand the peak temperatures that could occur during high-power operation.

Hail Strike Testing for a Thin Composite Radome

Three plies of the 4581 quartz/cyanate ester prepreg yielded a radome thickness of roughly 0.033 in., which is considered thin for a composite laminate in this type of application. Therefore, radome damage in the event of severe weather, like a tornado or hailstorm, was a concern. To understand the radome's damage tolerance in a hailstorm, the APL team conducted hail strike testing on a sacrificial radome assembly.

The team developed an approach to deliver simulated hailstones of varying diameters to the radome at different velocities in order to test for hail strike. The solution was to use an air cannon to propel molded ice spheres

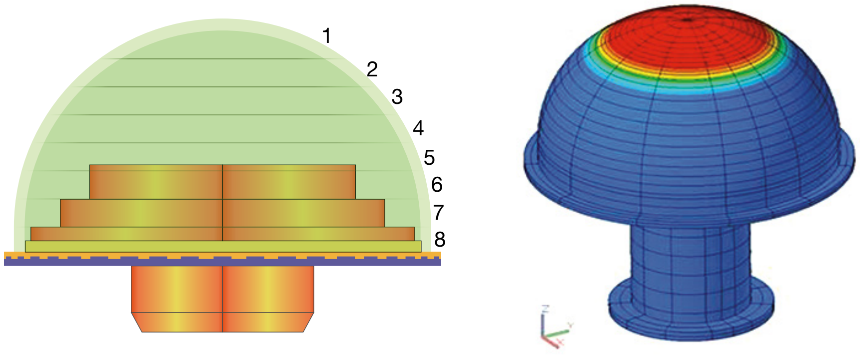

Figure 6. Analysis of composite materials for a deep-space radome. The team designing the radome chose five potential materials for simulation. Left, radome model showing stations for electrical and thermal analysis; dissipated power was calculated at eight stations around the radome for each material. Right, thermal model showing peak temperature location (red). The peak temperature of the radome during high-power operation was calculated to reach upward of 400°F.

Figure 7. Hail strike simulation to test radome resilience to damage. The team tested simulated hail strikes at various speeds using a silicone mold filled with ice to simulate hailstones (left). The ice was loaded into additively manufactured sabots (center), and an air cannon delivered the simulated hailstones to the radome (right).

supported by additively manufactured sabots (Figure 7) to simulate hail strikes at different speeds.

Using a 1-in.-diameter ice ball as the worst-case scenario for a hail strike event, the team simulated a hail strike and tested its impact on the thin composite radome. In addition to testing the worst case, very large hailstones, the team decided to test a few smaller hailstones to understand any potential failures that may result from strikes from hailstones of more common sizes. Terminal velocities were calculated for hailstones that were 0.375 in., 0.500 in., 0.625 in., 0.750 in., and 1 in. to define how fast a hailstone of each size could strike the radome. To determine whether there might be premature failures at slower speeds before the hailstones reached their terminal velocities, the team fired hailstones of each size at a few slower velocities first, then eventually fired them at their terminal velocities.

After each firing, the team visually inspected the radome and performed a tap test to detect any damage or delamination. A tap test is a form of ultrasonic nondestructive testing in which a small hammer is used to tap the surface of a laminate to detect defects based on pitch changes. Tapped areas that present a pitch that is different from the pitch of what is known to be a "good" section suggest a potential issue in the form of a delamination in the composite laminate. The radome did not suffer any internal or surface damage in any of the firing cases and survived a 1-in. hailstone delivered at >200% of its terminal velocity. The calculated terminal velocity of a 1-in. hailstone is 28.84 m/s, and tests achieved a delivery velocity of 63.30 m/s without damaging the radome. The team did not test to failure. After the testing concluded, the impact areas were sectioned from the radome and examined under a microscope to determine whether there were any undetected delaminations in each impact zone. No delaminations were detected, even in zones that had experienced multiple impacts.

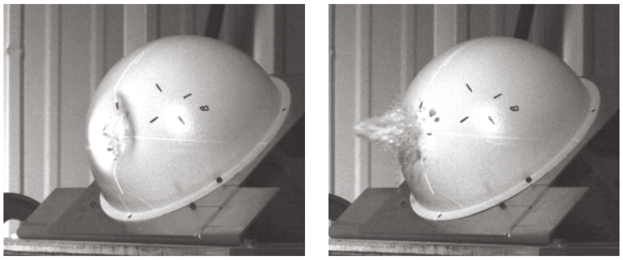

Figure 8. High-speed camera images capturing impact during testing. Left, the radome at impact using a sphere of ice with a 1-in. diameter delivered at 63.30 m/s. Right, the radome after impact, fully recovered.

The team used a high-speed camera to capture each hail strike so they could look at the radome's response at impact. Interestingly, the radome exhibited fully elastic behavior. At impact, the radome deformed around the impact area (Figure 8, left), and when the simulated hailstone shattered and fell away after impact, the radome returned to its original shape (Figure 8, right).

This testing confirmed the selection of the quartz/cyanate ester composite for the radome. Although quartz fibers are more expensive than fiberglass, they are stronger, stiffer, and less dense and offer about twice the elongation at break (stretch before failure), making them a good choice when durability is a priority.[1] The quartz fibers not only provide better electrical properties than fiberglass, but they also provide an advantage that was unknown before the teams' testing: they are resilient to damage in the event of a hailstorm. The quartz composite material was chosen for fabrication because of its manufacturability and electrical and thermal properties. Although the team suspected that a radome this thin would survive a common hailstorm, they were pleased to confirm through testing that it could endure even the worst-case impact without failure.

THE FUTURE OF COMPOSITES MANUFACTURING

APL has been actively investigating the additive manufacturing of true continuous fiber composite structures as a potential game-changer for next-generation composites manufacturing. Two identified technologies would allow the realization of the goal of truly building composite structures additively. The first is a multiaxis

CNC machine that leverages an FFF-type additive process where the polymer filament incorporates continuous fiber reinforcement that can be incorporated into a part in any direction. The reinforced filament could be applied not only in the *x* and *y* planes but also in the *z* direction to achieve strength and stiffness in three dimensions.

The second technology is a multiaxis CNC machine that uses the automated fiber placement (AFP) process for composite part fabrication. AFP typically involves a machine that applies slit tape thermoset composite material to a machined mold for layup. Once the layup is complete, the part is vacuum bagged, autoclave cured, and final machined. To get closer to a true additive-like process, the same machine would have one head that applies thermoplastic filament as well as continuous fiber thermoplastic slit tape that could then be swapped out with a head for machining. The available thermoplastic filament types would include both soluble and nonsoluble filaments to support rapid mold fabrication and high-performance thermoplastic composite structures using polyetheretherketone, polyetherketoneketone, or polyetherimide. All these functions would be programmed and run in a single build process, resulting in a finished continuous fiber thermoplastic composite structure in true additive fashion.

These technologies would enable engineers and fabricators to build one-piece composite structures with integrated internal channels or duct sections or could incorporate core geometries optimized for strength, stiffness, and weight. In addition, they would enable rapid manufacturing of complex composite structures. Additive manufacturing of continuous fiber-reinforced composites is a game-changing technology that has the potential to revolutionize the way composites are designed and built. Unique designs achieved only by additive manufacturing, combined with the performance of fiber-reinforced polymer material, could enable solutions to problems that cannot be solved by using legacy manufacturing approaches.

CONCLUSION

APL continues to use composite materials for applications with components that have performance requirements that other materials cannot achieve, often in extreme environments. APL teams use composite materials to build hardware for complex systems that make an impact for our nation, in aerospace, underwater, ground, and space applications. Innovative composite materials and manufacturing technologies will lead the way for future novel solutions to new challenges, enabling APL to meet the needs of its sponsors and the nation.

REFERENCES

[1] V. Giurgiutiu, *Structural Health Monitoring of Aerospace Composites*. Amsterdam: Elsevier, 2015, 12–13, https://doi.org/10.1016/B978-0-12-409605-9.00013-1.

[2] H. Mason, “Composites launch to Mars,” *CompositesWorld*, Aug. 12, 2020, https://www.compositesworld.com/articles/composites-launch-to-mars-.

[3] S. Francis, “The growing role of composites in infrastructure,” *CompositesWorld*, Mar. 2, 2020, https://www.compositesworld.com/articles/building-bridges-with-composites.

[4] A. Brasington, C. Sacco, J. Halbritter, R. Wehbe, and R. Harik, “Automated fiber placement: A review of history, current technologies, and future paths forward,” *Composites Part C: Open Access*, vol. 6, art. 100182, 2021, https://doi.org/10.1016/j.jcomc.2021.100182.

[5] M. Ashby, *Materials Selection in Mechanical Design*. 4th ed. London: Butterworth-Heinemann/Elsevier, 2010.

[6] R. D. Jamison, O. H. Griffin Jr., J. A. Ecker, and W. E. Skullney, “Use of graphite/epoxy composites in spacecraft structures: A case study,” *Johns Hopkins APL Tech. Dig.*, vol. 7, no. 3, pp. 290–294, 1986, https://secwww.jhuapl.edu/techdigest/Content/techdigest/pdf/V07-N03/07-03-Jamison.pdf.

[7] P. D. Wienhold and D. F. Persons, “The development of high-temperature composite solar array substrate panels for the MESSENGER spacecraft,” *SAMPE J.*, vol. 39, no. 6, 2003, pp. 6–17.

[8] M. Rooney, J. C. Roberts, G. M. Murray, and B. M. Romenesko, “Advanced materials: Challenges and opportunities,” *Johns Hopkins APL Tech. Dig.*, vol. 21, no. 4, pp. 516–527, 2000, https://secwww.jhuapl.edu/techdigest/Content/techdigest/pdf/V21-N04/21-04-Rooney.pdf.

[9] “Materials & processes: Fabrication methods,” *CompositesWorld*, Mar. 23, 2016, https://www.compositesworld.com/articles/fabrication-methods.

[10] G. Brown, “New UAV can launch from underwater for aerial missions,” press release, APL, Laurel, MD, Mar. 17, 2006, https://www.jhuapl.edu/PressRelease/160317.

[11] “Europa Clipper.” NASA, https://europa.nasa.gov (accessed Jan. 19, 2022).

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