2023
STATE OF THE TECHNOLOGY INDUSTRY REPORT

sampe
North America

Contents

SAMPE is pleased to present its **State of the Technology Industry Report**, authored by the below Technical Committees (“TC”) launched in 2022 under the leadership of the Technical Excellence Committee. Each TC facilitates knowledge sharing and networking by connecting experts, students, and interested professionals across a wide swath of disciplines.

- **TC 1** **Composites Factory of the Future-Industry 4.0**
- **TC 2** **Bonding and Joining**
- **TC 3** **High-Temperature Materials**
- **TC 4** **Recycling of Composites**
- **TC 5** **Rapid Manufacturing of Composites**
- **TC 6** **Thermoplastics**
- **TC 7** **Space Applications**

The report dives into the specific technologies and processes that are being developed and implemented by the industry. It provides an in-depth look at the current state of the technology, the challenges and opportunities associated with it, and potential applications.

Jeff Sloan | Brand VP | CompositesWorld
Editor | SAMPE State of the Technology Industry Report

Raj Manchanda | Chief Technology Officer | SAMPE N.A.

Chris Locke | Director of Marketing and Membership Services | SAMPE N.A.

sampe
North America

TC 1

Composites Factory of the Future – Industry 4.0

Robert Yancey
Business Development Director
Hexcel
Chair

Muthu Elen
Research Associate
Pacific Northwest National Laboratory
Vice Chair

Matt Thorn
Senior Manager
Magestic Technologies
Secretary

sampe
North America

TC 1

COMPOSITES FACTORY OF THE FUTURE – INDUSTRY 4.0

Executive Summary

For the last several years, the term Industry 4.0 has been used to describe the 4th evolution in manufacturing technology. The prior three evolutions are generally defined as follows:

- **Industry 1.0** – use of machines instead of hand labor to manufacture
- **Industry 2.0** – the electrification of manufacturing
- **Industry 3.0** – digital manufacturing

For **Industry 4.0**, this includes the automation of manufacturing, use of sensors to monitor processes, adaptive manufacturing, use of machine learning and artificial intelligence and cloud computing. The goal of Industry 4.0 is to manufacture with minimal human supervision and adaptability to reduce scrap and provide high-quality parts every time. For composites, this includes increasing automation in manufacturing, the software used to design and drive the automation equipment and the materials that lend themselves to more automated processing.

The following sections provide a summary of each of these areas. More complete information can be found in the Appendices.

Equipment and Processing

Many composites today are still made with hand layup methods with autoclaves or ovens to cure the matrix material. For long-term programs, many types of manufacturing equipment are used to provide some level of automation and control. The main equipment used are as follows:

- **Hand Layup tools:** laser projection, programmable cutting, robotic placement, spray guns, mixing and application tools
- **Automated fiber placement/tape laying (AFP/ATL):** Robotic equipment to lay down fiber tows or slit tapes to create a structure preform that is later consolidated and cured
- **Filament winding:** Equipment to create wound tanks and pressure vessels. Winding is done wet (tow is impregnated with resin during manufacturing) or with slit tape (prepreg is slit to specific width and then slit tape is wound)
- **Resin transfer molding:** Equipment to inject resin into a fiber preform and then cure with heat and pressure.
- **Thermoplastic composites equipment:** Requires different classes of equipment since thermoplastics require higher heat to process. Includes thermoplastic composite welding equipment; see report from TC7, Thermoplastics, for more on processing options
- **Curing equipment:** Autoclaves, ovens and compression molding equipment
- **Nondestructive evaluation equipment:** Ultrasonic, X-ray, tomography, shearography, and thermography

Highly automated processing equipment is very expensive and beyond the reach of small- and medium-sized manufacturers, so they typically rely on hand layup tools that can provide some automation and control over the manufacturing process. Highly automated equipment also requires high levels of expertise and significant programming time to perform a certain function. Because of this, automation is most beneficial for production over a long-term program that will produce thousands of parts over several years. For aerospace parts, frequent manual inspections are required during the manufacturing process, so automation is intermingled with manual labor, which impacts the overall efficiency of the process.

For the future, the following needs are identified:

- Lower cost and more easily programmable equipment
- More use of automated in-process inspection methods
- Technologies that can adjust a process inline to automatically correct defects during manufacturing

Software

Automated equipment makes use of sophisticated software to run the equipment, monitor the process, and capture data throughout the manufacturing cycle. Software is also used to do manufacturing planning so one can create a manufacturing process that produces high yield with high-quality. In addition, software tools are available to provide direction during design to create a more seamless and effective flow to manufacturing. The goal of this effort is to eliminate the “silos” between design and manufacturing so that the impacts on cost, quality and efficiency can be addressed during the design phase. The common software tools used for manufacturing are as follows:

- **Design for manufacturing:** CAD/CAM, finite element modeling, cure modeling
- **Manufacturing equipment programming:** Path planning, Cutting, NC programming
- **Data analytics:** Adaptive control, process improvement, quality control

These tools can take significant time and expertise to master. They are also often on different software platforms that are not always well integrated. For simulation modeling, there also exists the challenge that what you analyze is not an exact match to what is manufactured, so including more manufacturing information during design can lead to designs that closely match what can be and will be manufactured. For example, AFP/ATL machines will produce laps and gaps and stair-stepped boundaries on the edges. For design, these structures are generally designed and analyzed as continuous plies with smooth boundaries on the edges. Some path planning and machine simulation tools do provide feedback to the design tools that can allow the part as manufactured to be analyzed more accurately–adding a simulation burden, but providing more accurate designs.

Most modern manufacturing system have many sensors to monitor the manufacturing process and provide diagnostics when things go wrong. More processes need to be better integrated with machine learning and artificial intelligence tools so corrective action can be done before a problem occurs or to find ways to manufacture with greater efficiency.

For the future, the following needs are identified:

- CAD/CAM and finite flement tools that are more specific to composites produced with automated equipment
- Easier to use path planning, cutting and NC programming tools that are better integrated with CAD tools
- Better use of sensor data to create higher manufacturing efficiency with reduced scrap

Materials

Composite material properties are highly dependent on the manufacturing process. With the goal of improving manufacturing efficiency, enhancing quality and increasing manufacturing throughput, new materials and new processing methods are being developed to yield the types of improvements that are needed. In many cases, legacy materials are being evaluated for use with newer manufacturing processes. For example, traditional hand layup prepregs are being modified to work better with AFP/ATL equipment to provide greater tack during lay-down. Also, traditional autoclave cure materials are being evaluated for out-of-autoclave processing such as compression molding. There is also the tradeoff between material quality and manufacturing efficiency, so in some cases users are open to considering processing methods that may produce lower-quality parts but at much greater efficiency. The current material landscape includes:

- **Epoxy resin systems:** The vast majority of aerospace grade composites today, which include autoclave and out-of-autoclave systems
- **Vinyl ester resins:** Lower cost than aerospace-grade epoxies and often used in industrial applications such as transportation, marine, and infrastructure
- **Polyester resins:** Lower cost than vinyl ester resins but limited heat and UV resistance; most widely used resin system for non-aerospace composites, with significant use in the marine industry
- **Thermoplastics:** Highest cost system but with potentially lower manufacturing cost vs. thermoset resins; very good impact and chemical resistance

For manufacturing, many improvements have been introduced over the years for more automated mixing, more automated application of resin systems to dry preforms, and more automated consolidation and curing systems. Curing can often be highly dependent on part geometry, with thicker sections curing more slowly than thinner sections. Advanced sensors and modeling can help in identifying the best cure schedule for a particular application. With new manufacturing methods and equipment, legacy materials are adapted for these new processes. New materials are also being developed specifically for newer manufacturing methods. For example, thermoplastic composites are being further developed for more automated processing and for more demanding applications such as primary structure aerospace applications. There is always the balance of laying up the structure and consolidation and curing so trying to find the right balance for maximum efficiency and performance is an area where simulation tools combined with automated manufacturing can make a big impact.

For the future, the following needs are identified:

- Natural fiber and resin systems derived from sustainable materials
- Materials that are more amenable to recycling and reuse such as thermoplastic and vitrimer matrix systems
- Polymer fiber systems that can combine with carbon or glass fibers to provide better performance and processing
- Ultra-thin composite prepregs that can improve fracture performance but generally come at a much higher cost

Conclusions

Improving composite material performance, manufacturing efficiency, cost and applicability to high-rate manufacturing involves significant coordination between material suppliers, manufacturing and material processing equipment vendors, software tool vendors, structural designers and analysts and end users. Designing the Composite Factory of the Future will be different for different industries and applications. For example, aerospace requirements are likely the most stringent, but they are also a large percentage of the overall market. Any factory automation advances for the aerospace industry will likely have applications in other market segments. New industries such as advanced air mobility (AAM) are partnering with the automotive industry to design their factories to take advantage of the significant expertise of the automotive companies in laying out highly efficient factories. Manufacturing composite structures is much different than fabricating metal structures, but these collaborations can only bring improvements across the industry. As overall manufacturing efficiency improves and new manufacturing methods are developed, the overall composites industry will grow and find even more applications for composites.

SUB-COMMITTEE

PHIL VIVIANO
CHAIR
CALEB SCHOENHOLZ
WAYNE HUBERTY
TOMMY HYATT
CAMERON HOGUE

APPENDIX 1

Equipment and Processing

Composites Manufacturing Landscape

Hand Layup | Caleb Schoenholz

Current Market

The composites hand layup market is relatively mature, with a range of equipment available from numerous manufacturers around the world for both open- and closed-mold processes. Some of the largest aspects of the layup equipment market include accessories and consumables such as rollers, brushes, vacuum bagging, pumps, and release agents. Although the market is well-established, it is still evolving as the demand for complex-shaped large composite structures continues to increase in several industries (e.g., aerospace, automotive, construction, etc.). In 2021, the global composites market was estimated at US $89.32 billion, with the layup process segment accounting for the largest revenue share of 33.9 %. (Composites Market Size, Share & Trends Analysis Report [ID: 978-1-68038-917-3]. Grand View Research, San Francisco: 2021)

North America and Europe are currently the largest markets for composites hand layup equipment, due to their well-established aerospace and automotive industries. However, Asia-Pacific is also expected to be a rapidly growing market due to the increased use of composites in the construction, transportation and renewable energy sectors.

Current Equipment

Current hand layup equipment includes a range of tools and materials used in the manual hand layup process. The equipment is typically relatively affordable and accessible, making it a popular choice for small-scale composites fabrication projects, as well as for prototyping and repair work. Apart from fibers and resin, the most fundamental pieces of equipment for hand layup are hand tools, including scissors and/or knives to cut the reinforcing fabrics into a desired shape before transferring them to the mold. Brushes, rollers, mixing cups and stirring sticks are also essential for preparing and applying the resin and removing air bubbles. To facilitate the hand layup process, there are also a range of more advanced tools and equipment available. For example, spray guns can be used to apply the resin more quickly and evenly, reducing the time and effort required for layup. Pumps and mixers can also be used to prepare and dispense the resin more efficiently, while vacuum bagging materials and pumps are used as the gold-standard for removing air bubbles and ensuring a high end-part quality in the composite part.

Gaps in Current Equipment

While hand layup equipment is widely used and accessible, there some gaps and challenges that can impact the quality and efficiency of the processing method. For example, one of the most prevalent challenges in manual hand layup is achieving consistent resin distribution throughout the composite part with standard equipment. Achieving consistent resin distribution requires careful application of the resin, which can be time-consuming and difficult to achieve manually. Additionally, some hand layup equipment, such as brushes and rollers, may not be the most effective tools for applying the resin evenly or for removing air bubbles, which can also impact the quality of the final composite. Another challenge in hand layup is achieving high fiber volume fraction throughout the composite part, as this requires precise layering of the reinforcing fibers and careful control of the resin content.

In addition to the previously mentioned challenges, hand layup can be a relatively slow and labor-intensive process using current standard equipment, which can limit the efficiency and cost of composites fabrication. This is especially true for larger composite parts or higher production volumes. While some advanced equipment, such as spray guns and pumps can assist to speed up the process, these tools may not be as accessible or affordable for smaller-scale projects.

A final prevalent challenge with hand layup equipment is the required high skill and experience of the operator. Hand layup requires a high degree of manual skill and attention to detail that can be difficult to achieve for less experienced operators. This can result in variations in the final product quality, even when using gold-standard equipment and materials.

Funding Sources

Composites hand layup equipment is often used in smaller-scale composite fabrication projects, such as prototype development or small-batch production runs. As a result, funding for this type of equipment may come from a variety of sources, including research and development (R&D) grants, small business loans or venture capital investments. The use and development of composites hand layup equipment may also be funded directly from the end user or customer.

Key Developments

Although composites hand layup may not have seen as many significant technological advancements as other composites fabrication methods, there have been some key developments in recent years that have improved the functionality of the equipment, some of which are summarized below:

- **Increased use of automation, robotics, and digital technologies:** In parallel with many composites fabrication processes, the use of robotics has been explored in hand layup to reduce the risk of human error. Automated cutting and material handling systems have also been developed to improve the speed and accuracy of the process. The increased use of digital technologies, such as computer-aided design (CAD) and simulation software to optimize the hand layup process is also being explored. By simulating the layup process digitally, manufacturers can better understand the effects of different materials and process parameters on the final product and make adjustments to optimize the process before physically laying up the composite materials.
- **New materials and resins:** Highly processable materials are continuously being developed that are specifically designed to be effectively utilized with current standard hand-layup equipment. Ideally, such materials may be easier to handle and process, and can result in higher-quality and more consistent finished products.
- **Equipment safety:** Efforts have been made to improve worker safety and reduce the risk of exposure to harmful chemicals and materials during

the hand layup process. This includes the development of safer handling methods for materials and resins, as well as the use of personal protective equipment (PPE) and ventilation systems to reduce worker exposure to airborne toxins.

Major Influencers/Companies

Several major influencers and companies in the composites hand layup equipment market are listed below:

- Magnum Venus Products (MVP)
- Graco
- 3M
- Composites One
- Airtech
- Ashland
- Gurit

Future Market

The hand layup equipment is expected to continue to grow, although at a slower pace compared to some other composites manufacturing processes with more automated and advanced methods. There will likely always be a place for the versatility and low cost of hand layup in certain applications. A few points of emphasis for the future market are summarized below:

- **Increased use of automation:** While hand layup will likely remain an important part of composites manufacturing for some applications, there is also potential for more automation in the process. Companies may develop new technologies that combine the precision of automated layup with the versatility and low cost of hand layup.
- **Greater focus on worker safety:** One challenge of hand layup is the potential for workers to be exposed to hazardous materials and repetitive motion injuries. In the future, manufacturers may develop equipment that reduces these risks, such as tools with ergonomic designs or specialized ventilation systems.
- Development of new materials and applications: As new composite materials are developed for specific applications, the equipment used in the hand layup process will need to evolve as well. Manufacturers may need to develop new tools and techniques for working with different types of materials, such as thermoplastics or bio-based composites.
- Integration of digital technologies: As with other composites manufacturing processes, there is potential for hand layup equipment to be integrated with digital technologies such as sensors, data analytics and automation. This could enable manufacturers to improve the accuracy and consistency of their processes, reduce waste and improve overall product quality.

Future Equipment

In the future, composites hand layup equipment may see several developments aimed at improving productivity, worker safety and overall product quality. Here are some potential developments that could shape the future of the market:

- **Advanced materials and composites:** One of the biggest drivers of future developments in hand layup equipment will be the continued evolution of composite materials themselves. As new materials are developed with specific properties and applications, equipment manufacturers will need to develop new tools and techniques to work with them. This could include more advanced layup tools, specialized gloves or safety equipment, and improved ventilation and dust collection systems.
- **Integration of digital technologies:** Like other composites manufacturing processes, hand layup equipment may benefit from integration with digital technologies such as sensors, data analytics and automation. For example, manufacturers may develop tools with built-in sensors that can monitor the consistency and quality of the layup process in real-time. This data could be used to improve the accuracy and repeatability of the process, reduce waste and improve product quality.

- **Advanced ergonomic designs**: One of the challenges of hand layup is the potential for repetitive motion injuries and other physical strain on workers. In the future, equipment manufacturers may develop tools with advanced ergonomic designs that reduce these risks. This could include tools with adjustable handles and grips, as well as specialized cutting tools and other accessories that reduce the need for manual cutting and trimming.
- **Greater automation and robotics:** While hand layup will likely remain an important part of composites manufacturing for certain applications, there is also potential for more automation and robotics in the process. In the future, manufacturers may develop robotic systems that can work in concert with human workers, or even fully autonomous systems that can perform the entire layup process.

How can SAMPE support?

SAMPE can support the development and use of composites hand layup equipment in several ways:

- **Education and training:** SAMPE can support the use of hand layup equipment by providing education and training opportunities for production workers and equipment manufacturers. This may include workshops, seminars, and webinars on best practices, step-by-step training, and maintenance for hand layup equipment.
- **Standards and guidelines:** SAMPE can also support the development of industry standards and guidelines for composites hand layup equipment by providing input on best practices for processing and maintaining hand layup equipment.
- **Research and development:** SAMPE can support the development of hand layup equipment promoting research into new materials and equipment for hand layup.
- **Networking and collaboration:** SAMPE can support the use and development of hand layup equipment by assisting interaction between equipment manufacturers, suppliers and end-users. This could involve organizing trade shows and industry events where manufacturers can showcase their equipment and users can share best practices and learn from each other’s experiences.

Automated Fiber Placement/Tape Laying | Phil Viviano

Current Market

Automated fiber placement/tape laying (AFP/ATL) is the process by which machinery is used to lay up composites, replacing the traditional hand layup process. This process generally uses a higher performance tape material over large areas, therefore it's typically used in commercial aerospace and spacecraft applications.

The most common place to see AFP and ATL equipment is in an aircraft factory. Notable examples of this equipment are the machines used to lay up the Boeing 777X wing, the Boeing 787 wings and fuselages and the Boeing A350 wings and fuselages. These machines are also used on more advanced defense and space programs as well as for research purposes.

These machines typically replace anything that would be done by hand layup. This includes setting ply boundaries and delivering ply consolidations. They typically sit in a dedicated cell within a cleanroom. They receive prepared tools and materials and output a layup of an uncured part that is typically bagged and cured in an autoclave.

Current Equipment

AFP/ATL machines are commercially available from a variety of companies using a wide variety of concepts. These machines consist of an end-effector that moves along the surface of a tool. This end effector heats, applies, compacts and cuts strips of unidirectional composites. The machine generally accepts spools of material slit to a certain width, usually between 1/8” (3 mm) to 12” (25 mm) wide. The end-effector is typically mounted to one of a variety of motion platforms.

Some of the key differentiators are how/where the material is held and fed from when it's in-use and what kind of motion platform the machine is mounted on.

Material is typically held and fed from a location on the head of the end effector, or off head in a contained area called a creel-house. Each concept has its advantages and disadvantages.

Keeping material available on-head limits the length that the material must travel before it is applied to the tool. This simplifies material handling and improves quality; however, it limits the amount of material that can be held at once, it enlarges the head and limits the size of cavity that the head can deposit into, and it requires the machine to go off-line to replenish material.

Keeping material in a creel-house reduces downtime by storing more material and allowing the machine to continue running as material is replenished. It also means that the head itself is smaller and therefore can lay up in tighter, more complex cavities. However, a creel-house keeps the material far away from the application head, therefore the material must be routed over a distance. This causes issues in maintaining tension in the material and can reduce quality.

AFP/ATL machines are mounted on a variety of motion platforms, including gantries, posts and robots. Gantries and posts are generally used in production with dedicated tool cells where the parts are largely repeated. These systems are generally larger, faster and more robust. Robots are generally used in research cells, where flexibility is valued over speed. These systems are often equipped with head interchangeability to allow for process development.

Gaps in Current Equipment

Modern production AFP/ATL equipment is focused on the fabrication of thermoset composites for large parts. Gaps in the current equipment involve expansion of their applications to more materials, more types of parts and more process integration.

Thermosets are a type of composite matrix that undergoes a chemical reaction when they're processed, known as a cure. This cure means that the material is ‘set’ as a solid and can't be remelted or reshaped. Recent developments in composites have led to an interest in thermoplastic matrices, which can be remelted and reshaped. These materials are typically solid at room temperatures and process at higher temperatures than most thermosets. This means that the machinery used to process them or lay them up need to be capable of operating at higher temperatures with solid material.

Thermoplastic AFP equipment is well into development at many major companies. These machines need to be capable of repeatedly fabricating high-quality thermoplastic parts. Current developments are working towards laminate quality and the ability to consolidate the material in-process (in-situ consolidation) to avoid the use of a high-temperature oven or autoclave. In-situ consolidation of thermoplastics via AFP is a significant gap in AFP technologies.

Currently, commercial AFP is used on very specific parts. These parts tend to be large flat panels, such as fuselage skins or wing skins. Some particularly large spars, like on the A350 or 777X are also AFP'd. AFP is generally not practical for smaller parts, complex shaped parts or concave parts. AFP's that are small, flexible or inexpensive enough to buy themselves onto a wider range of parts is also a gap in the technology.

When a part is AFP'd, it is typically inspected manually. This is a time-consuming and expensive process that is subject to human error. Recent developments in AFP have attempted to incorporate in-process inspection of laminate quality, checking for twisted tows, fuzz balls, laps, gaps, etc.). This is proven relatively successful but has not been widely adopted by industry. Application and adoption of in-situ inspection is a smaller gap in the technology.

Some other gaps of AFP and ATL are:
- Processes to reduce material scrap and/or shorten minimum course lengths;
- The ability to perform other functions such as
  - › Pick and place of plies and core;
  - › Application of film adhesive;
  - › Application of a large variety of lightning strike protection material;
- Improved performance in layup of dry fibers;
- Improved performance in layup of out-of-autoclave materials with dry centers;
- The ability to steer over tighter radii during layup;
- The ability to apply fabric over large areas instead of UD tape;

Funding Sources

AFP/ATL systems are large, expensive machines that are treated as value sources for large composite parts. Because of this, funding for research often comes from large organizations. Some of these sources are:
- Commercial and defense aircraft OEMs;
- Commercial and defense aircraft Tier 1 suppliers;
- Large-scale spacecraft companies;
- Large governments and organizations such as the DOD, NASA and the EU;
- Materials suppliers looking to develop their materials for machines.

Key Developments

AFP and ATL have been around for several years and is used primarily today for large, long-term programs. There continues to be development of this technology such as:

- The inclusion of on-board sensing equipment to monitor layup conditions;
- The addition of advanced heating equipment such as lasers and bulbs to precisely heat composites as they're being laid down;
- Improvements in the accuracy and speed of robots and gantries used to lay down composites;

- Improvements in the speed with which tows are cut, to shorten the time off tool;
- The ability to use larger tows to lay down more material at once;
- Advancements in thermoplastic in-situ consolidated AFP to bring it closer to commercial viability;
- Modular heads that allow for multi-functionality and process development;
- Custom-shaped heads to allow for deposition on more shapes.

Major Influencers/Companies

As stated earlier, AFP and ATL are dominated mainly by large companies and research organizations. Some of these organizations are:

- **Users:**
  Boeing
  Stelia
  Lockheed Martin
  Airbus
  Collins
  Northrop Grumman
  Spirit AeroSystems
  Albany
  GKN Fokker

Future Market

The future market for automated fiber placement and automated tape laying includes smaller aircraft, spacecraft and non-aerospace applications. This includes but is not limited to:

- EVTOL aircraft
- GA and Part 23 aircraft
- Reusable spacecraft bodies
- Automotive and large-scale transportation
- Bicycle and recreational equipment

The future of AFP and ATL will involve an expansion of materials. This will include:

- High-modulus fibers
- Dry fibers
- Thermoplastics
- Lightning strike protection
- Adhesives

Future Equipment

The future equipment for AFP and ATL will expand the capabilities of the technology. This will include the following features:

- Advanced heating equipment
- In-situ quality inspection equipment
- Improved accuracy in robotics
- Smaller heads for smaller parts
- Larger heads for larger parts

How Can SAMPE Support?

SAMPE can support by bringing together ATL and AFP communities to expand applications. This could be most effective by:

- Projects that apply this technology to cars, bikes and small aircraft
- Advocating for the development of publicly available allowables and specs for materials that can be processed via AFP and ATL

Filament Winding | Caleb Schoenholz

Current Market

Filament winding is a popular method for producing hollow, circular, or prismatic composite structures such as pipes and tanks. The process involves winding continuous fibers, typically made from carbon or glass, around a mandrel to create a structure with high specific strength properties. The market for filament winding equipment has seen significant growth in recent years due to the increasing demand for lightweight and durable composite structures across various industries.

Aerospace, defense, and automotive industries are most significantly driving the growth of the filament winding equipment market. Composite materials offer improved strength-to-weight ratios compared to traditional metallic materials, making them an attractive choice for improving fuel efficiency and meeting increasingly restrictive emission standards. As a result, there has been an increased investment in the research and development of advanced filament winding equipment capable of producing large-scale composite structures. Another industry significantly contributing to the growth of the filament winding equipment market is the renewable energy sector. Wind turbines, for example, require large-scale composite blades that can withstand harsh environmental conditions. Filament winding equipment is an essential component in producing these blades, and as wind energy continues to grow, so will the demand for filament winding equipment.

One key trend in the current market for filament winding equipment is the adoption of automation technologies. Automated filament winding equipment is becoming more prevalent as it enables faster production rates, improves consistency and accuracy and reduces manual labor costs. In addition, robotics and machine learning advancements have enabled filament winding equipment to be integrated into complex, multi-stage manufacturing processes.

Current Equipment

Current filament winding equipment is designed to wind continuous fibers around a mandrel in a precise and controlled manner.A summary of the filament winding process is as follows:

First, the mandrel, a cylindrical tool around which the fibers are wound, is solvent-cleaned and treated with a release agent. Mandrels are custom designed according to the specifications of the desired final product and can be made from various materials, including metal, plastic or composite materials. Once the mandrel is prepared, the fibers, typically stored on spools or bobbins, are pulled through a resin bath to impregnate them with a resin. The fibers are then wound around the mandrel in a precise and controlled manner using the filament winding machine, which can control the speed and tension of the fibers. The pattern at which fibers are wound can be tailored to the specific requirements of the final product, such as strength, stiffness and fatigue resistance. After the fibers are wound around the mandrel, the structure is typically cured in an oven or autoclave. The length of the curing process depends on the size and complexity of the final product. Once the curing process is complete, the composite part is removed from the mandrel, leaving behind a hollow or solid structure with a precise and uniform winding pattern. The final product can then be finished and inspected for quality before being used in its desired application.

Another common method for filament winding is the use of towpreg where the fiber tows are impregnated with resin prior to winding. Towpreg can be stored much like prepreg and eliminates the need for resin impregnation in-situ. Towpreg also provides more control on the resin content for the filament wound vessel.

Gaps in Current Equipment

Although composites filament winding equipment has significantly evolved in recent years, several gaps and challenges remain. Some of the most prevalent gaps and challenges in composites filament winding equipment are summarized below:

Automation: One of the most significant shortcomings in current filament winding equipment is a lack of automation. Many aspects of filament winding still require manual labor, including mandrel preparation, fiber preparation and placement and post-process trimming. This manual labor can be time-consuming, costly, and can contribute to process variability.

Size limits: Current composites filament winding equipment has size limits that can impact its applicability to larger structures. The size and weight of the mandrel, length of the filament winding machine, and the post-winding curing process (e.g., autoclave) can all restrict the applicability of filament winding equipment.

Process simulation and optimization: While process simulation software is commercially available for composites filament winding equipment, it is not yet widely used for large-scale industrial applications. As a result, filament winding equipment and process optimization are restricted. This not only affects the quality of filament-wound parts, but also reduces the cost-effectiveness of the production equipment.

Training and expertise: Using composites filament winding equipment requires specialized knowledge and training. As filament winding equipment becomes more industrially prevalent, continuing education and training are needed to keep up with new technologies, materials and processes.

Funding Sources

Some of the most significant funding sources for the development of filament winding equipment are as follows:

- Government agencies: Several agencies provide funding for filament winding equipment research and development. The U.S. Department of Defense (DoD), National Science Foundation (NSF) and the Department of Energy (DOE) are among the largest funders of filament winding research.
- Industry association: The European Composites Industry Association (EuCIA) provides funding for composites filament winding equipment research and development, as well as for education and training programs.
- Research institutions: Universities and other research institutions provide funding for composites filament winding equipment research through grants, fellowships, and other programs. These institutions often work in partnership with industry and government agencies to conduct research and develop new technologies in the composites industry.

Key Developments

One key development in the current market for filament winding equipment is the integration of advanced sensors and monitoring systems. Such systems allow for real-time data collection and analysis, enabling manufacturers to optimize production processes and ensure consistent quality of filament-wound composite parts. Additionally, these monitoring systems can help manufacturers to identify potential issues or defects at early stages and thus improve overall efficiency and reduce costs.

Another significant development in filament winding equipment is the implementation of advanced materials. For example, ceramic matrix composites (CMCs) and metal matrix composites (MMCs) are being used in the development of mandrels and other components, as these materials offer improved durability and longevity compared to traditional materials (e.g., steel or aluminum). In addition, biodegradable/recyclable materials are also being explored as environmentally friendly candidates for mandrels and other equipment components to reduce energy consumption and meet sustainability concerns.

Filament winding equipment manufacturers are also developing more advanced and flexible systems capable of automatically producing structures with intricate shapes and sizes. This has resulted in the development of specialized equipment, such as multi-axis filament winding machines [insert photo], which are most prevalent in the aerospace industry. Advances in robotics and artificial intelligence are making it possible to integrate these filament winding systems into complex, multi-stage manufacturing processes.

Major Influencers/Companies

The composites filament winding equipment industry has several influencers and companies playing key roles in its growth and development. Some of the major influencers and companies are listed below:

Filament winding manufacturing equipment:

- Autonational
- Magnum Venus Products
- McClean Anderson
- MTorres
- Mikrosam
- Roth Composite Machinery
- Izumi International Inc.
- Engineering Technology Corp.
- American Autoclave Co.

Automation, control, and robotic solutions:

- Siemens
- Kuka
- Coriolis Composites

Future Market

The future market for composites filament winding equipment is likely to be driven by the persistent demand for high-specific-strength materials, advancements in technology/automation, a growing focus on sustainability, and emerging applications.

As composites are increasingly utilized throughout the aerospace, automotive and clean energy sectors, increased use of filament winding equipment will be necessary to meet production demands and environmental restrictions. As composites technologies and materials continue to improve, the quality and efficiency of filament winding processes will continue to increase, driving demand for more advanced equipment. As the world becomes more focused on sustainability, there is increasing demand for materials and processes with lower environmental impact. Composites are often seen as a more sustainable alternative to traditional materials. As a result, the demand for composites filament winding equipment is expected to increase in the coming years.

As the composites industry increasingly relies on automation and digitization to improve efficiency and reduce manual labor costs, there will be a growing demand for filament winding equipment that is highly automated and can be integrated into digital manufacturing processes. As the demand for composites continues to grow, there is increasing interest in emerging markets (e.g., Asia, South America, and Africa) and applications. These markets represent a significant opportunity for companies in the composites filament winding equipment industry, as they look to expand their reach and tap into new sources of demand.

There are many applications for filament wound structures. Today, filament winding is commonly used for rocket motors and compressed gas storage. With the emerging hydrogen economy, filament wound pressure vessels will be the likely storage method for the hydrogen. The potential widespread use of hydrogen for fuel storage will drive a lot of composites usage moving forward.

Future Equipment

As technology advances and industries evolve, some potential features of future filament winding equipment are as follows:

More automation: As the composites industry moves towards increased automation and digitalization, more advanced software and control systems should be integrated into filament winding equipment to make processing more efficient and less reliant on human intervention.

Multi-axis filament winding: Currently, most filament winding equipment is limited to uni-axis cylindrical shapes. However, there is increasing interest in producing complex-shaped composite structures, which will require equipment capable of multi-axis filament winding.

High-accuracy fiber placement: As the demand for higher precision and more complex geometries increases, there will be a need for more accurate fiber placement in filament winding. Advanced sensors and software will be crucial for precise fiber placement and for producing parts with the required tolerances.

How Can SAMPE Support?

SAMPE can support use and development of composites filament winding equipment through:

Education and training: SAMPE can provide education and training opportunities for professionals working filament winding equipment. This could include courses, workshops, and certification programs that help to build essential skills and knowledge.

Standards and guidelines: SAMPE can support the development of industry standards and guidelines for composites filament winding equipment by providing input on best practices for processing and maintaining equipment.

Research and development: SAMPE can support the development of filament winding equipment by promoting research into new materials and equipment for the process. This could involve partnering with universities and research institutions to promote research into new materials and techniques, as well as working with industry partners to develop and test new equipment designs.

Networking and collaboration: SAMPE can assist interaction between equipment manufacturers, suppliers, and end-users. This could involve organizing trade shows and industry events where manufacturers can showcase their equipment and users can share best practices and learn from each other’s experiences.

Resin transfer molding (RI, VARTM, etc.) | Wayne Huberty

Current Market

Resin transfer molding (RTM) is a method of producing composite structures by laying dry fabrics in a mold, applying compaction pressure to the preform, and injecting resin into the dry fabric. The various techniques use various forms of compaction pressure and unique consumables. Vacuum-assisted RTM (VARTM) uses a single hard mold matched with a single soft mold, which can be a single-use vacuum bag or reusable silicone bag. Lite-RTM uses matched molds and vacuum pressure to clamp the mold. RTM uses a press to clamp the matched mold for higher compaction pressures. Resin infusion has replaced other forms of composite manufacturing because it can offer low manufacturing costs, part-to-part repeatability, increased rates, parts integration and improved health and safety (HS&E).

Seemann's Composites has been using their patented SCRIMP resin infused process to produce marine structures, and the broader marine market has been using VARTM processes to produce fiberglass boat hulls since the 1970s.[1] The most economical process for producing boat hulls is using a chopper gun to layup short glass fibers; however, health and safety concerns around volatile organic compounds has pushed the market towards infusion[2,3] (the largest infused boat hull was 42.7 meters[4]).

An example of equipment for marine applications is the Magnum Venus Products Innovator models. The marine space uses catalyzed resin systems, such as vinyl esters and acrylates, requiring the correct pumping systems for the low catalyst loadings (< 2%). These resin systems have a low viscosity, allowing for room-temperature infusion rather than aerospace grade resins that require elevated temperature to reduce the viscosity of the resin to the appropriate range. For rapid manufacturing, these marine injection systems can inject up to 30 lb/min. Marine injection systems can either use a pumping system or rely on gravity. Additionally, heating may or may not be required, depending on the resin system used, although larger parts will likely require an injection system. Other injection system providers include Isojet, Applicator Group and Matrasur Composites.

Very similar to the marine market, wind turbine blades are made using a VARTM process. Although the marine space makes large, integrated structures, it pales in comparison to the largest wind blades produced at 107 meters.[5] Wind blades use vinyl ester and epoxy infusion resin matrices and glass or carbon fiber. Injection systems similar to the marine space are appropriate for wind blade production, depending upon size — larger injection systems, such as those from Hübers, can be used. Wind turbine manufacturers include TPI Composites, LM/GE, Vestas Blades, and Nordex SE.

The aerospace market has seen much slower adoption of resin infusion than in other markets. Arguably, the most significant resin-infused aerospace structure is that fabricated by Spirit AeroSystems for the Airbus A220 wing.[6] The A220 wing is produced with Spirit's patented resin transfer infusion (RTI) process, a variation of the VARTM process, and consolidated in an autoclave. It uses Solvay's Cycom 890 resin, a single-part resin system that is injected above 176°F, requiring higher temperature capable injection systems, such as those from Isojet and Radius Engineering. Other aerospace resin systems, such as those from Hexcel, are two-part systems that require separation of the resin and hardener in individual tanks. Injection systems designed for the marine space do not typically reach the temperatures required for aerospace resins. Boeing uses its patented CAPRI infusion process, another VARTM variation, to produce many trailing edge parts for the 787.[7]

While VARTM is used for very large and price-sensitive applications, RTM is used for high part count production and "smaller" parts, finding application in specific aero parts and automotive applications. GE Aviation produces the GEnx engine fan cases and carriable bleed ducts,[8] and the GE9x fan case is produced via RTM. [9] The composite layup is produced using hand layup, but the RTM is completed in a Radius Engineering press. Automotive applications include a large-scale RTM press for an integrated monocoque chassis,[10] which has expanded into the McLaren Composites Centre to focus on RTM chassis for future electric vehicles. High-pressure RTM has been used by Carbon Revolution to fabricate automotive wheels.[11]

Current Equipment

A process flow diagram is found below for high-level processes required for resin infusion.

Cutting → **Preforming** → **Injection** → **Cure**

CUTTING

Knife cutter

- Gerber Technology
- Gunnar
- Eastman Machine
- Century Design
- Assyst-Buller Inc.

Laser cutting

- Elen
- Ultrasonic
- GFM Ultrasonic

PREFORMING

2-D

- Airborne
- Composite Alliance
- Electroimpact
- Coriolis
- Radius Engineering
- Techni-Modul Engineering

3D

- Cevotek SAMBA Uses UD patches to make a 3D preform[12]

3D Weaving

- A&P Technologies
- Albany Engineered Composites

Stitching

- KSL stitching head

Thermoforming

- Aeroform Ltd
- Fill
- ElectroTherm Industry
- Techni-Modul Engineering

INJECTION

Disposable container

Pressure pot

Injection system

VARTM/RTM

- Radius Engineering/Coexpair
- IsoJet
- Magnum Venus Products
- Composite Alliance
- JHM Technologies
- Viscotek
- Ciject

VACUUM SOURCE

- Becker
- Dekker

OVEN

- ASC
- EPCON
- Wisconsin

PRESS

Pneumatic

- Radius Engineering

Hydraulic

- Wickert
- Pinette Emidecau
- Beckwood
- Ingersoll

PROCESS SENSORS

Wet out sensors

Fiber optic[14]

- Luna Inc.

Heat flux[15]

- TFX SA

Dielectric sensors[16]

Pressure sensors

- Kistler

Optical sensors

- Kistler

Electromagnetic

Ultrasonic

Microwire

Gaps in Current Equipment

Despite the maturity of resin infusion equipment, there still exists gaps in the current equipment. First, automation of the preform is a method to increase the speed and repeatability during preforming. Hand layup, although it has been proven for current production rates in aerospace, would never meet automotive needs. However, many methods of auto-preforming make flat preforms, which will require hand layup or another preforming step to produce a near-net shape before being put into a mold. Also, translating flat structures into 3-D structures may induce wrinkles and/or kinks in the reinforcement. 3-D preforming using automated fiber placement (AFP) will be a more easily adopted preforming process for aerospace as the aerospace market is comfortable with automated tape layering (ATL). However, AFP and ATL capital-intensive and can be limited in their application to specific parts. 3D forming beyond AFP is in its infancy, and only works for with small, unidirectional tapes. An alternative is a 3D braided preform, produced by companies such as A&P Technology. The braiding gives more support to the overall preform but the extra step to produce the braided preform increases costs.

The various injection systems also have limitations, based on the method used. Gravity fed and/or only vacuum injection systems (i.e., when using a pressure pot) tend to struggle to inject a specific amount of resin. Similar to a wet layup, a "fill and bleed" process is often used where an excess of resin is injected into the part and then attempted to be removed through the vacuum outlet port. This is a way to ensure complete wet out of the preform but can cause higher variation in the fiber volume fraction, both between sample-to-sample, and within a single sample. Also, mixing can be an issue as an atmospheric injection system will require the resin to be mixed offline, which creates potential for mistakes. Last, any part made via atmospheric injection that requires elevated temperature will need to be complete in an oven – this can be a health and safety concern as it requires personnel to enter a hot, enclosed space. Automated resin injection systems are much more versatile for resin processing conditions than atmospheric injection systems, but are much more costly, more complicated to use, and lack the versatility in hardener loadings of a pressure pot.

Another limitation for current equipment is the need to highly control vacuum sources, at least for VARTM processes. Although a vacuum leak in an autoclaved prepreg can also be an issue, the loss of vacuum during processing of a VARTM part will cause a scrapped part. Tight tolerances and extreme repeatability are the only ways to ensure a high-quality VARTM part. Vacuum is also integral for RTM processes to prevent voids and to increase the speed of infusion.

Funding Sources

Sources of key funding opportunities for resin infusion are from federal funding agencies, such as NASA, the FAA, or the European Union.

Key Developments

The resin infusion market has seen key developments to progress the technology. The automotive industry requires much faster processing than other markets, such as marine or aerospace. High-pressure RTM (HP-RTM) is a method to dramatically decrease the takt time by injecting resin under significant pressure; this high pressure can cause issues such as fiber distortion or movement at the injection point. Compression RTM (C-RTM), also known as gap infusion, allows race tracking of resin to attain HP-RTM speeds without the fiber distortion issue.

Other key developments include the highly automated RTM process developed by Spirit AeroSystems for production of Airbus A320 spoilers, reusable shape memory tooling, resin cartridge systems for rapid resin changes, automation of vacuum bagging placement, replacing tacky tape with reusable seals additive,[17] manufactured tools, and the largest resin infused aerospace structure, the Airbus A220 wing.

Major Influencers

Most of the major influencers in aerospace resin infusion are found in Europe: Spirit AeroSystems, FACC, and GKN Aerospace, to name a few. The major influencers for the resin infusion market in the U.S. are GE Aviation, Albany Engineered Composites, NASA and Seemann's Composites

Future Market

The future for resin infusion is strong. More and more recreational marine manufacturers are using resin infusion, the aerospace market desires a significant increase in production rate that resin infusion may provide, the automotive market's drive to electrification would benefit from high-rate composite structures, and emerging markets such as advanced air mobility need economic composite parts. It is expected growth of the markets already using resin infusion will be the main driver for increased usage, as opposed to adoption of resin infusion in place of prepregged composite structures.

How Can SAMPE Support?

SAMPE can support by connecting material providers, equipment producers, and manufacturers to develop efficient and robust processes for resin infusion. With the increased interest in infusion and the growing applications, SAMPE can play an important role in moving this technology forward.

---

1. Strong and light: the evolution of the epoxy infusion revolution. https://epoxycraft.com/news/strong-and-light-the-evolution-of-the-infusion-revolution/.
2. Hoge, J. & Leach, C. Epoxy resin infused boat hulls. *Reinforced Plastics* 60, 221–223 (2016).
3. Rubino, F., Nisticò, A., Tucci, F. & Carlone, P. Marine Application of Fiber Reinforced Composites: A Review. *Journal of Marine Science and Engineering* 2020, Vol. 8, Page 26 8, 26 (2020).
4. Horizon Single-Shot Vacuum Infusion Record-Breaker. *News Industry* (2019).
5. Reliable rotor blade types to power your wind turbines | LM Wind Power. https://www.lmwindpower.com/en/products/blade-types.
6. Patented Processes (R&D) | Spirit AeroSystems. https://www.spiritaero.com/programs/research-technology/spirit-innovation/.
7. Resin-infused MS-21 wings and wingbox | CompositesWorld. https://www.compositesworld.com/articles/resin-infused-ms-21-wings-and-wingbox.
8. GE Aviation, Batesville, MS, US | CompositesWorld. https://www.compositesworld.com/articles/ge-aviation-batesville-ms-us.
9. Longer, wider, higher - Aerospace Manufacturing. https://www.aero-mag.com/ge-aviation-ge9x-boeing-777x/.
10. F1-inspired MonoCell: Racing safety for the road | CompositesWorld. https://www.compositesworld.com/articles/f1-inspired-monocell-racing-safety-for-the-road(3).
11. Carbon Revolution | High Performance Carbon Fiber Wheels. https://www.carbonrev.com/.
12. Automation for next-generation aerostructures - Cevotec GmbH. https://www.cevotec.com/en/automation-for-next-gen-aerostructures/?_gl=1*8gudd*_up*MQ..*_ga*MTI0MjU0MjA5MC4xNjc0NTA4NTY0*_ga_V7H8BMTPRL*MTY3NDUwODU2My4xLjAuMTY3NDUwODU2My4wLjAuMA..
13. Sensors for monitoring resin infusion flow front and cure | CompositesWorld. https://www.compositesworld.com/articles/sensors-for-monitoring-resin-infusion-flow-front-and-cure.
14. Marrazzo, V. R. et al. Liquid Resin Infusion Process Validation through Fiber Optic Sensor Technology. Sensors 2022, Vol. 22, Page 508 22, 508 (2022).
15. Monitoring Resin Infusion in Composites Manufacture Using Heat Flux Sensors. https://www.azom.com/article.aspx?ArticleID=5693.
16. Yenilmez, B. & Murat Sozer, E. A grid of dielectric sensors to monitor mold filling and resin cure in resin transfer molding. *Compos Part A Appl Sci Manuf* 40, 476–489 (2009).
17. Digital Demo: Secure Vacuum Bag Seal Eliminates Single-Use Sealant Tapes in Closed Mold Process | CompositesWorld. https://www.compositesworld.com/articles/digital-demo-secure-vacuum-bag-seal-eliminates-single-use-sealant-tapes-in-closed-mold-process.

SQRTM | Steve Eyberg

Current Market

SQRTM (Same Qualified Resin Transfer Molding) is a method of producing high-quality carbon fiber-reinforced plastic (CFRP) structures in closed-mold tooling using toughened prepregs. The term “Same Qualified” is used because it allows customer-qualified prepreg materials to be fabricated in an out-of-autoclave (OOA) process following the same qualified process specification that is approved for autoclave curing.

SQRTM is very similar to resin transfer molding (RTM), with the main exception being that the tooling is filled with prepreg instead of a dry fiber preform. The tooling is clamped in a work cell, which consists of a clamping press, resin injection system and a control system for regulating heat, pressure, cooling and time. A typical work cell is shown in Fig. 1

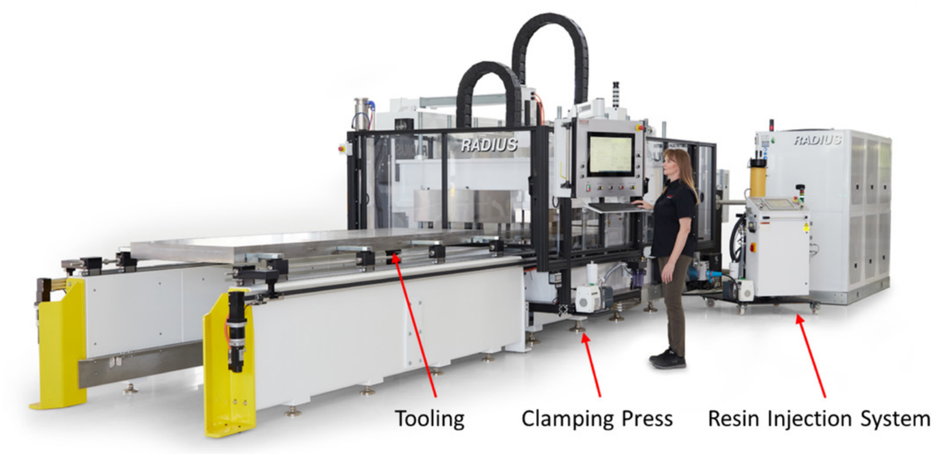


Fig. 1. SQRTM / RTM work cell

The resin injection system injects a small amount of pressurized resin to the interior via resin “runners” around the perimeter and edges of an evacuated tool, sealed with an O-ring like in RTM. The injected resin is the same base resin as in the prepreg, sometimes without tougheners to increase flow for large parts. A cross-section of a SQRTM mold or “tool”, with injection and vacuum ports, is shown in Fig. 2.

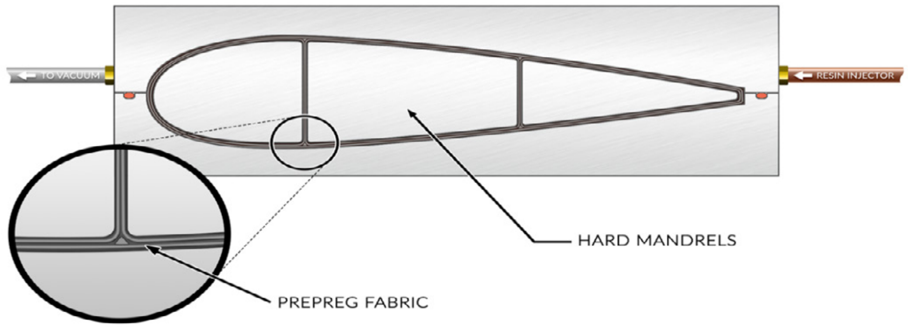


Fig. 2. SQRTM Tool

The tool part-forming cavity is accurately designed and precisely machined so the prepreg laminate will be at the correct fiber volume (Vf) at the cure temperature. (Thermal expansion of the tooling to the cure temperature has been accounted for in the design.) The only free space inside the tool is along the part edges where the injected resin runners and shallow “gates” leading to the part surface along the mold split line will provide hydrostatic resin pressure. This pressure will suppress void growth in the prepreg due to air pockets or evolved volatiles during the heat-up to cure temperature, when gelation of the resin in the laminate occurs. One half of a tool with runners and gates is shown in Fig. 3.

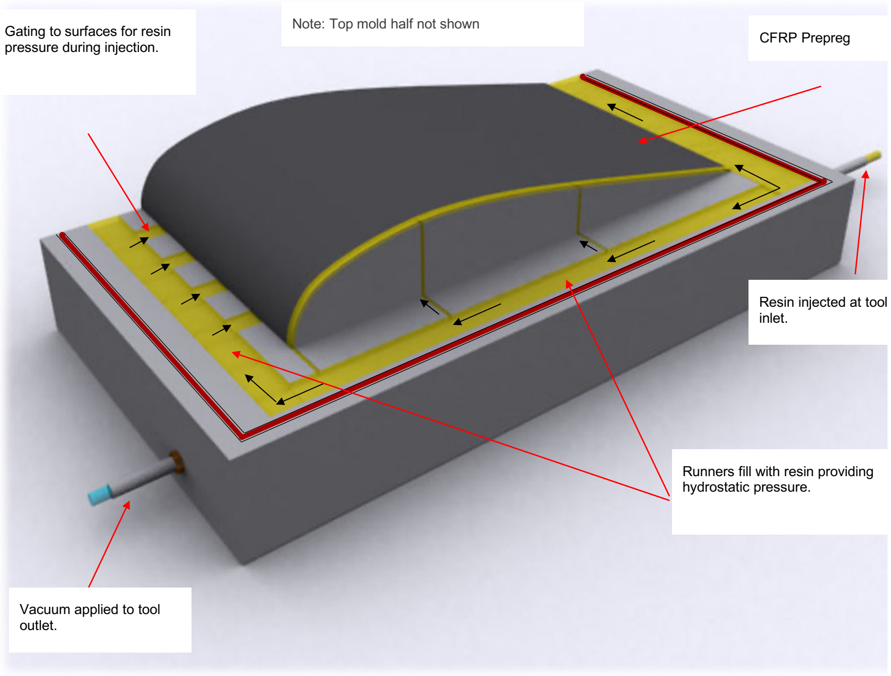


Fig. 3. SQRTM Tool Half showing runners and gates for resin distribution.

As the tool and laminate heat up the prepreg viscosity drops. At this time, if the prepreg resin is not controlled somehow, it will expand and flow out of laminate and into the edges of the tool, due to the volumetric thermal expansion of the prepreg resin being higher than the carbon fiber laminate and the tooling material, typically hard-anodized aluminum or steel. Should that occur, voids will form in the laminate.

A key difference from RTM, which also uses injected resin to control hydrostatic pressure for void suppression, is that none of the injected resin infiltrates the layup. Instead, the injected resin acts as an "edge dam" to counteract the prepreg resin expansion by providing hydrostatic pressure to the edges of the prepreg laminate. Likewise, the laminate resin blocks the injected resin from entering the laminate. A photomicrograph of this phenomenon is shown in Fig. 4, graphically illustrating the balance of volumes and forces that allow SQRTM to provide high-quality laminates while sealing off the closed mold interior.

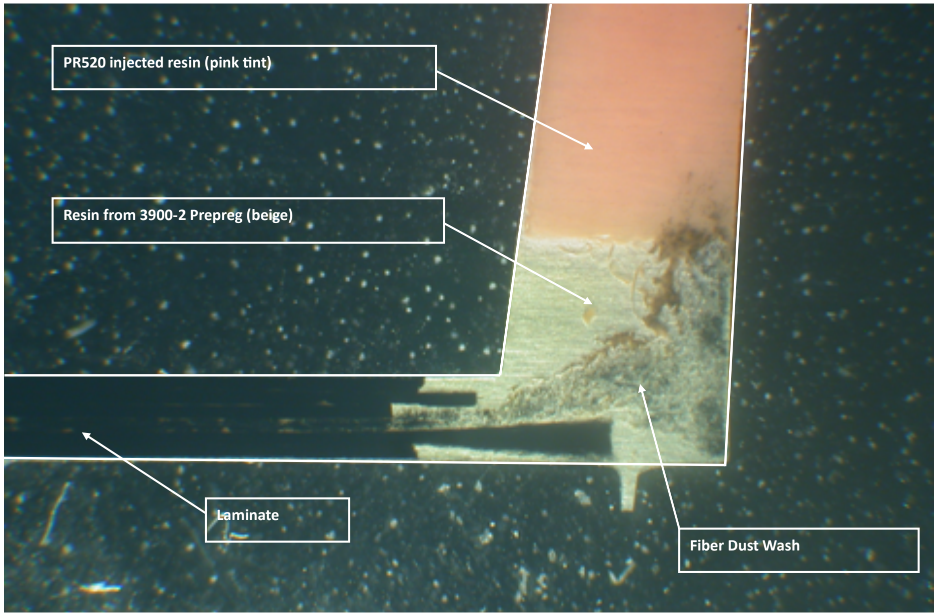


Fig. 4. Concerns of un-toughened resin entering part were answered by injecting pink PR520 resin into a flat panel tool with Toray 3900-2. Micro-sections clearly show no injected resin enters prepreg laminate.

Prepreg is commonly used for aerospace applications with many established databases used by structural design engineers. Because SQRTM uses toughened prepregs commonly found on today's aircraft, it can produce composite structures with higher material allowables than most RTM laminates, particularly in toughness and strength-to-weight ratio.

The market for SQRTM came into being initially because of the difficulty that exists when introducing a new material system to a given customer – specifically when trying to convert an autoclave part design into an OOA process such as RTM. Often, the legacy materials and processes continue to be used simply because it would be prohibitively expensive to characterize and qualify a new material system. When the same (already qualified) prepreg material system can be processed in an OOA closed mold method using the time, temperature, and pressure parameters specified for the autoclave process, the level of effort associated with qualifying the materials and process is significantly more streamlined than introducing a wholly new material system. Hence the name: Same Qualified Resin Transfer Molding.

Advantages of using SQRTM mirror the advantages of RTM.
They are:

- Design advantages such as integrating parts to reduce subsequent assembly and fasteners, reducing costs and weight.
- Faster cycle time due to better thermal conductivity of the tooling in a work cell clamping press, while staying within the autoclave process specification.
- High-tolerance surfaces on all sides of the product from the finely machined metal tooling.
- Close control of laminate thickness fiber volume (Vf) due to precise tooling tolerances, which may allow lighter weight structures to be built, while remaining within qualified material specifications.
- Ability to provide exact features on the product which can be used for "determinant assembly" of the finished product, reducing assembly costs.

Applications

The following list provides a sample of some notable commercial applications of SQRTM.

SQRTM parts certified and flying:

- *Global Hawk* RQ-4B: Multi-spar wingtip extension
- *Global Hawk* MQ-4C: Multi-spar wingtip extension
- Boeing 787: Leading edge slats
- E175-E2: Inboard flaps
- E190-E2: Inboard and outboard flaps
- E195-E2: Inboard and outboard flaps

SQRTM demonstration parts developed:

- Airbus A320: Outboard flap
- Airbus A320: Nose landing gear door
- Airbus A350: Nose landing gear door
- UH-60: Fuselage roof
- Toyota Aviation: Wing

Current Tooling & Equipment

SQRTM uses closed-mold metal tooling which offers excellent dimensional control of the composite structure. The tooling also offers an opportunity to integrate many individual pieces into one co-cured structure. This integration or unitization of the structure provides several benefits. First is the elimination of many post-cure assembly operations. This reduces the recurring labor and assembly fixtures needed. Second is a reduction in the weight of the composite structure. Integration of the composite will reduce the number of fasteners and amount of adhesive needed. Pad-ups needed for the fastened joints can also be eliminated. The result is an optimized composite design that provides a reduction in weight and manufacturing costs.

The tighter dimensional control and repeatability offered by the closed-mold tooling also allows determinant assembly features to be molded into the composite structure. These features can aid in the alignment of the composite trim fixtures, inspection equipment and/or other structures during assembly. These determinant assembly features offer greater control in assembly operations while reducing the associated costs. The dimensional control and repeatability offered by SQRTM is not achievable in autoclave or other vacuum bag OOA manufacturing processes.

Similar to RTM, which uses an injection system to infuse dry fabric and apply pressure in a closed mold, SQRTM uses an injection system to selectively apply fluid pressure to prepreg. However, during an SQRTM injection, no infusion of the preform occurs. Resin is pushed through tooling passages to create a liquid edge dam at the perimeter of the preform. This allows precise resin pressure control throughout the laminate because of the incompressible nature of the resin and inherent design characteristics of the tooling. Resin pressure during the cure cycle suppresses void formation and improves laminate quality. During an autoclave process, the resin pressure within the laminate depends on the bag pressure and resin bleed, which depend on edge bleed control and tool temperature. With SQRTM, the resin pressure within the laminate is controlled directly with the SQRTM injection system. It is this direct control of the resin pressure that suppresses void formation and allows high-quality laminates to be produced consistently.

SQRTM utilizes the same layup methods as other prepreg structures but instead of an autoclave, a work cell, clamping press, injection system and control system are used during the cure cycle. The injection system is used to preheat and inject resin into the tooling at the specified flow rate and pressure. The ability to precisely control and monitor resin temperature, flow rate and pressure are key to an effective injection system. Clamping the tooling in a press is an ideal method to contain the internal resin pressure and minimize part deflection by distributing pressure uniformly across the tool surface. Heated platen presses are an effective means of providing temperature control throughout the cure profile and help reduce the complexity of tooling. This allows tooling to remain as simple as possible, minimizing wear and allowing for rapid tooling changeover. State-of-the-art SQRTM equipment includes all functions for the press and injection system in an integrated cell that minimizes operator involvement and ensures precise control of all process parameters.

Gaps in Current Equipment

Composites manufacturing, SQRTM included, has traditionally required skilled manual labor with process quality playing an important role in material properties of the finished part. With many composites processes, the largest contributor to manual labor is in layup, where complex fabric shapes are assembled ply by ply, building to the final part geometry. Not only do these processes require skilled labor but also require a great degree of organization and logistics.

Funding Sources

The SQRTM process development and demonstration during the early years of application, starting in 2000, were funded by organizations such as Radius Engineering, Coexpair, Lockheed Martin Missiles and Fire Control, Northrop Grumman, the United States Air Force, the United States Navy and Boeing Commercial Airplanes.

Key Developments

Technology improvements and the commoditization of automated tape laying and fiber placing equipment (ATL/AFP) are enabling broader adoption of these methods to reduce the cost of layup. Such improvements and new automation technologies are directly applicable to SQRTM. For preform designs that are not compatible with ATL/AFP, robotic arms with customized end-effectors are being utilized to collaborate with operators and reduce cycle times. Layup technicians can still perform prepreg layup, while robotic handling systems eliminate non-value-added tasks by automatically presenting workflow in an ergonomic position to the operator. This can improve operator efficiency and reduce the necessary skill and organization required for layup.

Major Influencers/Companies

Radius Engineering

Radius Engineering was one of the first adopters of SQRTM in the late 1990s and early 2000s. Radius demonstrated the process and provided tooling and equipment for early developments, which provided confidence for many later applications.

Lockheed Martin Missiles and Fire Control

One of the first companies to investigate SQRTM was Lockheed Martin Missiles and Fire Control (LMMFC) in Orlando, Fla., U.S. In 2003, LMMFC assessed RTM for application on the F-35 Electro Optical Targeting System (EOTS) structure. Because of significant flight loads experienced by the EOTS, SQRTM was favored because of prepreg's superior material properties. Development parts were fabricated and tested successfully. A view of EOTS is provided in Fig. 5.

Fig. 5. Lockheed Martin Electro Optical Targeting System (EOTS).

United States Air Force

Northrop Grumman in Rancho Bernardo, Calif., U.S., working for the United States Air Force on the *Global Hawk* RQ 4B UAV in 2003, was an early adopter of SQRTM. Northrop Grumman applied SQRTM to the Wingtip Extension used to increase performance on the RQ-4B Block 20, with work beginning in 2003. The AFRL Materials and Manufacturing Chief at the time, Dr. Frances L. Abrams, termed the structure and its use of SQRTM with a legacy Air Force qualified material, "An elegant solution." The SQRTM Wingtip Extension is shown in Fig. 6.

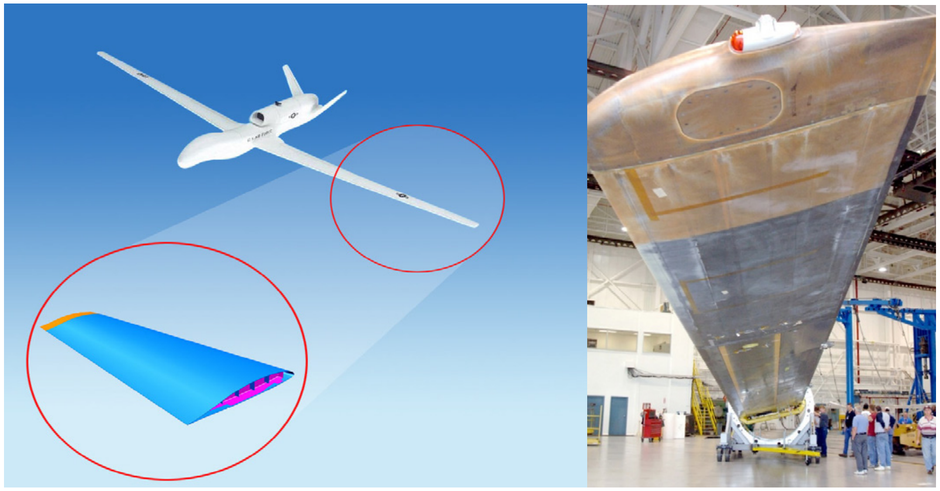


Fig. 6. *Global Hawk* SQRTM Wingtip Extension.

United States Navy

The Northrop Grumman RQ-4B UAV variant, which was the successful candidate in the United States Navy's Broad Area Maritime Surveillance (BAMS) competition, began development in 2008 and used SQRTM in a similar section of the aircraft for a redesigned version of the RQ-4B, later known as the MQ-4C. Naval Air Systems Command (NAVAIR) research personnel examined coupon testing records of the USAF's SQRTM RQ-4B production and verified that the SQRTM material properties had tighter data spread and higher quality than the autoclave database for the material.

Safran

Safran Systems Aerostructures and Coexpair further demonstrated the potential for SQRTM with development and test flight-approval of an Airbus A320 nose landing gear door shown in Fig. 7. This was done as part of the AFLoNext development program, intended to demonstrate a cost-effective alternative to the legacy sandwich solution.

Fig. 7. Airbus A320 Nose Landing Gear Door.

Boeing Commercial Airplanes

Boeing, at its Tulsa, Okla., U.S., facility (now Spirit AeroSystems), initiated work on the Leading Edge Slats of the 787 in 2004, seeking an improved design more resistant to hail damage than the 777 Slats. SQRTM was chosen and implemented for all 787 Leading Edge Slats using Boeing's standard BMS8-276 material (Toray 3900-1) and Boeing process BAC 5578. Photos of the 787 Leading Edge Slat SQRTM tooling and parts are shown in Fig. 8.

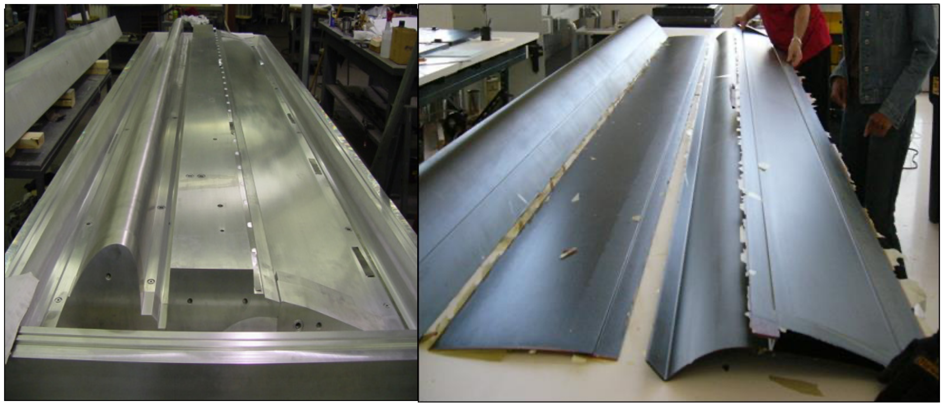


Fig. 8. Boeing 787 SQRTM Leading Edge Slats Tooling and Parts.

Future market

Aerospace composite structures are becoming increasingly large and complex. SQRTM can produce highly integrated structures that reduce weight by reducing the part count and labor by eliminating bonding and fastening steps. SQRTM equipment is increasing in size accordingly, and automated tool-handling systems are improving to enable movement of large tools. Efforts are underway to design tooling with reduced mass and develop effective mold temperature control methods that reduce energy consumption. Structures more than 40 feet long have been demonstrated using closed molds and SQRTM-compatible equipment as of Q1 2023.

The production rates for composite aerostructures are also increasing, particularly for nascent markets like advanced air mobility. For high-rate manufacturing, SQRTM provides efficiency increases thanks to the inherent nature of the process to deliver more repeatable results. By moving away from batch processing in an autoclave and into a lean process that can achieve single-piece flow with tightly controlled process parameters, manufacturers are achieving higher first-pass yields. Further equipment automation and manufacturing digitization will continue to reduce labor costs and eliminate costly scrap and rework.

Future equipment

Like many advanced manufacturing methods, SQRTM is being adapted to enable smart manufacturing and the creation of digital twins. A digital twin requires a digital thread that has traceability throughout the manufacturing process. This is accomplished with the integration of sensors at the device level to allow data acquisition from raw material to finished part. Once collected, the data must be analyzed automatically to provide nearly instant feedback to operators, engineers and managers. Smart manufacturing then becomes possible with the inclusion of statistical process control, workflow optimization and enterprise capability as a part of full factory integration.

How can SAMPE support?

A barrier to broader adoption of SQRTM is the lack of widespread understanding of process development and tool design. Organizations such as SAMPE can play a role in spreading knowledge with the collaboration of private industry partners and educational institutions that are willing to share their experiences and information on SQRTM best practices and evolving equipment technology.

Trim/Drill | Wayne Huberty

Composite material trim and drill operations require specialized equipment and cutters to prevent damage to laminates. Composite laminates and metals differ significantly in how the material behaves while the machining operation is taking place. Metallic materials are removed in uniform peeled pieces allowing for predictable, calculable behavior. Composite materials are fractured through the fiber reinforcement and are much less predictable than metals because there are myriad of variables that affect composites trimming, including fiber and resin types, incidence angle of the cutting tool, thickness of the laminate, heat generation, and environmental conditions.

Current equipment falls into one of two categories: waterjet or rotary cutting. Abrasive waterjet cutting uses an abrasive material mixed with water delivered at very high pressure (up to 60,000 psi) through a nozzle at high pressure to erode the material. Rotary cutting uses a cutting tool attached to a rotating spindle linked to a numerically controlled (NC) traditional machining center, typically a router or mill. Rotary cutters offer the ability to perform interface machining and small-diameter precision drilling, neither of which are possible by using waterjet cutting. NC machining is built around existing infrastructure of legacy metallic and wood machining equipment. In many composites shops, equipment formerly used or designed to machine metallic hardware has been retrofitted and revised to machine composite materials.

Composite NC machining requires additional considerations as well, including dust collection, cooling and heat management, enhanced control of spindle speed and feed rate and specialized cutters to ensure quality requirements are met. In practice, NC machining is defined as automated, but in reality it quite often is anything but. In composites shops with automated NC routers, often a highly trained machinist must make manual adjustments on-the-fly during cutting operations to ensure that the part is being machined, trimmed, or drilled correctly. These specialized machinists train themselves to determine the status of the cut based on the sound of the cutter and laminate interface or the smell of the laminate to know whether or not manual intervention is needed. In many cases, the machine is simply aimed at the part with a set of basic toolpath parameters and the machinist must constantly adjust the machine to derive a set of suitable machining parameters. An opportunity exists in this area to apply machine learning technology to existing machining centers to decrease the number of manual interventions needed.

Machining post processors, such as MasterCAM, have capability to generate automated NC toolpaths based on the geometry and material properties of the part, but they cannot predict every nuanced change that is needed. Additional research using artificial intelligence (AI) to adapt toolpath geometry to contoured composite surfaces could be beneficial to determine trouble spots before sending the toolpath to the machine for processing.

Composite cutter technology has matured significantly over the last decade. Specialized cutters designed specifically for composite materials have been introduced and have improved the laminate cut qualities.

Assembly | Phil Viviano

Current Market

Composites assembly describes the joining of separate composite parts into a single assembly. Assembly is performed in most composites manufacturing facilities that fabricate large parts, and it is most common in aerospace composites manufacturing. This is typically done by a variety of methods:

- **Fastening**
  - This is the more conventional method or drilling holes and installing mechanical fasteners
- **Bonding**
  - This method uses adhesives to join two or more parts. This can be done with two cured parts (secondary bonding) or with a cured and an uncured part (co-bonding)
- **Co-curing**
  - This is done with two uncured parts that are cured at the same time, creating a bond in the matrix of the composite itself
- **Welding**
  - This is applicable only in the case of thermoplastics where heat is applied at the interface to weld the two thermoplastic parts together. Methods include ultrasonic, induction, and resistive welding techniques.

Current Equipment

Equipment for assembly of composite structures is similar to metallic assembly equipment. This equipment is generally used as an aid or a means for manual assembly. Typical equipment used are:

- Pneumatic tools for installing fasteners such as hi-loks
- Pneumatic adhesive deposition tools for hand-application of adhesive
- Fixed tooling to hold parts in place during assembly
- Drill jigs to assist determinate assembly
- Large drill and fill machines that automatically install locating fasteners into large composite structures

Gaps in Current Equipment

Composites assembly is still largely done by hand, except for some automated riveting machines that drill and fill holes on programs like the Boeing 787. The main gap in current equipment is the inability to automate any of the processes of composites assembly. Some advanced applications employ some automated assembly methods, but this is done on a case-by-case basis and lacks the broad application of manual processes.

Funding Sources

Composites assembly is rarely the focus of large research organizations. Instead, developments in composites assembly are pushed by organizations with legacy programs seeking process improvements. This typically comes from the manufacturing R&D organizations of large companies. Examples of these companies are:

- Large commercial OEMs (Boeing, Airbus, etc.)
- Large defense OEMs (Lockheed, Northrop Grumman, etc.)
- Spacecraft companies (SpaceX, Blue Origin, NASA)
- Tier 1 suppliers with large or high-volume structures

Key Developments

Most of the key developments in assembly involve increased automation and the use of determinate assembly. These developments:

- Powerfeed drilling replacing pneumatic drilling
- Automated wet install and tightening of fasteners
- Full-size determinate assembly to prevent drilling during assembly
- Automated sealant dispensing for edge sealing

Major influencers/companies

Assembly needs are specific to the organizations using them. Because of this, most developments in assembly equipment are on a one-off basis. Some of the significant influencers in this area are:

- CAD/PLM system companies that enable determinate assembly
- Manufacturing R&D organizations of large companies
- Automation integrators that build custom automated assembly solutions
- Fastener companies
- Adhesive companies

Future Market

Composites assembly will grow as the composites marketplace grows. This will be across all sectors, but the most growth will be seen in the following segments:

- Next commercial aircraft programs
- General aviation and business jet programs
- The eVTOL industry
- The EV automotive industry

Future Equipment

The future equipment used in composites assembly will likely be variations around a platform that involves holding parts in location, dispensing adhesives and/or fasteners and integrating with tooling to hold or transport parts. Examples of this equipment might be:

- Automated drill and fill cells that use robotic end effectors to locate and hold parts
- Automated bonded assembly cells that locate parts, apply adhesive, apply pressure to parts and cure the adhesive at an elevated temperature
- Automated assembly cells that are capable of building and installing shimming as needed
- Increased use of power-feed drilling especially for complex stack-ups of materials
- Automated thermoplastic welding systems that join two composite parts together.

How can SAMPE support?

Assembly is much less a material challenge as it is an industrialization and process challenge. SAMPE can support the advancement of assembly equipment by assisting in the development of assembly processes. This could look like:

- Developing process specs and joint allowables for adhesives
- Developing quality requirements and joint allowables for fastened assemblies using various fasteners
- Research on the capabilities of automated drill/fill or bonded assembly methods.

SUB-COMMITTEE

MICHAEL SPELLMAN
CHAIR

MATT THORN

DMYTRO KUKSENKO

AVNER BEN-BASSAT

ANOUSH POURSARTIP

APPENDIX 2

Software

Automated fiber placement (AFP) and automated tape laying (ATL) is widely used in the aerospace and wind industries, which typically requires high deposition rates for large scale tools. This is typically run using gantry or robotic equipment. Software is an important piece necessary for the AFP/ATL process. It consists of the following typical components.

- Manufacturing design
- Tool path creation and NC programing
- Postprocessing and machine simulation
- Machine control

Advantages

- Consistency in layup
- Automation
- Speed of layup
- Software can program the same part on different equipment

Disadvantages

- Cost of equipment/materials/software/tooling
- Complexity of layup process
- Prone overlaps or gaps depending on the process/parts.
- Need skilled labor to program machine.

Software companies in AFP/ATL

Accudyne
Airborne
Automated Dynamics
CGTech
Coriolis
Electroimpact
Fives
Ingersoll Machine Tools
Magestic Technologies
Mikrosam AD
MTorres
Trelleborg Sealing Systems

Equipment manufacturers develop their own software solutions to run their equipment as well as using some 3rd party tools.

Traditional Applications and Markets

Applications are typically aerospace and wind energy. The automotive industry has researched the technology but has not fully adopted the process. Traditional AFP parts are wing skins, fuselage skins, fuselage frames, spars, and other larger components. In addition, AFP/ATL will lay flat charges which will then be used in other forming processes to create the 3D shape. Software plays a big role in making these processes affordable and viable.

In the area of manufacturing, design software can give feedback on how the quality of a particular material will work on a particular surface, where problems will arise and how to overcome those situations. Tool path creation and NC programing are necessary to drive the equipment in laying up the material in the most efficient manner and can achieve this is an automated fashion, while producing the solution very quickly. This is important as traditional NC programming on machines with multiples axes could take days to program.

Software also plays a key role in postprocessing and machine simulation. With the right software, postprocessors can be created to program a specific machine without any recurring engineering and with a thorough understanding the machine kinematics. Machine simulation is also necessary to ensure quality, avoid collisions and gather statistics on time, cost and material usage. Most equipment will use a specific machine control produced by the machine vendor, however, this can be a barrier as many machines in this space will insist on the use of very specific software and solutions. There tends to be fewer standards in this area, with each vendor providing their own solution.

Change Drivers

The market is starting to get bigger with more equipment manufactures making individual heads that can be mounted on any robot or gantry. These heads can reduce the cost of entry into the market but usually target simple or specific applications. In addition, smaller machines driven by smaller robots are making it possible to make smaller parts. Smaller robots coupled with in-process inspection tools will continue to improve the quality of parts made with these systems. Emerging technologies like AI and machine learning will push software to make these machines/processes easier to use.

Emerging Applications and Markets

More advanced programming strategies are being developed for tow steering and thickness buildup in AFP/ATL laminates — beyond traditional quasi-isotropic orientations — to improve strength while using less material. Advanced software is increasingly necessary to find the right place to use these techniques.

Competitive Materials

Typical material for AFP/ATL is unidirectional thermoset prepreg, however, there are some heads in use designed to process thermoplastic prepregs as well. In addition, there are new 3D printing systems that process fiber-reinforced thermoset resins that can be cured on the fly with UV light. More exotic 3D printing systems (Continuous Composites, Orbital Composites) are being developed that can combine multiple material types with composites. These include fiberoptics, sensors, copper, metal, etc. It is important that the software can adapt to new materials and processes as they emerge on this equipment.

Finite Element Analysis

Finite element analysis (FEA) is a powerful engineering tool used to model and analyze complex systems. Myriad dedicated and generic FEA software packages are available on the market. By simulating the performance of the manufacturing system, it's possible to gain valuable insights into its performance, which can facilitate improvements. The FEA pipeline can be described as having these key steps:

- **Pre-processing:** Involves CAD model simplification, FEA model generation, assignment of boundary and loading conditions, etc.
- **Analysis:** Used to obtain the response of the generated FEA model
- **Post-process:** Incorporates the extraction and visualization of modeling results

Advantages

- Analysis of complex systems
- Trade studies
- Reduction of a costly experimental campaign

Disadvantages

- Software cost
- Computationally expensive
- Needs extensive computational resources
- Necessity of several dedicated software packages

Top FEA software companies

- Dassault Systems
- Altair
- COMSOL Multiphysics
- MSC Software | Hexagon
- Siemens
- Ansys

Traditional Applications and Markets

FEA software has been used by many industries, including but not limited to aerospace, defense, construction, infrastructure, marine, wind energy and others. Carbon fiber-reinforced plastic (CFRP) composites are now widely used in these fields as they offer unique properties compared to monolithic materials. However, accurately predicting the behavior of composite structures in different environments and under various loading scenarios requires sophisticated software tools.

A great deal of effort has been dedicated to creation of appropriate material models to capture the response of CFRP composites under static and fatigue loading. There is no single software tool or approach that can seamlessly analyze all composite structures in all applications. Typically, ad-hoc solutions are necessary to facilitate the analysis of a composite structure.

Most of the key software companies offer tools to analyze CFRP as well as provide pre- and post-processing of the FEA results to capture the behavior of CFRPs. However, it's worth noting that each software product offers fidelity in one or several aspects of analysis, but rarely all. Consequently, a combination of several software packages may be necessary to gain a better understanding of the performance of composite structures.

Given the peculiarities of composites manufacturing processes, which can exacerbate the performance of composite structures, and the inherent complexity of damage modes under various loading conditions, it can be computationally expensive to analyze a composite structure. This computational cost prohibits the adoption of FEA tools at a large scale. Nonetheless, with the continued development of more sophisticated software and hardware solutions, this challenge can be overcome, enabling wider adoption of these tools in the future.

Change Drivers

The development of FEA software is driven by the latest advancements in computer science, which can be broadly classified into three categories: cloud computing, high-performance computing (HPC) and data-driven technologies.

The adoption of cloud computing is revolutionizing the way FEA models are simulated. It eliminates the need for expensive on-site computing infrastructure (e.g., CPU and/or GPU clusters) and provides on-demand analysis capabilities. However, using a vendor's computational resources to scale with computational demands may also prove costly.

HPC is primarily focused on the adoption of large-scale GPU clusters to analyze FEA models. Parallelization of FEA analysis on GPUs substantially reduces analysis time. It's worth noting that most FEA software has limited capacity to perform analysis at scale on dedicated GPUs, which makes HPC adoption even more critical.

Another avenue of improvement is the adoption of data analytics tools and AI/ML algorithms to enhance the FEA pipeline. These tools help minimize simulation time, improve pre- and post-processing capabilities and optimize FEA software's performance. With data analytics, engineers can make informed decisions and draw insights from vast quantities of simulation data. Additionally, AI/ML can automate manual processes and optimize the performance of FEA software.

Overall, the adoption of these computer science advancements in FEA software development is driving innovation, increasing efficiency, and improving FEA simulations.

Emerging Applications and Markets

Data analytics and AI/ML technologies are the front and center of the FEA software advancements. The adoptions of these technologies is anticipated across all markets. The data management systems can optimize the FEA pipeline and drive further improvements.

SUB-COMMITTEE

KEVIN SIMMONS
CHAIR

MUTHU ELEN

YAO QIAO

DON KINARD

RUSHABH KORTHARI

MATTHEW THOMPSON

JACOB GIBBS

LES COHEN

APPENDIX 3
Materials

Purpose

The purpose of this document is to provide forward-looking views of the state of materials that would be used in the factory of the future. The interrelationship between materials, processes, environmental factors, and properties are key drivers in material selection for components. This document will provide existing and future material views for readers to understand the current and future status. The document is not comprehensive and will be updated with additional content in the future.

Introduction and History to Composites

From the earliest civilizations, plant fibers were used as reinforcements for ropes, chords, clothing and nets. The strength of the fibers was found to help reinforce mud materials to form shapes for making shelters.

Often in the history of materials, innovation and change grew out of necessity — for example, demand for lower costs, faster processes (cycle times), higher performance, or safety and health. Although these needs continue to be improved upon, the current challenges are more related to recycling and decarbonization of both materials and processes. How can we reuse the materials that have been put into our ecosystem for secondary, tertiary and quaternary cycles? As we are able to recover fiber and matrix systems multiple times, we reduce the demand on virgin materials. The results can be a significant reduction in the composite carbon footprint.

New materials systems and reevaluation of existing systems are also under development, driven in part by manufacturing process needs as well as necessity. For example, Vitrimer material systems allow for rehealing of damaged materials and reprocessing. Ultra-thin composites driven by new techniques such as airflow tow spreading and ultrasonic waves provide new composite performance not realized in existing systems. Natural fiber-reinforced composites are the focus of much attention now because of their smaller carbon footprint, compared to carbon and glass fiber-reinforced system. Similarly, out-of-autoclave material systems allow for the fabrication of large structures without the energy penalty incurred by the autoclave curing process.

Lastly, materials processing automation in the composites industry is helping drive innovation as well. Automated material processing equipment can enable more complex designs, make the layup process more repeatable, and enable layup design to be input to finite element analysis to insure the manufacturing process meets design requirements.

Composite Material Systems

Thermoset and Thermoplastic

The modern composites industry was born in the 1960s with the development of boron and then graphite fibers impregnated with resins of various kinds. It was subsequently kick-started by the U.S. Department of Defense (DoD), which wanted to take advantage of the potential weight savings using high-modulus fibers to increase range and payload on military aircraft. The DoD sponsored programs where industry aerospace engineers attended master's programs at various universities where they learned the basics of design with composites, mechanical structural analysis, and processing and test technologies to facilitate their adoption on new aerospace programs.

The DoD followed up with several aircraft programs intended to stimulate R&D by the aircraft industry toward the use of composites. The aerospace industry took the encouragement to heart and worked with its customers to develop certification programs for composite structures; these were applied on aircraft programs in the early 1970s. The F-16 program utilized composites for fracture-critical structure, including horizontal and vertical tails, with first deliveries containing 5% composites by structural weight in the mid 1970s. Composites usage increased to about 30% in subsequent military programs, including the F-22, F-18, F-35. In parallel, composites started making inroads into the commercial aviation business where several major programs have today 50% composites by weight.

The drive for composites in the early days was 100% driven by weight savings opportunities, especially for wing and empennage structures that could take advantage of laminate tailoring and the lower density equivalent stiffness and strength compared to traditional metallic parts. The promise of composites was incredibly robust in the early days; the expectation was that composites would eventually comprise perhaps 80% of the structural weight of next-generation aircraft.

The composites industry in the 1980s, encouraged by the increasing potential of composites use, spawned dozens of companies producing many different types of composite materials including epoxies, bismaleimides and thermoplastics. Epoxy-based composites were initially favored because of epoxy's the ease of processing into prepreg and their inherent tack, which facilitated hand layup and eventually automated fiber placement.

Demand for higher temperature performance drove development of polyimides such as bismaleimides, which had better properties than epoxies at temperatures near 350°C, consistent with requirements for high-performance fighters. Not to be outdone, the thermoplastics industry developed many resin systems and the technology to impregnate fibers to create prepregs. These dry, boardy materials were difficult to lay up; most early work was done by using hot irons to melt the thermoplastic tape to stick one ply to another, creating a layup with a significant bulk factor (thickness of layup compared to consolidated laminate thickness). In addition, processing of aerospace thermoplastics required autoclaves to operate at temperatures near 900°F and pressures of 200-250 psi (whereas epoxies and polyimides required 400°F and 100-psi autoclaves). For a time, there were wet thermoplastics where solvents were used to provide tack to the raw prepreg. The curing of these materials resulted in condensation products that had to be transported out of the laminate during cure. Process temperatures and pressures for aerospace-grade wet thermoplastics were also 800°F and 250 psi.

The 1980's are often termed as the golden age of materials in the aerospace industry. The promise of composite materials becoming the primary structural material for military and commercial aircraft spawned dozens of traditional plastics companies and smaller resin manufacturers to invest in the technology, hoping to win in a market with high expectations of growth for the next couple of decades.

The metals industry challenged the growth of composites with advanced metals such as aluminum lithium and similar products, some which combined composites and metals into structural hybrids. The stage was now set for the aerospace companies, the government and composites industry to compete for preeminence in this dynamic field. Aerospace companies invested hundreds of millions of dollars in composites and metals, looking for the technology that would increase their chances of winning new DoD programs and support their commercial industry with weight savings, fuel savings and affordability. Interesting enough, aerospace companies tended to focus on thermosets (epoxies and BMIs), dry thermoplastics, and wet thermoplastics because of their perceived property advantages.

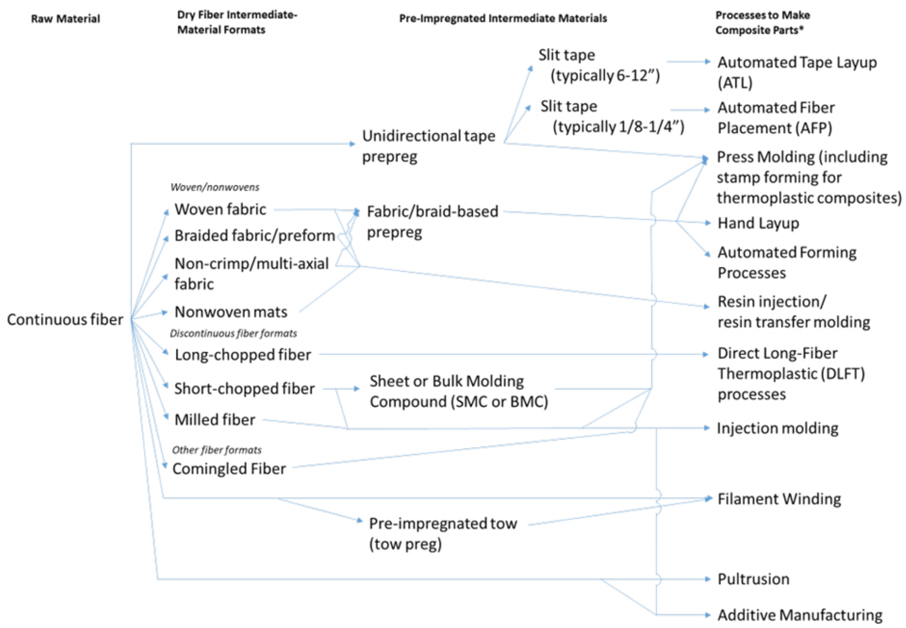
Thermosetting composites were the first commercial materials to arise and capture early sales for production programs. Epoxy-based composites (tape and fabric) had sufficient tack for hand or automated tape placement and were relatively easy to process with good resin flow during cure at conventional, commercial autoclave temperatures and pressures (350-400°F, 100 psi). In addition, there were precursors to autoclaves, such as bladder presses, that could be used for part production.

The introduction of BMIs in the early 1980s increased the operating temperature capability for composites in high0performance aircraft. This technology was demonstrated in the production of the F-16 XL wing skins, first flown in 1982. BMIs were typically not as tacky as epoxies and could require additional debulking for processing, but it still became a key material selection for industry. Years later, heat-assisted fiber placement technology would dramatically increase the ability to lay up less tacky materials such as BMIs. One of the critical weaknesses of epoxies — especially high-temperature thermosetting polyimides — was damage tolerance, sometimes defined as compression after impact and driven by the size of delamination resulting from impact events. The industry was focused on providing superior structural properties and a balance with material toughness to meet government certification requirements.

Fiber Forms

To achieve high mechanical properties — e.g., tensile strength modulus — in the material system, fiber reinforcement is used. Types of fibers include carbon fiber, glass fiber, aramid fiber, boron fiber, silicon carbide (SiC) fiber and natural fibers like jute, flax, bamboo, etc. This Materials Section will mainly focus on carbon fibers. More information related to new fiber systems, including natural fibers, are described later.

For synthetic fibers like carbon fiber, the fiber is produced in continuous tow format. It may be used in this form in subsequent processes to make composite parts, or it may be reformatted into a variety of intermediate materials. A plethora of options exist for material formats and processes that can be used to make composite parts; the most common are shown in Fig. 9.



*Does not distinguish between different curing methods, e.g. ATL and AFP usually use autoclave cure, and fabric-based prepregs with hand layup or automated forming may use autoclave or vacuum-bag oven cure.

Fig. 9. Fiber formats and processes

Fig. 9 does not represent an exhaustive list. Discussion of the cure method, e.g. autoclave vs. out-of-autoclave (OoA), is given in Section 3.c.ii. Further information about composite material formats may be found in the literature, e.g. CompositesWorld, "Materials & Processes: Fiber formats for composites," published 3/17/2016, updated 3/7/2023, https://www.compositesworld.com/articles/fiber-reinforcement-forms. Some notable exceptions to Fig. 9 include the Materials of the Future as described in Section 6 and recycled fiber. Recycled fibers may be in continuous format, but more often, they are supplied in discontinuous formats and would thereby be used as a raw material for subsequent processes like those shown in Fig. 9.

Composites market landscape in industries

Fiber and composite material demand is strong for many industrial composite markets. In wind energy, demand for large-tow (50K filament count) carbon fiber far exceeds or nearly exceeds global supply. Carbon fiber is used in the pultruded spar cap, which is a primary structural component of wind turbine blades, including those for onshore and offshore applications.

For standard tow carbon fiber (<50K filament count), a great deal of fiber continues to go to the composite-overwrapped pressure vessel (COPV) market. These COPVs may be Type III or Type IV, with aluminum or plastic (typically high-density polyethylene, HDPE) liners, respectively, and are used for transport and storage of compressed natural gas (CNG), systems for natural gas-powered transportation vehicles, transport and storage of compressed hydrogen gas (CHG), and several other applications such as pressurization vessels in rocket launch vehicle applications. For high-performance filament wound systems, such as those for space and defense applications, higher tensile strength carbon fibers are being selected.

Another strong market for carbon fiber is pultruded cable core for high-efficiency, long-span electric power transmission lines. Additionally, use of carbon fiber in oil and gas applications continues to expand, including CF/thermoplastic composite materials used in flexible tubulars for offshore drilling. In general, CF/thermoplastic composites continue to grow and mature with increasing demand in a range of application areas.

Composite materials and processes relations

Materials and Processes

The discussion of this section is focused primarily on polymer matrix composites; other ceramic/metal/carbon matrix composites and materials are covered by the other technical committee of SAMPE. See Table 2.

CompositesWorld (CW) has prepared a sourcebook for a list of manufacturers and suppliers, which can be accessed by the public at https://www.compositesworld.com/suppliers. This particular resource is a one-stop solution for all markets to learn about the current new materials available, and their end uses.

For aerospace and defense applications, the FAA and a group of organizations from industry, academia, and national labs, produce the Composite Materials Handbook (CMH) which can be found at https://www.cmh17.org/ and https://www.sae.org/publications/books/content/r-422.set6/
For industries and researchers who work with various plastic applications, Plastics Technology - https://www.ptonline.com/ has similar resources of books, magazines, suppliers' information and processes, and materials.

Material type	Advantages	Limitations	Property ranges	Common process used
Epoxy	• High strength and stiffness • Excellent adhesion to a wide range of substrates • Good chemical and water resistance • Excellent fatigue resistance • Low shrinkage during curing • Good electrical insulation properties • Low toxicity and odor	• Limited UV resistance • Can be brittle at low temperatures • Limited heat resistance • Relatively expensive compared to other resins • Requires careful handling due to toxicity	• Tensile strength: 50-150 MPa • Modulus of elasticity: 2-10 GPa • Flexural strength: 80-250 MPa • Heat deflection temperature: 50-150°C • Glass transition temperature: 50-150°C	Hand layup, vacuum bagging, resin transfer molding, filament winding, and compression molding.
Vinyl ester	• High resistance to chemicals, including acids, alkalis, and solvents • Good resistance to impact and fatigue • Excellent adhesion to various substrates • Good weather ability and UV resistance • Low shrinkage during curing	• Can be brittle at low temperatures • Limited heat resistance compared to other resins • Higher cost compared to polyester resins • Can be more difficult to handle and process compared to other resins	• Tensile strength: 60-120 MPa • Modulus of elasticity: 2-4 GPa • Flexural strength: 100-200 MPa • Heat deflection temperature: 60-100°C • Glass transition temperature: 60-100°C	Hand layup, spray-up, resin transfer molding, filament winding and pultrusion
Polyester	• High strength and stiffness • Good chemical resistance • Low cost • Good dimensional stability • Easy to process • Good weather resistance	• Susceptible to water and UV degradation • Limited heat resistance • Can be brittle at low temperatures • Shrinks during curing • Can emit harmful fumes during curing • Requires careful handling due to toxicity	• Tensile strength: 50-100 MPa • Modulus of elasticity: 2-5 GPa • Flexural strength: 100-200 MPa • Heat deflection temperature: 50-100°C • Glass transition temperature: 60-100°C	Open mold layups / hand-layups, compression molding, resin transfer molding, casting, pultrusion
Thermoplastics	• High impact resistance • Good chemical resistance • Good fatigue resistance • Good dimensional stability • Ability to be repeatedly molded or reshaped • Low processing temperatures compared to thermosetting resins	• Generally lower strength and stiffness compared to thermosetting resins • Limited heat resistance compared to some other resins • Can have limited weather ability and UV resistance • Can be more expensive compared to some other resins	• Tensile strength: 50-100 MPa • Modulus of elasticity: 2-5 GPa • Flexural strength: 50-150 MPa • Heat deflection temperature: 50-100°C • Glass transition temperature: 50-100°C	Injection molding, compression molding, extrusion, thermoforming, and additive manufacturing

Table 2. Advantages and Limitations of common composite matrix systems.

Materials of the Future – Identify New Material Systems That Are Changing Composites and Processes

Natural Fiber Systems

For sustainability purposes, composites reinforced by natural fibers from plants and rocks have been investigated over the last decades, but still require more study. The reinforcements include hemp, jute, flax, palm, kenaf, sisal, henequen, Tampico, bamboo, basalt, coir, ramie, etc. Their hybrids as reinforcements have also been investigated in the literature. Five aspects can be different from CFRPs/GFRPs:

1. Fabrication of long nature fibers and related weaving techniques
2. Specific surface treatment on natural fiber for better bonding with polymer matrix
3. Different processing parameters for cutting, drilling, and riveting, since these actions can cause more damage in natural-fiber-based composites compared to that of CFRPs/GFRPs
4. Environmental performance
5. Reduction of carbon-based fibers to reduce carbon footprint.

Polymer Fiber Systems

Thermoplastic polymer fibers as reinforcements in composites have also been studied over the last decades, but still require more study. Among a large family of thermoplastic polymers, some of them have been investigated in the literature in the form of reinforcing polymer fibers, for instance, polypropylene, different grades of polyethylene (i.e., low/medium/high-density, ultra-high-molecular-weight), polyethylene terephthalate, polyamide, polylactic acid, liquid-crystal polymer, etc. Seven aspects can be different from CFRPs/GFRPs:

1. Fabrication processes and related parameters to make strong polymer fibers by stretching
2. Accurate temperature control including heating and cooling for the fabrication of polymer fiber-based composites due to temperature-dependent behaviors of polymer fibers
3. Specific surface treatment on polymer fiber for better bonding with polymer matrix
4. Different processing parameters for cutting, drilling and riveting due to the ductile behavior of polymer fibers compared to carbon and glass fibers
5. Improved composites ductility compared to CFRPs/GFRPs
6. Opportunities for ultra-lightweight composite structures due to lower densities of polymer fibers
7. Reduction of carbon-based fibers for green environment and improved recyclability.

Ultra-thin Composites

A typical standard- and thick-ply prepreg has an areal weight of 100-450 g/m^2 for carbon-fiber-based lamina, and 150-800 g/m^2 for glass-fiber-based lamina. By leveraging several techniques (e.g., airflow tow spreading, ultrasonic waves, etc.), an ultrathin-ply prepreg can be achieved with an areal weight of 15-100 g/m^2 and a thickness of about 20-60 ɥm.
Four aspects can be different from standard CFRPs:

1. Opportunities for very thin composite structures
2. Opportunities for deployable composite structures
3. Oncreased fiber volume fraction, reduced defects and improved physical properties
4. Hybrid composites using thin-ply prepregs to improve ductility.

Others

Vitrimers are now commonly considered as the third class of polymeric materials, alongside thermoplastics and thermosets, due to the reprocessing capability of vitrimer polymer matrix (covalent adaptable networks). Thus, vitrimer-based composites have been receiving more and more attention. Four aspects can be different from thermoset/thermoplastic-based composites:

1. Different processing parameters for the fabrication of vitrimer-based composites
2. Different flowability compared to thermosets and thermoplastics
3. Specific surface treatment on the reinforcing fiber for a better bonding with vitrimer matrix;
4. Self-healing capability similar to thermoplastic-based composites, but not for thermoset-based composites.

References

John Vickers, “Advanced Manufacturing Transformation” in the SME 2022 Industry Report for Aerospace & Defense Manufacturing, https://digitaleditions.walsworth.com/publication/?m=67292&i=769474&p=6&ver=html5

TC 2

Bonding and Joining

Louis Dorworth
Direct Services Manager
Abaris Training Resources, Inc. | Chair

Maggie McKenney
Technical Service Senior Engineer
Bostik,Inc. | Co-Vice Chair

Hardik Dalal
Director | Visioneering | Co-Vice Chair

Nicole Larson
Program Director
Western Washington University

Moutushi Dey, Ph.D.

Felix Chen, Ph.D.

Susan Ruth

sampe
North America

TC 2
BONDING AND JOINING

Executive Summary

Assembling separately fabricated items to create a new capability date back more than 2 million years with the cracking of stones to make points that were then fastened to wood to make arrows and spears [1]. The technologies associated with assembly have enabled some industries to come into existence and enabled advancements in others.

Most of the systems in development or operation today depend upon a number of assembly technologies. Mechanical assembly methods are some of the earliest that were used and are still important. Over time, the development of materials, processes, advanced components, and systems as well as industries has encouraged the creation of additional assembly technologies such as welding and bonding.

The assembly methods of interest to this Technical Committee are bonding with adhesives and joining of different materials. Our efforts are focused on adhesive bonding and thermoplastic welding. This document is a dynamic document and will include updates as we move forward.

Technology and Material

Bonding and joining is the process of chemically or mechanically joining two materials together, whether similar or dissimilar. Adherends can be a variety of materials — natural (bio-based), metallic, or polymeric, and these can be processed in preparation for bonding via physical or chemical means.

Bonding materials can include different forms of adhesive — film, liquid, hot melt, and paste as well as different processes like co-bonding, diffusion bonding, etc. Adhesives can be either thermoplastic, allowing for either reusability/recyclability, or reactive thermoset, allowing for improved environmental resistance and properties. Examples of these types of polymer-based materials are phenol-formaldehyde, polyesters, polyurethanes, polyacrylates, polymethyl methacrylate (PMMA), cyanoacrylates, silicones, epoxies, and elastomers.

In addition, bio-sourced polymer adhesives can include protein-based bio-adhesives like fibrin sealants, gelatin, collagen, and polysaccharide-based bio-adhesives like alginate, chondroitin, and chitosan [2]. Adhesive materials can also include green wood adhesives like lignin-based wood adhesives, tannin-based wood adhesives, protein-based wood adhesives, and natural rubber latex [3].

Shape memory polymers (SMP) are a class of stimuli-responsive smart polymers that show reversible changes in their mechanical properties under the impact of external stimuli. SMP polymers show rubbery behavior (elastic and soft) above the glass transition temperature (Tg) and display glassy behavior (hardness) below Tg [4]. SMP foam adhesives are increasingly being used as shoe insoles and mattresses, etc.

Adhesives offer a number of benefits and challenges when compared to traditional mechanical fasteners. Adhesives far exceed mechanical fasteners in their ability to resist fatigue and vibrational forces, contour to organic geometries, and greatly reduce overall weight. Adhesives also seal the joint. However, adhesives have their challenges. Designers must choose the correct adhesive and surface treatment processes for the application to ensure that any failure is a cohesion failure or far field substrate failure. (Fig. 1.) Adhesion and cohesion failure below maximum limit loads of the adhesive are unacceptable failure types and are one of the reasons that adhesives are often discounted as being the safest method of joining two surfaces. Adhesive joints are also more challenging to inspect and do not offer the ease of disassembly that mechanical fasteners can offer.

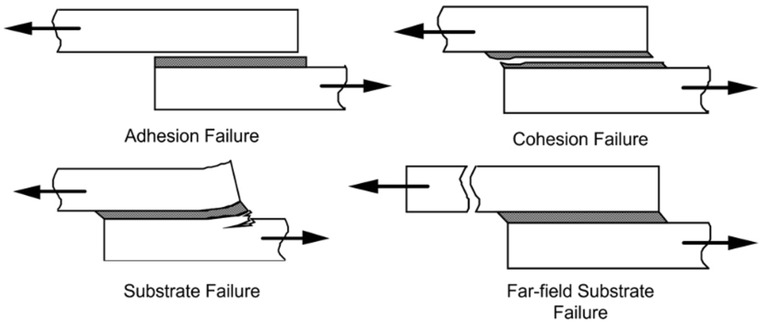


Fig. 1. Comparison of failure modes. Source: Abaris Training Resources Inc.

Composite adhesive bonding methods fall into three categories: co-curing, co-bonding, and secondary bonding. Co-curing refers to the act of curing a composite laminate and simultaneously bonding it to some other uncured material, or to a core material such as balsa, honeycomb, or foam core.

Co-bonding is the curing together of two or more elements, of which at least one is fully cured and at least one is uncured. An example is co-bonding an uncured laminate to an already cured or prefabricated substrate using an adhesive interface.

Secondary bonding describes joining together, by the process of adhesive bonding, two or more cured composite parts, during which the only chemical or thermal reaction occurring is the curing of the adhesive itself. Both co-bonding and secondary bonding require surface preparation or treatment of one or more substrates.

In aerospace applications, bonding has traditionally been used in primary and secondary structural applications. In primary structure, bonds such as a skin/stringer, or fabricated skin panels like GLARE panels on the A380, are typical applications. Secondary applications are typically interior applications and control surfaces. These are typically face sheets bonded to a core material such as foam or honeycomb.

Other important bonding techniques are diffusion bonding and superplastic forming technique (DB/SPF) [5]. This is a solid-state bonding process and is generally used for joining metal alloys in aerospace/space applications. The joining region is generally homogeneous and does not contain any liquid phase in between.

Traditional Applications

Traditional adhesive applications are typically sorted into structural and nonstructural applications. Bonding for structural applications is common in transportation, and infrastructure can include panel bonding, window glazing, stringer bonding, and metal bonding. Structural adhesive chemistries include epoxies, two-component polyurethanes, hybrid and modified silane adhesives, methyl methacrylates, and acrylics.
Nonstructural applications include packaging, tapes and labels, interior trim for transportation, interior décor, personal care items, electronics, and medical devices. Nonstructural chemistries include hot melts, pressure-sensitive adhesives, instant acrylic adhesives, water-based adhesives (typically acrylic), solvent-based adhesives, and sealants.

In structural applications, adhesive bonding, especially for metals, is favored in applications with dissimilar substrates where welding can be expensive and traditional fastener methods can face varying corrosion effects across mixed metals and selected metals with carbon fiber. Bonding is also favored for composite applications to protect the integrity of the composite or in highly visible applications where the adhesive allows for a smooth visible surface uninterrupted by fasteners or weld spots (aerodynamic).

Processes to condition surfaces for bonding range from mechanical abrasion to chemical surface treatment. In co-bond and secondary bonding applications, the use of (wet prepreg or dry) peel ply or release fabrics are commonly used (typically nylon, polyester, or fiberglass). After cure, they can be stripped from the part and provide a consistent surface, reducing the need for additional surface preparation. Chemical surface preparation processes include plasma treatment or applied primers/coupling agents. Mechanical abrasion techniques include sanding, grit blasting, and even laser ablation. Some of these processes can also create reactive sites to aid in the bonding process.

Adhesive bonding is the most common joining method for nonstructural applications too, as there are a variety of nonstructural adhesives available, many of which are very cost-effective. Additionally, many of these applications, such as interior doors, labels, packaging closures, etc., cannot be achieved without adhesive bonding.

Change Drivers

Materials

Industry is still in need of additional investigation into surface-tolerant epoxy film and paste adhesives that are resistant to failure in the presence of common surface contaminants and low temperatures (<122°C). Other technologies deserving of attention include rapid “snap-cure” epoxy paste and film adhesives with equivalent or better thermal and structural properties than current formulas and sustainable thermosetting thermoplastic epoxy adhesives that allow for disassembly of adhesively bonded joints and end-of-life recycling. In addition to these areas, more experimentation needs to be performed in the area of surface preparations and treatments, including the next generation of primers for metals and composites and enhanced treatment methods such as plasma.

Additional materials that also need exploration are bio-based adhesives and shape-memory polymers. And finally, given that materials are often selected based on criteria pertaining more to top-level performance rather than intrinsically being able to be bonded together, adhesives that can accommodate interfaces with differing elastic properties and CTEs (coefficient of thermal expansion) are needed.

Joint Design

Along with more materials investigations, the joint design itself needs to be revisited. Studies are needed to further develop shear, tension, and compression designs while avoiding peel and cleavage forces, novel system geometries, self-indexing joints, and how to further design for weight reduction. Along these lines, the popular lap shear and peel tests for measuring adhesion strengths provide useful engineering assessments. Fundamentally, however, adhesion is more accurately modeled with energy methods such as strain energy release rate. This is a sub-branch of fracture mechanics that treats the strength and reliability of adhesive bonds by presuming the existence of small defects that initiate delamination. Although this approach obscures the distinction between damage accumulation and steady state delamination in adhesive bonds, the theory appeals to their fundamental thermodynamics and can accommodate intricacies such as edge singularities and mode mixity (the distribution of shear and tensile loads across adhesive bonds comprising differing elastic properties). The additional effort needed to extract strain energy data for adhesive bonds may not always be feasible but is in order for a deeper understanding of their mechanics.

Tooling Design

Traditional fixturing and tooling for joining parts and materials would also benefit from further investigation. Many joining tools are heavy and cumbersome without precise heating or pressure capabilities. Lightweight bonding jigs and fixtures that allow for localized heating and pressure to adhesively bonded joints (ABJs) without thermal exposure of the entire bonded assembly are needed moving forward.

Emerging Applications and Markets

The advanced packaging market is expected to grow up to $26.7 billion by 2024 and up to $69.17 billion by 2031, because of rising demand for cost-effective and more efficient smart packaging in different markets ranging from food packaging [6], sensors in food packaging, and the high-end chip market for consumer electronics integration.

E-beam irradiation curing of composites is a well-known process in complex composite structure manufacturing. This market will expand because the process is environmentally clean, cold, requires less cure time and is, therefore, a sustainable solution [7]. There will also be emerging markets in adhesive applications in 3D vision systems and automation solutions including robotic end effectors.

Adhesive systems (adhesives, additives, and modifiers) are being designed for rapid, low-temperature cure for military field applications under cold, wet, and underwater applications [8].

E textiles, including textiles used for tracking physical activity, sports performance, healthcare, and conductive textiles, will also see expansion as research is being conducted to make the bonding and joining techniques more user-friendly (examples include Lilypad Arduino, Loomia Packs & Parts, Kobakant).

1. Groeneveld, Emma. “Stone Age Tools.” *World History Encyclopedia*. World History Encyclopedia, 21 Dec 2016. Web. 04 Apr 2023.
2. Bio-based adhesives for orthopedic applications: sources, preparation, characterization, challenges, and future perspectives, Designs, 6(96), 1-23, 2022.
3. Latest advancements in high-performance bio-based wood adhesives: A critical review, Journal of Materials Research and Technology, 21;3909-3946, 2022.
4. Shape Memory Polyurethane-Based Smart Polymer Substrates for Physiologically Responsive, Dynamic Pressure (Re)Distribution, ACS Omega, 4 (13), 15348–15358, 2019.
5. Diffusion Bonding of 1420 Al-Li Alloy assisted by pure Aluminium Foil as interlayer materials, 13(5), 1103, 1-12, 2020.
6. Fruit quality monitoring with smart packaging, Sensors, 21(4),1509, 1-30, 2021.
7. Polyurethane based PSAs using e-beam irradiation for medical application, J. Polym. Mater., 28(4), 525-542, 2011.
8. Advanced Fast Curing Adhesives for Adverse Conditions, Daniel De Bonis, and John la Scala, Proceedings of the SAMPE 2007 conference, Baltimore, MD,3-7 June 2007.

TC 3

High-Temperature Materials

Robert Cook, Ph.D.
Director
Hexagon Manufacturing Intelligence
Chair

Tanaya Mandal
Ph.D. Candidate
Texas A&M University
Vice Chair

William Guzman
Ph.D. Candidate
The University of
Southern Mississippi
Secretary

Madelyn Milligan
Toray Composite Materials America

Susan Ruth

Les Cohen, Ph.D.

sampe
North America

TC 3
HIGH-TEMPERATURE MATERIALS

Executive Summary

High-temperature materials, roughly defined as materials that retain long-term thermomechanical performance over the range 200-1000°C, are a growing market segment across multiple industries. The global high-temperature materials market was valued at approximately USD $4.3 billion in 2020, according to a report by Grand View Research. The market is expected to grow at a compound annual growth rate (CAGR) of 7.7% from 2021 to 2028, reaching a value of approximately USD $7.8 billion by 2028.

The growth of the high-temperature materials market is being driven by several factors, including the increasing demand for materials that can operate at high temperatures and harsh environments in a wide range of industries such as aerospace, defense, energy, automotive, and industrial. The growing focus on energy efficiency, environmental sustainability, and renewable energy sources is also driving the demand for high-temperature materials in emerging markets such as renewable energy and electronics.

Regionally, North America and Europe are currently the largest markets for high-temperature materials, due to the presence of key industries such as aerospace, defense, and energy. However, the Asia-Pacific region is expected to be the fastest-growing market for high-temperature materials, driven by the increasing demand for these materials in emerging markets such as automotive, electronics, and renewable energy.

Traditional applications and markets

High-temperature materials are utilized in applications and markets where they are exposed to extreme temperatures and harsh environments where traditional materials may fail or degrade. Some of the traditional applications and markets for high-temperature material systems include:

Aerospace and defense

High-temperature materials are extensively used in the aerospace and defense industries. For example, titanium alloys are used in aircraft engines and airframe structures, while superalloys are used in the hot sections of jet engines. Ceramic matrix composites are used in thermal protection systems, such as heat shields and tiles for spacecraft.

Energy

High-temperature materials are also used in energy-generation systems, including gas turbines, steam turbines, and nuclear reactors. These materials are used in components such as turbine blades, combustion chambers, and heat exchangers where they must withstand high temperatures and corrosive environments.

Automotive

High-temperature materials are used in automotive applications such as exhaust systems, turbochargers, and brake systems. For example, high-temperature polymers are used in engine components and high-performance braking systems.

Industrial

High-temperature materials are used in various industrial applications, such as furnace linings, refractory materials, and chemical-processing equipment. For example, refractory metals such as tungsten and molybdenum are used in high-temperature furnace components.

Change drivers

There are several key change drivers within the high-temperature materials industry. One is the growing demand for materials that can withstand higher temperatures and more severe operating conditions. This is particularly true in the aerospace and defense industries, where high-temperature materials are used in engines, turbines, and other critical components. The market for high-temperature materials is also being driven by the increasing demand for energy, particularly in emerging economies. The use of high-temperature materials in power-generation systems, such as gas turbines and nuclear reactors, is expected to increase in the coming years. Additional market drivers include:

Technological advancements

Advances in materials science, manufacturing techniques, and design methodologies are driving the development of new high-temperature materials with improved performance characteristics, such as higher strength, durability, and resistance to extreme temperatures and harsh environments.

Evolving industry needs

The needs of industries that use high-temperature materials, such as aerospace, defense, energy, automotive, and industrial, are constantly evolving, driving demand for new materials that can meet specific performance requirements, such as improved fuel efficiency, increased power output, and reduced emissions.

Environmental concerns

The focus on environmental sustainability and reducing greenhouse gas emissions is driving the development of high-temperature materials that can enable more efficient and sustainable energy generation and use.

Government regulations: Government regulations and standards, such as those related to emissions reduction and safety, are driving the development of high-temperature materials that can meet these requirements.

Economic factors: Economic factors, such as the availability of raw materials, labor costs, and market demand can drive changes in the high-temperature materials industry, leading to shifts in manufacturing processes, supply chain dynamics, and product development.

Emerging applications and markets?

Emerging applications and markets for high-temperature materials are being driven by technological advancements and evolving industry needs. Some of the emerging applications and markets for high-temperature materials include:

Additive manufacturing

Additive manufacturing, also known as 3D printing, is an emerging application for hightemperature materials. 3D printing with high-temperature materials can create parts and components with complex geometries and high-temperature resistance, which are difficult or impossible to produce using traditional manufacturing methods.

Renewable energy

The renewable energy market, including wind and solar power, is an emerging market for high-temperature materials. Materials for this market are used in components such as turbine blades, solar concentrators, and heat exchangers, where they must withstand high temperatures and corrosive environments.

Electronics

High-temperature materials are also being used in electronics applications, such as in high-temperature sensors, power electronics, and electronic packaging. These materials enable electronic devices to operate in high-temperature environments without degradation.

Space

The space market is an emerging market for high-temperature materials, as materials that can withstand high temperatures and harsh environments are critical for space exploration and travel. These materials are used in thermal protection systems, propulsion systems, and spacecraft structures.

Competitive materials

High-temperature materials consist of families of monolithic and reinforced systems. Examples of reinforced (composite) systems include:

Ceramic matrix composites (CMCs)

These composites are made by reinforcing a ceramic matrix material such as silicon carbide with ceramic fibers. CMCs have excellent high-temperature properties, including high strength, thermal stability, and resistance to thermal shock. They are used in applications such as gas turbine engines, aerospace, and energy.

Metal matrix composites (MMCs)

These composites are made by reinforcing a metal matrix material such as aluminum or titanium with metal fibers. MMCs have high strength, stiffness, and thermal stability, making them suitable for high-temperature applications in aerospace and automotive.

Polymer matrix composites (PMCs)

These composites are made by reinforcing a polymer matrix material such as epoxy or phenolic resin with a fiber, usually glass or carbon. PMCs have good high-temperature properties and are used in applications such as aerospace, defense, and industrial.

Hybrid composites

These composites are made by combining two or more types of reinforcement materials or matrix materials, such as carbon fiber-reinforced ceramic matrix composites. Hybrid composites can offer a combination of high-temperature properties and other desirable characteristics, such as improved toughness or wear resistance.

Non-composite materials that are competitive against high-temperature composites include:

Refractory metals

Refractory metals such as tungsten, molybdenum, and tantalum have high melting points and excellent high-temperature properties, making them suitable for high-temperature applications in aerospace and nuclear markets.

Ceramics

Ceramics such as silicon carbide, alumina, and zirconia have excellent high-temperature properties, including high strength, hardness, and thermal stability. They are used in a wide range of markets, including aerospace, defense, and energy.

Intermetallics

Intermetallics such as titanium aluminides and nickel aluminides have high strength and good high-temperature properties, making them suitable for use in aerospace and automotive applications.

Single crystals

Single crystal materials such as nickel-based superalloys have excellent high-temperature properties, including high strength, creep resistance, and fatigue resistance. They are used in gas turbine engines and other high-temperature applications.

In summary, non-composite materials such as refractory metals, ceramics, intermetallics, single crystals, and metal matrix composites offer excellent high-temperature properties and can be competitive with high temperature composites in certain applications. The choice of material depends on the specific requirements of the application, including temperature range, mechanical properties, and cost.

TC 4

Recycling of Composites

Spencer A. Hawkins, Ph.D.
Composites R&D Engineer
Texas Research Institute Austin Inc.
Chair

Zhe Qiang, Ph.D.
Assistant Professor
University of Southern Mississippi
Vice Chair

Matt Jacobs
Engineer Planning Analyst
Northrup Grumman
Secretary

Davis Tran
Boeing

John Misasi
Western Washington University

sampe
North America

TC 4

RECYCLING OF COMPOSITES

Executive Summary

- Multiple pathways exist to recycle carbon fiber composites. Methods include solvolysis, vitrimers (reprocessable materials), pyrolysis, electromagnetic fields, superheated and pressurized water.
- Growth is driven in part by strong government support in some areas of the world (Europe), increasing consumer demand for recycled carbon fibers (rCFs) and other sustainability metrics, and general public support for sustainable technologies.
- Technologies can be affordable to implement, with startup and legacy companies working to make recycling more attractive. However, not all recycling technologies are fully matured.
- Thermoset polymers are especially difficult to process and resin is usually unrecoverable.
- Recycling applications often require short chopped-strand fibers for easy processing and recovery, which limits their useful post-consumer applications.
- As price of virgin fibers decreases, cost per pound of rCFs may also decrease.
- Significant opportunity exists to research recycling of composite in the United States.
- There are relatively few academic labs dedicated to investigating/developing commercially viable methods for composite recycling in the US, delaying innovation and putting the onus on industry, which is beholden to cost and shareholder interest.

Continued >

- There should be more crossover between US/European/Asian labs, companies, and governments as world becomes more connected and concerned about sustainability/recycling.
- Development of national and international standards for recycled materials (fiber, resin, other constituents) are forthcoming from NIST, ISO, and other regulatory bodies. These reports will answer important questions regarding applications and fiber performance.
- Industry perception of degraded mechanical properties of rCFs appears to be pervasive.
- The ultimate factor that prohibits widespread recycling of composites is cost-efficiency compared to virgin fibers and resins, while maintaining similar performance and assuming short fiber length issue can be overcome.
- If cost is low enough without too much of a performance knockdown, recycling and sustainability efforts will be achieved.

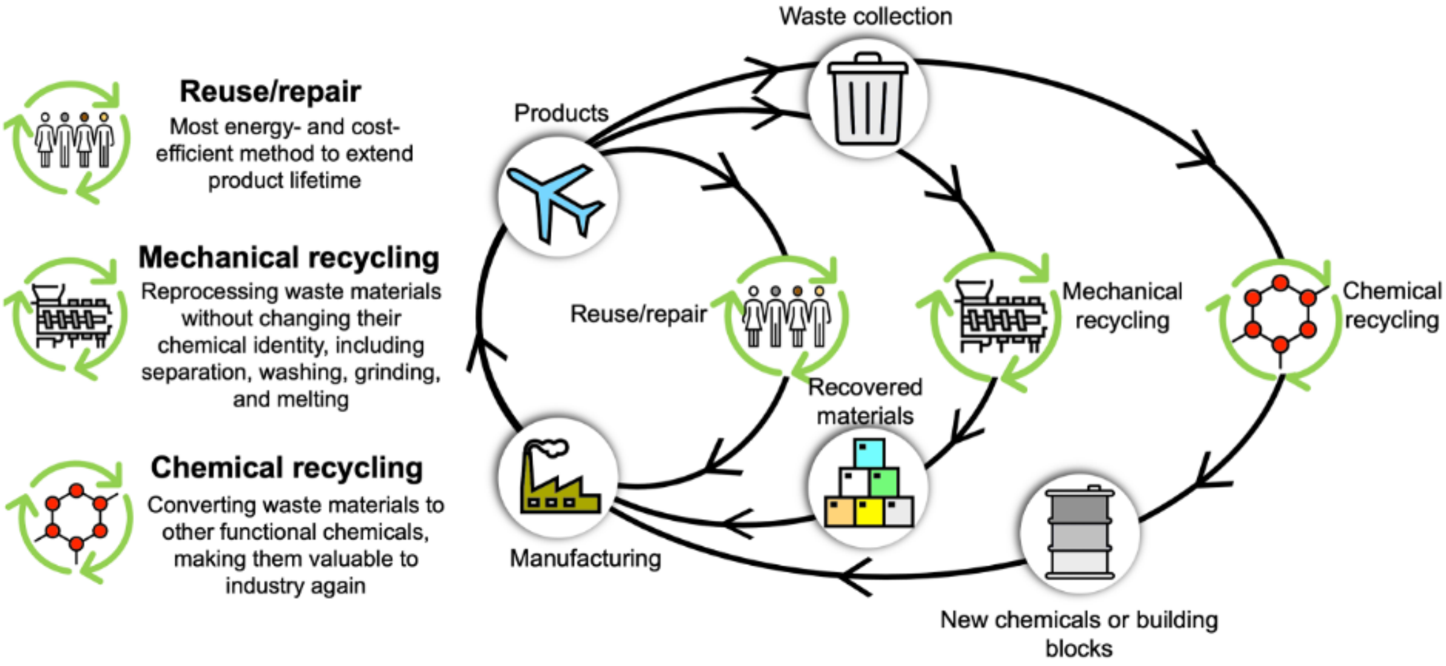


Fig. 1. A scheme demonstrating the opportunities of composite recycling for developing a circular economy.

Sustainability and Recycling of Composites

Materials form the foundation of how we live our lives and consumers and OEMs are increasingly demanding products and services that conform to a higher standard in terms of decarbonization, waste reduction, energy efficiency and more. From the clothes that we wear, the cars that we drive, the packaging that our products are shipped in, to the airplanes that connect us, sustainability is interwoven into every aspect of our lives.

Sustainability (reclaim, recycle, repurpose, reuse) will become the norm in the composites industry, as it has for legacy materials (aluminum, steel, glass, wood). Furthermore, there will be increasing regulatory pressure pushed by consumers, companies, industries, and governments to drive sustainability within the composites industry. This is currently being worked on in the U.S. by the Securities and Exchange Commission (SEC), whereby quantitative and qualitative climate-related risks and opportunities will need to be disclosed by individual companies. The reporting metrics will be tailored by industry and publicly traded companies will likely pass their requirements down through their supply chains.

In the European Union (EU), the Corporate Sustainability Reporting Directive, which supports the European Green Deal, is a set of policies designed to combat climate change. All companies that are listed for EU-regulated markets will need to disclose sustainability related information (business models, strategy, and supply chains) that will allow investors to perform a one-to-one comparison of companies. This new norm will drastically change how businesses approach sustainability efforts and share them with their shareholders.

Polymer composites, both thermoset and thermoplastic, are widely employed in a variety of industries, including aerospace, automotive, marine, recreation, and renewable energy. While composite materials are often designed to be durable, strong, and long-lasting, their end of life presents several challenges, particularly associated with how they can be reused and recycled. Waste management solutions are needed to reduce their impact on the environment and recovery and reuse standards should be established. This will lead to lower carbon emissions and energy consumption. Additionally, several government policies and initiatives have been established to promote or mandate recycling of products at end of life (EOL). Ideally, composites recycling will become an integral part of the global effort to transition the entire industry to a circular economy, thereby achieving a carbon-neutral society.

The feedstock of waste composites is typically from post-industrial and post-consumer products, primary structures (aerospace and wind energy), and secondary structures (automotive) via manufacturing scrap and after reaching EOL when they are no longer repairable or useful. Recycling of this waste can be performed mechanically, thermally, or chemically to yield milled, chopped, or pelletized fibers that can be further processed into sheet molding compound for thermoforming. Mechanical recycling processes waste materials into new products by breaking them down without changing their chemical composition. Thermal recycling degrades the resin at high temperatures and can potentially degrade the fibers as well. Chemical recycling uses solvent (with and without temperature and pressure) to remove the resin and reclaim the fiber. A noncomprehensive summary of the companies involved in each recycling area are below.

Mechanical recycling

- BCA Industries (shredding equipment)
- Isodan Engineering ApS (mobile wind blade size reduction)
- Veolia North America (wind blade recycling)
- Global Fiberglass Solutions (all fiberglass mechanical recycling and WPC compounding)
- Van Wees (prepreg manufacturing and recycling equipment)

Thermal recycling

- Reciclalia (mechanical/pyrolytic recycling targeting large parts)
- Carbon Conversions (pyrolytic recycling of CFRP)
- Fuji Design (CFRP pyrolysis)
- Carbon Rivers (pyrolysis of all composites, focus on GFRP/wind)
- carboNXT/Mitsubishi Chemical Advanced Material (pyrolysis and rCF materials supplier)

Chemical recycling

- Vartega (prepreg recycling via matrix dissolution)
- Shocker (prepreg recycling via matrix dissolution)
- DEECOM (supercritical water equipment, resin and fiber reclamation)
- Adherent Technologies Inc. (combination pyrolysis/chemical recycling)

Recyclable thermosets

- Swancor (recyclable thermoset epoxy)
- Mallinda (imine vitrimers)
- CIDETEC (epoxy vitrimer based on disulfide)
- Aditya Birla (recyclamine pH-responsive amine curative)

Resale of recycled prepregs and fibers

- R&M International (fibers from Shocker)
- CRTC/Swiftnet (out-of-spec aerospace prepreg)

Others

- Procotex (purchased ELG, sells several different recycled fibers)
- Gen2Carbon (rCF from pyrolysis, nonwoven rCF mats and comingled nonwoven rCF with thermoplastic)
- Mitsubishi Chemicals Advanced Materials (MCAM, sells rCF mats with comingled thermoplastic fibers for compression molding).

For mechanical recycling of uncured composites, sorting of prepreg scrap is still a challenge, as is effectively removing the backing paper. Furthermore, tacky prepreg has proven to be difficult to cut and results in clumping of cuts and chips. These lead to non-uniform fiber orientations upon remanufacturing (some alignment is possible, but not to the degree of unidirectional tape). Finally, the pressures required for compression molding consolidation produce excessive resin flow in parts. The main benefit with mechanical recycling, however, is that none of the materials experience any degradation aside from reduction in fiber length. Some of the benefits of using recycled cured composites in downstream products include the replacement of lower performance fillers and enhancement of low-performance matrix material properties. However, there are several challenges to overcome before this becomes more widespread. Recycled materials need to be classified effectively and efficiently during the process, but a broad particle size distribution and the need for multiple cycles make this difficult. Moreover, broad particle size distribution and chemical makeup leads to broad property ranges. These will also affect matrix adhesion, which will effectively limit the markets and applications available for a given type and size of recycled fiber.

Chemical recycling yields rCFs with minimal impact to properties that is dependent on the recycling conditions. Also, matrix resin can be recovered as dissolved prepolymer (prepreg) or depolymerized chemical mixtures (cured) that can be separated and reused as new chemicals. Unfortunately, this process requires several factors to be optimized: solvent, catalyst, temperature, pressure, purification, feedstock concentration, etc. Furthermore, thermoset matrices are very solvent/chemically resistant by nature and maintaining fiber lengths of more than 2 inches has proven to be a challenge. The state of chemical recycling of uncured composites is as follows: Several commercial processes have been developed that remove uncured matrix from fibers (mostly CFRC prepreg) resulting in little to no fiber damage (virgin-like properties). Estimates put the energy use of these processes at around 95% less than virgin fiber production, while costing around 50% less. For cured composites, however, no commercial processes exist for scaled recycling. Several processes have been developed at the pilot scale, and lab scale recycling has demonstrated rCF properties of 90-100% of virgin properties. Finally, lab scale processes allow for relatively easy reuse of depolymerized matrix resin.

Thermal recycling pyrolyzes the uncured or cured resin and may yield rCFs with compromised properties — at least that is the potential worry among potential consumers. More demonstrations are needed to show the value of rCFs and minimize concern about potential knockdowns in performance. Finally, ongoing development and innovation in fiber forms (nonwovens, alignment of discontinuous fibers, etc.) is needed to ensure wide market adoption.

Mechanical recycling is typically preferred for single-stream thermoplastic waste, while chemical and thermal recycling is preferred for multiple-stream and non-processable (e.g., thermoset) materials. It is important to note that composites are inherently heterogeneous, containing several different constituents (reinforcing fillers, polymers, fibers, etc.) and this is what makes recycling of composites an enigma without an easy, one-size-fits-all solution.

In summary, mechanical recycling is most mature recycling technology that also consumes the smallest amount of energy compared to the other methods. One outstanding issue, however, is the adoption of rCFs by consumers. Thermal recycling requires further development and innovation of fiber forms to drive demand for rCFs, while also demonstrating a minimal property knockdown compared to virgin fibers. Chemical recycling will need additional funding and collaboration from industry to demonstrate the scalability of current processes. Furthermore, recycled matrix material properties need to be sufficiently characterized for their eventual reuse in the material supply chain. Finally, more case studies need to be performed with recyclable thermosets to demonstrate full circularity.

Notably, pressolysis is an emerging technology for recycling high-performance fibers from composites, through pressure-enabled reduction of matrix resin, established by DEECOM in the U. K. By combining compression and decompression cycles, a key advantage of this pressure-based recycling method is that both fibers and uncured resins (without an added curing step) can be recovered, which is uniquely suited for addressing composite waste. Additionally, pressolysis allows for high-yield recovery of continuous fibers at high quality, which can be directly reused since they are free from polymeric residue. As an example, the recovered, high-quality fibers can be directly upcycled through resizing. This method results in extremely clean fibers with comparable properties to their virgin counterparts.

Sustainability drivers for rCF

Decarbonization is a central topic that is driving sustainability strategies in several different areas: natural fibers, bio-based precursors and resins, hydrogen economy, fuel efficiency, electric vehicles, renewable energy, waste reduction, recycling/reuse of materials, and customer/government mandates. Several recent social, political, environmental, and health events have played a role in driving sustainability on a global scale such as COVID, climate change, and supply chain disruptions. Sensitivity has been heightened by the response of governments to the COVID pandemic along with several climate events (wildfires, flooding, drought, heat waves, freezes, etc.). Consumer habits and buying decisions changed to favor companies that are more conscientious with how their products are made and where the materials are sourced from. The attitudes of employees about their employers and work impact have shifted focus toward social impact, inclusivity, and sustainability. Recent surveys among Gen Z suggest that a large majority prefer buying from companies that demonstrate their willingness to protect and improve the environment.

A new ecosystem will be established by policymakers, public authorities, consumers, suppliers, manufacturers, and providers to collaborate on a global scale to ensure corporate social responsibility. Furthermore, sustainability can be achieved by altering how we live our lives: what, how, and the way we eat, move, and power our societies.

With regards to composites, poor manufacturing scrap rates and waste reduction efforts are driving the adoption of sustainable practices (reclaim, recycle, repurpose, reuse). Recycling of CF thermoset composites has only been around for the past 10 years and is still considered to be in its infancy, with several big players and start-ups entering the market and competing for customers. Also, there is no economically competitive advantage in a given supply chain for companies that develop a sustainability strategy. As an industry, we strive for lightweighting of structures without compromising performance or profit. However, end-of-life composite structures along with the increasing demand for CF (that will significantly outpace the available global capacity in the short term) are poised to negatively impact the composites industry in the foreseeable future. Landfilling of uncured CF scrap is becoming prohibitively expensive and will be untenable if governments mandate sustainability metrics for industry. This has emboldened the recycling business case, which has driven the development and maturation of several key technologies.

Unfortunately, best practices for sustainability (reclaim, recycle, repurpose, reuse) are just now being developed by academia, government, and industry coming together to form working groups. There is no low-hanging fruit or cure-all identified and implemented across the industry. Therefore, the effort to adopt sustainability efforts will be incremental, multi-disciplinary, and require the entire market to succeed. The composites recycling market is immature, quickly evolving, and dynamic with regards to available technologies, waste streams, customers, and applications. Finally, an interesting paradox has arisen: As an industry, we have desired highly consolidated, multi-material structures that are inherently strong and durable throughout their lifetimes, but need to be easily broken down into their constituent materials at end-of-life for recycle and reuse.

Emerging applications and markets for sustainably derived and recycled materials

The automotive industry seems like the perfect market for rCFs in terms of potential. They are able to combine lightweighting and good surface finish, both of which are paramount for automotive manufacturing, and are a natural fit for body panels, interior components, and cosmetic structures. Unfortunately, cost and process time continue to be insurmountable obstacles for the industry, but are seen by several key players in the rCF world as mere excuses offered by a risk-averse market. If widescale adoption were to happen, the global supply of rCFs would be quickly consumed and used in targeted programs where they would be the most effective. In general, composites are slowly making headway into the automotive industry for sustainable products (battery boxes for EVs, pressure vessels for hydrogen, leaf springs, and even lift gate systems).

One specific example of adopting rCFs into a niche market is ProDrive Composites (Milton Keynes, U.K.), a manufacturer of advanced lightweight composites for applications ranging from automotive and motorsport to aerospace and defense. An ongoing collaboration with the University of Sheffield Advanced Manufacturing Research Centre (AMRC, Sheffield, U.K.) and Gen 2 Carbon aims to develop its P2T (Primary to Tertiary) process that uses a reactive thermoplastic resin to manufacture recyclable composite components. In this process, a plastic monomer reacts with a catalyst that was previously mixed in the presence of rCFs to cure a laminate out-of-autoclave. The process enables the composite to be used several times (3+) before needing to be recycled, wherein the part will be chopped and remolded into a new part.

An ongoing technical collaboration between Vartega and the Institute for Advanced Composites Manufacturing Innovation (IACMI) is focused on addressing the technical challenge of producing consistent rCF-reinforced thermoplastics for use in vehicle lightweight applications for the automotive industry. The two-year project is advancing toward a robust dataset that contains a full suite of material characterization data, from fiber interface to finished part. EVs and autonomous vehicles may offer additional opportunities for composites to play a significant role. This can also be seen in the eVTOL space within the commercial aerospace industry, where multiple startups are vying to be the first to market and gain significant market share, while driving down cost for consumer transportation.

Outlook for sustainability-focused composites

Common estimates of CF waste from composites production hover around 30%. This valuable material ends up in landfills and most analysts agree that the annual demand for virgin CF will outpace the available production capacity within the next few years unless CF suppliers commit to expanding global production. Dan Pichler and Tony Roberts, at CompositesWorld's 2022 Carbon Fiber Conference, forecast 2027 global carbon fiber demand at 208,000 metric tonnes (MT), with nameplate supply at 235,000 MT. Given a knockdown of 25% between nameplate and actual production, a shortage of carbon fiber appears imminent without expansion of manufacturing capacity.

Commercial suppliers of rCF point to rCFs as a way to bridge this supply gap. However, the technologies to recycle CF, while having existed for several years and capable of producing rCFs with mechanical properties close to virgin CF, are still relatively young and are in the early stages of developing markets and a customer base for their adoption. Confidence in the quality of the rCF properties is inching forward, while questions about cost and availability are being thrust into the minds of potential consumers.

Supply chain security in terms of a consistent waste stream and consumer demand is one of if not the largest challenge for the industry. Andrew Maxey, CEO of Vartega, has said that "the technologies are actually there, and they've existed for quite a while, but the supply chain just hasn't been vetted," at least not to a sufficient degree for widespread adoption by several downstream industries (automotive, recreation/sporting goods, additive manufacturing, etc.). "Without the right pieces coming together you can have the best technology in the world, but you're not going to have material to recycle and you're not going to have any products to put it in."

The aerospace industry is often seen as the premier source of production scrap and EOL material to be used as recyclate, however, many OEMs and fabricators are reluctant to rely on it as a steady supply source for high-volume product lines due to the inconsistencies associated with aircraft manufacturing programs and the relatively long product lives. That doesn't mean that it cannot be done, as seen by Boeing announcing in 2018 that it will supply uncured and cured CF waste to Gen 2 Carbon (ELG Carbon at the time). This formal agreement is the first of its kind between a major aircraft OEM and a CF recycler.

Sustainability isn't the only argument for using rCFs — reduced cost is one of the main benefits. Gen 2 Carbon's rCF costs around 40% less than virgin CF, and other commercial suppliers offer rCF that is 20-40% less than virgin CF. Discontinuous rCFs, which are the primary product from commercial CF recyclers, are a more sustainable and economical alternative to virgin CFs, especially in industries where chopped CFs are routinely used. The common thought among CF recyclers used to be that rCFs should be downcycled into lower-performance products. However, this has recently shifted towards finding applications that benefit from other properties associated with rCFs, such as drapability and surface finish, both of which are better than virgin CF.

As several industries move towards increased adoption of thermoplastic composites, thermoset composites are seen as less viable to recycle when it comes to closing the loop. Thermoplastic polymers can be melted and reshaped into new forms without the drawbacks associated with thermoset composite recycling (hazardous solvent waste from chemical recycling and high energy use and potential property degradation with pyrolysis). Thermoplastic composites represent an opportunity for manufacturing scrap to be recycled internally and reabsorbed into secondary applications. This makes internal recycling of thermoplastics a natural fit for aerospace OEMs, where traceability is a major concern.

Several major industry leaders representing several aspects of the value chain from material, manufacturing, design, and application (GKN Fokker, Toray Advanced Composites, Cato Composite Innovations, Dutch Thermoplastic Components, and Nido RecyclingTechniek) are involved in the TPC-Cycle project, which aims to reuse production scrap from thermoplastic composites for aerospace and high-volume applications by reducing environmental impact, while retaining mechanical performance at an affordable cost. Cost and life cycle analyses are currently being done to prove that the TPC-Cycle processes are economically beneficial. Further efforts to use thermoplastic composites are driven by the intent to reduce environmental impact through the use of factory waste and a reduction in the number of fasteners used on fuselages, which will save on materials, energy, cost, and overall weight. Thermoplastic composite waste can be commercially viable and reprocessed using low-shear mixing/compression molding.

Additive manufacturing is another market that could be a large adopter of rCFs. ABS filament has been compounded with rCFs by Shocker Composites, while Vartega is advancing polymer feedstocks for powder bed fusion additive manufacturing using its CF recycling technology. They are also developing a process to reinforce thermoplastic powders with rCF for infrared additive systems.

The identification of other markets is a prime directive of the Composite Recycling Technology Center (CRTC) in Port Angels, Wash., U.S. Park benches, high-performance sporting goods, and composite tubing have been identified as potential applications. The CRTC works with material supplied by Toray Composite Materials America and Gen 2 Carbon. Dave Walter, CEO of CRTC, has also identified the construction industry as a potential market. The company developed a construction grade cross-laminated timber (patent pending) that combines thermally modified lumber with rCF. Wood veneer reinforced with rCF has been developed for interior and exterior applications.

Recently, suppliers have indicated that they want to be part of the solution. Prior to 2020, suppliers only wanted to offload their scrap and had no interest in using the recycled material. Now, potential customers are spending significant resources to ensure commercial adoption into their production processes. In order to drive the recycling of composites and use the yielded materials, Detlef Drafz, CEO of Gen 2 Carbon, has rightly pointed out that we should examine the recycling history for legacy materials to guide our industry.

TC 5

Rapid Manufacturing of Composites

John Unser
VP Program/Project Management
Composite Applications Group | Chair

Max Schultes
Chief Technology Officer | RAMPF
Composite Solutions, Inc. | Vice Chair

Philip Barnett, Ph.D.
Energy Science and Engineering
University of Tennessee Knoxville
Member

Susan Ruth
Member

sampe
North America

TC 5

RAPID MANUFACTURING OF COMPOSITES

Executive Summary

This report describes the SAMPE Technical Committee's efforts to assess the attributes and state of the industry with respect to rapid manufacturing, specifically of composites. Rapid manufacturing has different meanings for different people. In this report, rapid manufacturing has two simple definitions: make things fast and concept to production fast. The goal is to promote awareness of the more recent technologies that fall under these definitions.

At a high level, organizations that pursue "rapid manufacturing" are generally interested in attaining an economic benefit, generally reduced timeline and/or reduced cost (i.e., significant efficiencies). In addition, the strategies for "rapid" also are influenced by the socio-economic requirements (i.e., carbon emissions reductions, new forms of mobility, new applications, reuse/recyclability) as well as the need for rapid manufacturing to achieve the throughput required by users, including the restocking of products and components and the replacement of attritable systems and components.

Both of the above mentioned needs for rapid manufacturing are important to review and evaluate in terms of the time and cost requirements to take a solution from concept to finished product. The need for rapid manufacturing in order to rebuild depleted stockpiles can also be reviewed and evaluated with a focus on just the attainable manufacturing rates and takt times.

In a less general scope, the ability to manufacture components — either start-to-finish including development and qualification, or at a high rate of a legacy, mature product — can be a key differentiator for a business looking for competitive advantage.

In either case, this report will describe contributors to “rapid” including processes, associated materials, and consumables, equipment and infrastructure. Each process will also be classified in terms of its size and complexity, relative cost (capital expenditure, non-recurring and recurring), typical quality, and performance and rate capability. While many of these processes may be highly part-dependent, a precise quantitative evaluation may not be possible and in these cases a more qualitative, relative classification will be used.

While the dominant efforts for “rapid” are related to the process, some of efforts are related to the materials used for feedstock for the process. This document describes some of the production methods and the attributes that are defined by the production method. Some of the processes are mature for resins and are separate from the derivations of these basic processes.

There is also a section on the materials related to “rapid.” The initial objective is to compile a reference resource for those looking for a “rapid manufacturing” method while providing enough information for the reader to make an educated decision of which approaches may be suitable candidates for a problem at hand.

Approaches to Rapid

Prototypes and limited runs: The ability to rapidly and efficiently develop, evaluate, and iterate prototypes as part of the design process, resulting in a better end product, with a reduced time to market.

3D printing, in all of its forms, is a significant contributor to this form of rapid. For other processes useful to the rapid infrastructure, they must be affordable, either processes with a low-cost infrastructure (equipment and tooling) and/or an infrastructure that is easily shared across multiple products/product lines (e.g., presses to produce flat stock).

Rapid production” for minimum cycle time: The ability to create many parts with a short cycle (nominally seconds to a few minutes). Typically, the goal is either reduced cost/schedule and/or the ability to make large numbers of parts quickly.

Injection molding is one of the processes in this category. For the processes in this category, the methods to achieve minimal cycle time depend on the type of resin being used. For thermoplastics, the time to heat the resin to melting point, form it in a mold, followed by the time to cool to room temperature, dominate the cycle time. The specific equipment to be used is important to overall cycle time. For thermosets, the cure profile (time/temperature) dominates the cycle time.

For continuous fiber-reinforced composites, there is a sub-category for high performance. High performance, in this context, is about achieving near-theoretical capability consistently for the parameter of interest (often strength or stiffness). Though the cycle time for manufacture of high-performance composites is usually not low, any reduction of cycle time results in reduced cost per unit. In addition, repeatability and consistency of component performance is key.

Early composites were of this type, with the initial process flow of prepregging fabric, followed by cutting and laying the prepreg in layers on a one-sided tool, then vacuum bagging the tool and curing in an autoclave. A number of variations of materials, equipment and processes have been developed to reduce the timeline and cost, e.g., out-of-autoclave processes.

Descriptions of processes:

When describing processes, the evolving state of the industry means that the terminology is evolving also. The table below summarizes the processes included in this document and is followed by descriptions of each process. First are the general processes. The processes that are modifications of the baseline processes and/or are trademarked, are identified separately.

			COST		
PROCESS	PART SIZE	VOLUME	CAPITAL INVESTMENT	NONRECURRING COST	RECURRING COST
Injection molding	Very small to large	>1,000	High	Medium	Low
Compression molding	Small to large	>1,000	High	Medium	Low
Organosheet compression molding	Medium	100-1000	High	Low	Medium
Autoclave	Medium - Large	<10	High	High	High
Resin transfer molding (RTM)	Medium	10-100	Medium		
Light resin transfer molding (LRTM)	Large	<10	Low		
Vacuum-assisted resin transfer molding (VARTM)	Medium	10-100			
Medium					
Vacuum-assisted resin infusion (VARI)	Large	<10	Low		
EnableX™					
RapidClave^{R}	Medium	10-100	Medium	Medium	Medium
CF3D	Medium	<10	Medium	Low	High
Frontal polymerization	Large	<10	Low	Low	Medium
Vitrimers	Medium	<10	Medium	Medium	Medium
Additive fusion technology	Small		Low	Low	Low

Modified processes:

Process	Foundation	Summary
EnableX™	Compression molding	Modifies a process that is high speed and combines selective reinforcement; rapid is based on part consolidation
RapidClave™	Autoclave	Improves the cure rate over a normal autoclave process via integrated sensors and tooling to produce high-performance components and part consolidation
Continuous Fiber 4D printing (CF3D)	Additive process	More agile than rapid (relatively slow, but huge design space and ability to rapidly iterate); currently using very expensive T1100 fibers to maximize performance
Additive Fusion Technology (AFT)	Hybrid	This is a process that hybridizes additive manufacturing with compression molding

General Processes

Injection molding

This process involves conveying a low-viscosity thermoplastic or thermoset resin system through a small orifice into a mold. A thermoplastic material goes from a hot barrel to chilled mold and a thermoset material goes from a cooler barrel (~100°F) to a heated mold (~300°F).

Injection molding capital costs can be quite high at the front end of the design process as a precision-machined, matched-metal tool is required to manufacture the parts. The initial capital costs necessitate the need for a large number of parts over the life of the program to amoritize the costs.

The process allows a large number of parts to be produced in a short period of time. Cycle times are usually measured in seconds. The cons associated with the process are that the parts typically have low strength relative to a fiber-reinforced part. The process does allow the use of reinforcements like chopped glass or fiber, but the conveyance of the material through the small gate degrades the glass, weakening the strength of the resulting part. Very complex designs are feasible with injection molding.

Compression molding

This process, as with compression molding, can require large up-front capital costs for a matched metal mold. This process, which is most prevalent with thermoset materials, requires the placement of a molding compound in the center of a heated tool (~300°F). The mold is closed under high pressure (150 – 1000 psi) at temperature. Typical cycle times range from 60 – 300 seconds.

This process is suitable for a large number of parts and is scalable for large, heavy parts. There is little reinforcement degradation, but a discontinuous reinforcement is typically required as the molding compound and reinforcement must flow in the tool to make a complete part.

Organosheet compression molding is in this category, described as compression molding of discontinuous or continuous preconsolidated carbon fiber-reinforced thermoplastics.

Resin transfer molding (RTM)

In this process, dry fibers (usually fabric) are placed into a hard tool. The tool is subsequently closed (top half is also hard) and heated and a vacuum is pulled. Resin is injected into the mold to infuse the fibers. This process is somewhat of a hybrid of the closed mold of injection molding and out-of-autoclave consolidation of fiber preforms. Injection pressures of the RTM process 1-5 bar; temperature is typically less than 100 °C.

Light resin transfer molding (LRTM)

In this process, the lower mold half is rigid and the upper half is semi-flexible. The process uses a vacuum pump to guarantee the clamping between the upper and lower mold halves. A vacuum pump is used to draw the resin from its tank to the mold cavity.

Vacuum-assisted resin transfer molding (VARTM)

This process is a variant of the RTM process and differs with the addition of a vacuum pump. The vacuum pump is connected to vents while the injection machine is connected to inlet gates. This option enhances the quality of the part by evacuating air bubbles from the mold cavity and increasing the pressure gradient.

Vacuum-assisted resin infusion (VARI)

In this process, the upper mold of the RTM process is replaced with a vacuum bag. Instead of “pushing” the resin via injection, a vacuum pump is used to suck the resin from its tank in order to impregnate the fabric preform. The pressure gradient between the inlet and outlet is less than 1 atmosphere.

Additive manufacturing

Although additive manufacturing is not a new technology, it is rapidly evolving. There are several general and modified AM processes that use feedstocks of metals, neat plastics, and reinforced plastics. For this report they are treated as a single general family characterized by the sequential layering of material into a final configuration directly from a design file. Though this process is not intrinsically rapid, it has spawned two important areas of technical focus. One is rapid prototyping, with many more iterations possible during the product development cycle. The second is flexible manufacturing capability at a low capital investment.

Modifications and Improvements for Rapid

EnableX™

Norplex/Micarta’s EnableX™ molding system is one that uses both woven (prepreg) and discontinuous (molding compound) reinforcements simultaneously in a compression molding process. The woven material is placed at a relatively flat portion of the part while the molding compound is allowed to flow over and around the woven reinforcement to yield sections with more complex geometry.

This process allows one to make parts with thin sections with low geometric complexity by utilizing the superior strength of the woven reinforcement while providing complex geometric sections with discontinuous reinforcement. The resin system of the prepreg and molding compound must be of similar chemistry (currently phenolic or vinyl ester are available) to ensure that the materials co-cure simultaneously, resulting in a chemical bond and not a mechanical bond.

RapidClave®

RapidClave® is an out-of-autoclave consolidation and cure system developed by Globe Machine that emulates or improves upon autoclave process conditions while demonstrating faster heating and cooling rates through the implementation of evolutionary tooling, thermal management systems, and application-specific machine configurations. The technology has evolved from mid-volume automotive part production to include lower volumes of higher part/sku counts for aerostructure and other applications. Globe’s RapidClave® process offers integrated direct tool heating/cooling, bag-side composite heating/cooling options, vacuum, thermocouple/RTD, and automated tool and material handling.

Continuous Fiber 3D printing (CF3D)

The CF3D process is an additive manufacturing technique in which dry fiber tows are pulled through a liquid resin bath and then extruded through a nozzle and compacted before undergoing a snap-cure. Developed by Continuous Composites, this technology relies on photocurable acrylic thermoset and UV-curable epoxy thermoset resins to print complex geometries with fiber volume fractions in the range of 40-50%[5]. The rapid curing allows for the printing of rigid structures that hold their shape during a free-standing oven post-cure, resulting in composites with high mechanical strength and stiffness comparable to epoxy prepregs. Currently, printing of composites relies on layer-by-layer deposition of single tows, resulting in relatively slow processing but highly complex geometries and the ability to rapidly iterate design changes. Scaling such a system to higher deposition rates may aid in material throughput but will reduce the allowable design intricacy as each print road becomes larger.

Addition Fusion Technology (AFT)

Additive Fusion Technology (AFT) is a hybrid process developed by 9T Labs for smaller, complex, highly structural parts traditionally made of metals. AFT uses a 3D printer (Build Module) to generate highly tailored 2D preforms with industrial thermoplastic prepreg tapes and chopped fiber-filled thermoplastic filaments. These preforms are then molded/co-consolidated in a compression molding step, complete with necessary metal inserts, BMC, organosheets, injection granulate, etc. for high-quality parts at production volumes (up to 100,000 parts/year). Fibrify software is part of the solution that performs design optimization, generates G-code, and creates digital thread/traceability for parts throughout the full process.

Resin Developments to Improve Rapid

Frontal polymerization

Frontal polymerization is a method of rapidly curing a thermosetting resin by initiating cure and using the heat of polymerization to sustain the reaction, resulting in significant energy savings relative to traditional autoclave cure cycles that last several hours and must be continuously heated. The cure front can be initiated using either thermal or photoinitiation (or a combination of the two), resulting in a domino effect in which the local exotherm drives the reaction to self-propagate into the bulk material[3]. Woven carbon fiber reinforced polydicyclopentadiene composites of 900 cm2 surface area (12 plies thick) containing roughly 50% fiber volume fraction have been manufactured using frontal polymerization in less than 5 minutes by supplying electrical current to embedded resistive wires to initiate the front[4]. UV photoinitiation may also be used to generate a front but requires the addition of a thermal initiator when reinforced with carbon fibers that prevent penetration of the light into the part. In such cases, a UV initiator creates a thermal front that is then enhanced as the thermal initiator reacts. This process is currently in the research and development stage – as such, the scalability is not yet known.

Snap-cure or cure-on-demand epoxy

Snap-curing epoxies are thermosets specially formulated for rapid curing in a heated mold. These epoxies are typically used in compression molding processes including prepreg molding, platelet compounds (also referred to as forged composites), and wet compression. The resins typically cure in less than 5 minutes with mechanical properties comparable to traditional structural epoxies. For example, the Dow Vorafuse P6300 is designed to cure in 2 minutes at 150 °C for an overall cycle time of 3 minutes, allowing for up to 100,000 parts per year per tool on RTM processes[6] and up to 300,000 parts per year per tool using wet compression[7]. Solvay has developed SolvaLite 730, a thermoset prepreg resin capable of curing in 60 seconds to achieve high volume (150,000 vehicles per year) manufacturing using out-of-autoclave processes[6]. These materials allow for the manufacture of high-performance parts that can yield significant weight savings over traditional automotive composites and metals.

Vitrimers

Vitrimers are a class of thermosets that offer many of the benefits of thermoplastics (reformability, high toughness, recyclability) and traditional thermosets (high stiffness, chemical stability). Vitrimers, also known as covalently adaptive networks, undergo dynamic covalent bond exchange when heated above their vitrification temperature. This bond exchange may be either dissociative, resulting in crosslink breakage and loss of network integrity until reformation upon cooling, or associative, in which the crosslink density is constant and bonds simply switch from one functional site to another[8]. In their uncured state, epoxy vitrimer composites may be processed using wet compression, pultrusion[9], and powder infusion[10]. The cured parts can then be stamp-formed or recycled through a grinding process[11]. Some vitrimers have been commercialized, but scalability is uncertain. The state-of-the-art requires long initial cure times to form the crosslinked network, but then short processing times to reform the resulting composites, showing promise for high-rate manufacturing.

Future Opportunities

Other fabrication techniques that potentially contribute to rapid manufacturing have been identified, but the details of how they support the rapid manufacturing approach are proposed for future work.

- Braided preforms
- COATS: Tailored fiber placement; dry fiber preforms
- Long-fiber Infusion, high-pressure RTM
- Molded Fiber Glass–PRIME (Prepositioned Reinforcement Ensuring Manufacturing Excellence)
- Long Fiber Injection
- Incremental Sheet Forming
- Wet Press Molding
- Rapid Cure Resins
- Relaxation Compression Resin Transfer Molding under Magnetic Field new variant of Liquid Composite Molding

Summary

This document addresses developments identified via the technical committee members' expertise. They illustrate approaches to creating or modifying processes and materials to accelerate composites manufacturing. In this document the maturity of the process, the industries where they are used (e.g., aerospace, automotive, marine, etc.) and the types of shapes that can be made (e.g., flat, simple contour, complex contour) is information that is being collected but is not included.

---

1. Barnett PR, Gilbert CL, Penumadu D. "Repurposed/recycled discontinuous carbon fiber organosheet development and composite properties". *Composites Part C: Open Access*; 4. Epub ahead of print 1 March 2021. DOI: 10.1016/j.jcomc.2020.100092.
2. Cetin M, Thienel M. "Large-series Production of Thermoplastic Door Module Carriers". *Lightweight Design worldwide* 2019; 12: 12–17.
3. Li Q, Shen HX, Liu C, et al. "Advances in frontal polymerization strategy: From fundamentals to applications". *Progress in Polymer Science* 2022; 127: 101514.
4. Robertson ID, Yourdkhani M, Centellas PJ, et al. "Rapid energy-efficient manufacturing of polymers and composites via frontal polymerization". *Nature* 2018; 557: 223–227.
5. Baur JW, Abbott AC, Barnett PR, et al. "Mechanical properties of additively printed, UV cured, continuous fiber unidirectional composites for multifunctional applications". *Journal of Composite Materials* 2022; 0: 1–18.
6. Holmes M. "High volume composites for the automotive challenge". *Reinforced Plastics* 2017; 61: 294–298.
7. Bank DH, James A, Belli S, et al. "Composite technology for high volume lightweight manufacturing". *Reinforced Plastics* 2018; 62: 314–317.
8. Denissen W, Winne JM, Du Prez FE. "Vitrimers: Permanent organic networks with glass-like fluidity". *Chemical Science* 2016; 7: 30–38.
9. Aranberri I, Landa M, Elorza E, et al. "Thermoformable and recyclable CFRP pultruded profile manufactured from an epoxy vitrimer". *Polymer Testing* 2021; 93: 106931.
10. Yu L, Zhu C, Sun XH, et al. "Rapid Fabrication of Malleable Fiber Reinforced Composites with Vitrimer Powder". ACS *Applied Polymer Materials* 2019; 1: 2535–2542.
11. de Luzuriaga AR, Martin R, Markaide N, et al. "Epoxy resin with exchangeable diselenide crosslinks to obtain reprocessable, repairable and recyclable fiber-reinforced thermoset composites". *Materials Horizons* 2016; 3: 241–247.

Thermoplastics

David Leach, FSAMPE
Director | Business Development
ATC Manufacturing
Chair

Julieta Barroeta Robles, P.Eng, PMP
Research Officer
National Research Council Canada
Co-Chair

Alberto Lario-Cabello
Manager of European Projects
AITIIP Centro Tecnológico
Secretary

Jean-Philippe Canart
Teijin

Sana Elyas
Orbital Composites (Former)

Lina Ghanbari
University of Southern Mississippi

Waruna Seneviratne &
Jerome Theo
National Institute for
Aviation Research

TC 6
THERMOPLASTICS

Executive Summary

Continuous fiber-reinforced thermoplastic composites have been used in aerospace and other industries for over 30 years. These materials are capable of meeting the industry needs in terms of performance (i.e, toughness, corrosion resistance, flammability and fatigue resistance), sustainability (i.e., lightweight materials that are key to meeting net zero goals), cost-effective (reduced fabrication costs vs. other composite technologies such as thermosets), rate (short cycle times), and circularity (materials and parts are readily recyclable).

This committee performed a technology assessment with regards to thermoplastics. The approach used is illustrated in **Fig. 1.** The thermoplastic materials to be included in this report will be defined and introduced (i.e., semi-crystalline and amorphous materials). Then, the existing methods of processing and fabricating thermoplastic components will be outlined, followed by on methods on how to assemble, repair and inspect these parts. Design and modelling tools are then introduced, providing information on the most recent technology that is applicable to thermoplastic processes. After providing an overall understanding of the technology, market and applications are described, followed by a strength, weakness, opportunities and threats (SWOT) analysis of the materials, technologies and sustainability.

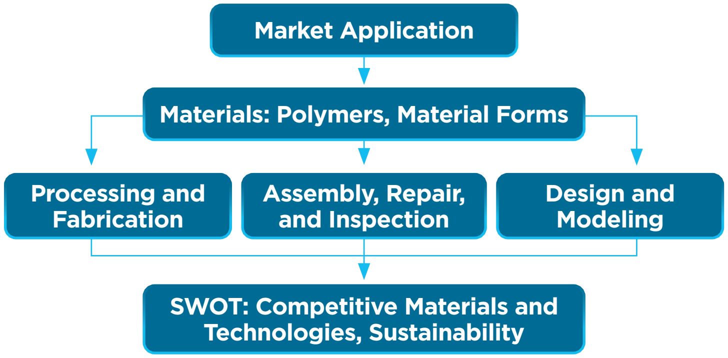


Fig. 1. Strategy and structure of the technology assessment of thermoplastic composites

Applications and markets

The major market areas where thermoplastics are applied include, but are not limited to, aerospace, ground transport, medical, consumer electronics, energy storage, industrial, oil and gas, sports and recreation, and marine. Depending on the market and application case, various material formats (Section 2) and manufacturing processes (Sections 3 and 4) are used in combination to produce end products. Examples of state-of-the-art thermoplastic applications for select market areas are described in further detail in the following subsections.

Aerospace

Thermoplastics are used in the aerospace market for commercial aircraft (single- and twin-aisle), general aviation and recreation (drones and helicopters), military (helicopters, freight aircraft and fighters), urban air mobility (UAM)/advanced air mobility (AAM), and space (spaceframes for spacecraft, satellites, and habitation). All applications use fiber-reinforced thermoplastics in primary structures and combinations of reinforced and neat thermoplastics for secondary structures. See Fig. 2 for examples of state-of-the-art applications.

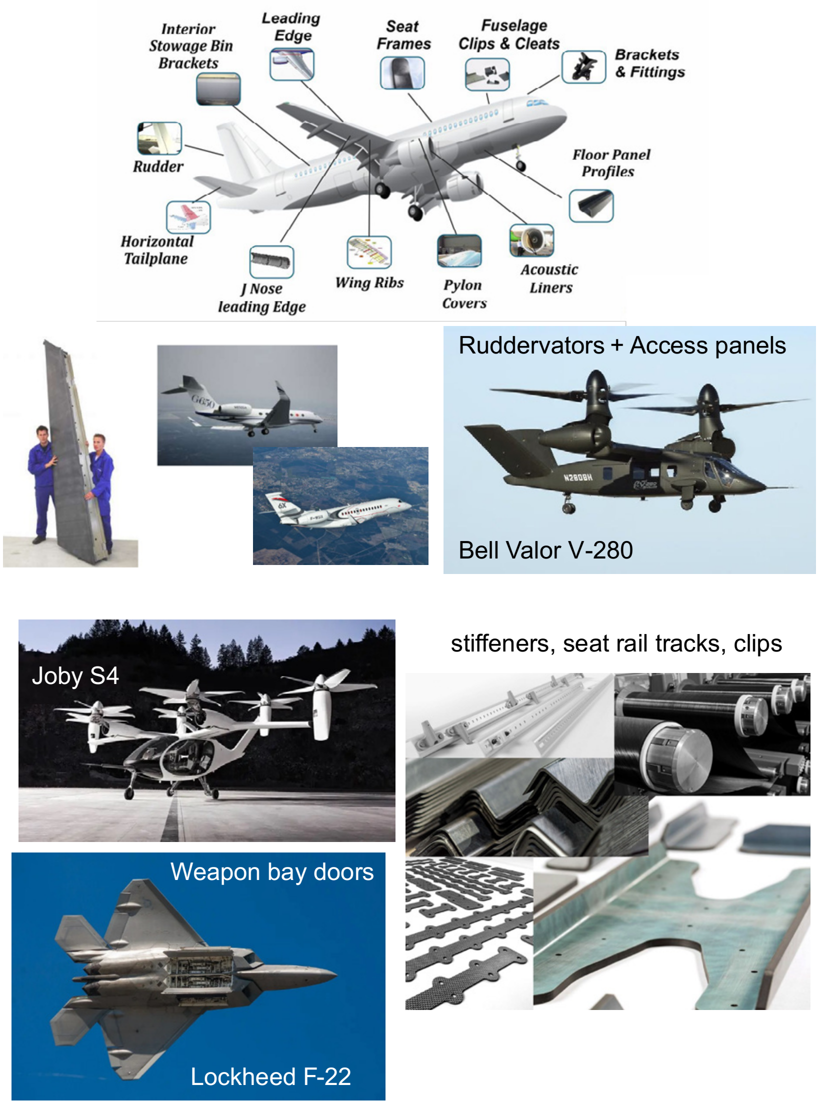


Fig. 2. State-of-the-art thermoplastic applications in aerospace.

Ground Transport

For ground transportation, combinations of neat and reinforced thermoplastics are utilized in passenger and commercial vehicles and in performance/race vehicles. Applications include exterior fairings, interior panels, rims, piping, seat pans, wheel wells, and roof frames (Fig. 3).

Fig. 3. State-of-the-art applications for mobility/automotive.

Oil and Gas

Due to harsh environment requirements such as chemical/solvent, temperature, and wear resistance thermoplastics are used in multiple applications in the oil and gas market. These include risers, flowlines, jumpers, seals, wear rings and plugs for downhole and offshore applications (Fig. 4).

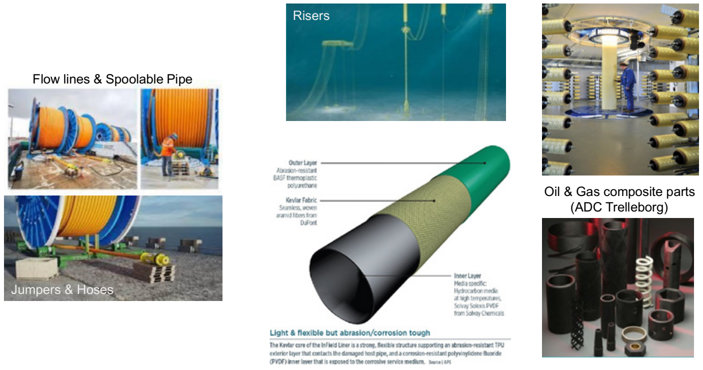


Fig. 4. Oil and gas thermoplastic applications.

Sports and recreation

Thermoplastics are used in a range of sports and recreation applications due to their ability to manufacture parts economically and at high rates, and due to their performance, particularly toughness. Examples of thermoplastic composite applications used in the sports and recreation industry are shown in Fig. 5.

Fig. 5. Sports and recreation applications.

Materials: Polymers and Material Forms

Thermoplastic composites (TPCs) are comprised of a continuous phase of linear polymer chains and a discontinuous phase of long or continuous fiber reinforcement. TPCs are uniquely processed compared to thermoset composites — the heating of the polymer matrix causes the chains to disentangle and flow, allowing for the material to be re-formed and subsequently cooled to demold [1]. Thermoplastic matrices classified by their solid-state morphology (amorphous vs. semi-crystalline) and their temperature performance (commodity, engineering and high-temperature), as shown in Fig. 6.

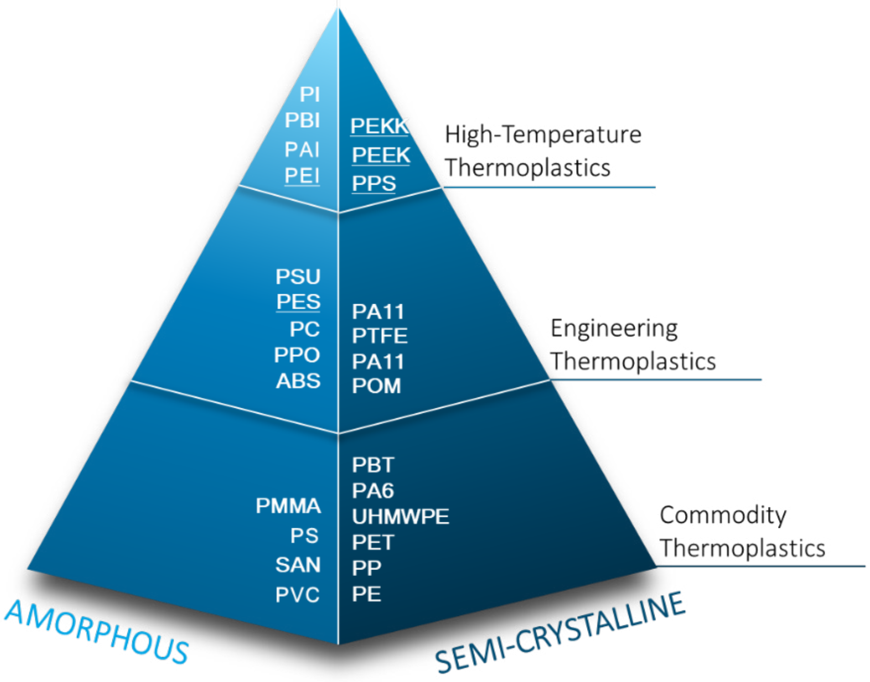


Fig. 6. Summary of thermoplastics — underlined are key matrices for TPCs (adapted from Ref [2]).

Amorphous polymers are traditionally tougher compared to their semi-crystalline counterparts; however, they are less resistant to solvents. On the other hand, the crystal domains present in semi-crystalline thermoplastics are formed due to polymer chains being packed tightly together, leading to improved stiffness and solvent resistance. However, these materials must be processed at very high temperatures to surpass their melting points.

Key properties of thermoplastic composites include their ability to be formed at high rates (heating to the process temperature, reshaped and cooled), self-welding capabilities through melt flow and entanglement across the weld line, and crystallization-driven performance [3–7]. Crystallinity and melt flow/rheology are driven by the process temperature, cooling rate, polymer molecular weight and dispersity, and polymer backbone architecture.

Thermoplastic polymers are combined with reinforcing fibers to form the composite. A range of product forms are available including fully impregnated materials, partially impregnated materials (which combine the polymer in a form such as powder or fiber with the reinforcing fiber) and semi-finished products such as laminates also known as organosheet. Fiber types for thermoplastic composites can be glass, carbon fiber or recycled/naturally sourced fibers. Fiber reinforcements are available in unidirectional, woven or long-strand chopped forms, depending on the application.

A material of particular interest consists of a combination of a high temperature, semi-crystalline thermoplastic prepregged into unidirectional carbon fibers to form unidirectional thermoplastic tapes. These materials offer a short processing time and toughness, without compromising solvent resistance or strength. These materials include polyaryletherketone (PAEK), low-melt PAEK, polyetherketoneketone (PEKK), polyetheretherketone (PEEK) and polyphenylene sulfide (PPS) [8, 9]. Processing temperatures (Tp) for these polymers are in the range 300-400°C; glass transition temperatures (Tg) range from 90°C for PPS to 140-150°C for PAEK polymers.

Processing and Fabrication

Overview

Processing and fabrication of TPCs is significantly different than processing and fabrication of thermoset composites and represents a major opportunity for benefits in cost and rate. Even though process temperatures and viscosities of TPCs are higher than thermosets, TPCs can be processed relatively quickly and can be repossessed multiple times. A general overview of the typical TPC processing flow is shown in Fig. 7.

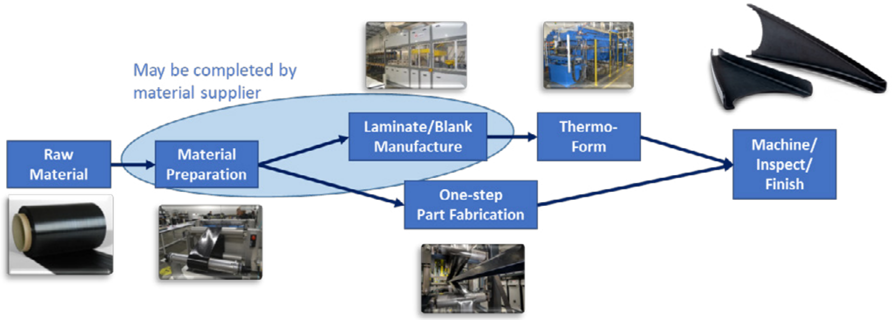


Fig. 7. TPC processing and fabrication (Leach).

Material Preparation – Ply Assembly

TPCs are stable at room temperature but have no tack or drape. Typically, flat lay-ups are prepared and the plies are held together with thermal or ultrasonic tack welds. Plies can be assembled into the required shapes and lay-ups using manual methods, tape placement or automated pick-and-place methods.

Blank Consolidation

In most cases, plies are melted and consolidated into a laminate which is then cut into blanks for subsequent forming. Laminates can be consolidated by a variety of methods including press, vacuum bag/oven or continuous compression molding.

High-Energy Fiber Placement

Fiber placement of narrow prepreg tapes/tows with high-energy laydown can be used to manufacture a consolidated blank or a finished part with full "in-situ" consolidation. Energy is applied using laser, high energy light source, or hot gas. The incoming prepreg and existing substrate layers are melted at the nip point to consolidate the incoming material to the plies which that have already been placed.

An advantage of using fiber placement methods is that tailored blanks or parts can be manufactured, for example including complex curvature, custom shapes, ply build-ups, and steering of the plies. A significant effort has been put into achieving full in-situ consolidation using these methods, but the lay-down rate is limited and there are challenges in managing the thermal history and consequent crystallinity and residual stresses in the part. For this reason, high-speed lay down to manufacture a blank that will be subsequently re-formed or consolidated is the preferred method.

Part forming

Stamp forming is the most common method of forming the finished part. In this process, a consolidated blank (see 3.3 and 3.4) is heated rapidly to the process temperature and transferred to a matched die tool. The tool then closes quickly to form the finished part. The pre-heating is usually done in an infrared oven with an automatic transfer system (e.g., robotic) to transfer the hot blank to the dies quickly. The dies are kept at a constant temperature to ensure fast cycle times. The die temperature must be selected for the particular polymer to ensure that:

- The dies are at a high enough temperature so that the part can be formed
- To prevent the blank from freezing when having immediate contact with the die
- To cool the formed part so it is dimensionally stable when removed.

For semi-crystalline polymers, the temperature and time on the die must be sufficient to achieve the desired level of crystallinity. Cycle times as short as three minutes can be achieved using these rapid forming methods. The plies can also be directly molded using a variety of techniques including compression molding, autoclave and vacuum bag/oven. The process cycles for these methods are generally hours due to the need to heat the tool to the process temperature and cool it to below the Tg of the material.

Profiles (such as ''L', 'C', 'T' and 'H') can be fabricated using a continuous compression molding process with shaped dies. This is a highly automated and cost-effective process to manufacture beams stiffeners and similar profiles.

Assembly, Repair, and Inspection

As there is an increased use of TPCs in industries including aerospace, advanced air mobility (AAM), automotive and transportation in general, there is a need to assemble structures made from these materials. Thermoset polymer matrix composites are typically assembled using mechanical fasteners or structural adhesives. One advantage of TPCs is that they can be melted to promote assembly. While it is possible to use mechanical fastening with TPCs, fasteners pose similar challenges as with thermosets (i.e., added weight, stress concentrations and corrosion). On the other hand, while it is possible to assemble thermoplastic composites using adhesive bonding, this method is challenging due to the lower surface energies of the substrates. This report will not report on mechanical fastening or adhesive bonding of TPCs.

Fusion bonding (i.e., thermoplastic welding) of TPCs works by increasing the temperature of the mating surfaces of the adherends above the Tg or melt temperature (Tm) for amorphous and semi-crystalline materials, respectively (Yousefpour et al., 1994). The main three welding techniques that have been used to assemble thermoplastics are induction, ultrasonic and resistance welding. Induction and resistance rely on a heating element located at the interface between the adherends where heat is generated via induced eddy current, hysteresis losses or Joule heating. Heat is generated via friction with ultrasonic welding.

Thermoplastic welding has also been considered for repair of thermoplastic structures, despite having been primarily introduced as a method for assembly. Thus, it is possible to attain the same level of fidelity as the assembly processes. In a welded repair, a patch is joined to a damaged thermoplastic structure so that it can sustain the required design load level (i.e., ultimate or limit load). Temperature control at the interface is critical to prevent melting the parent structure. In addition, it is required to apply enough pressure to obtain a high-quality welded joint.

For inspection of welded parts, the challenge is to access and record the temperature at the welding interface. Because this is difficult, post-process ultrasonic inspection is mandatory to guarantee the structural integrity of the weld. Conventional ultrasonic methods used in thermoset polymer matrix composites are applicable, however, the signal cannot detect kissing welds nor evaluate the mechanical strength of the welded joints. Process monitoring of the weld must be recorded to certify the part.

Design and Modeling

Stress analysis of TPCs can be performed using established finite element methods, although thermoplastic materials require assessment ogf nonlinear viscoelastic behavior. Specific modeling techniques are required to evaluate the forming, crystallization and thermo-mechanical behavior. During rapid forming, plies often rearrange, resulting in inter- and intra-ply slip that can cause rearrangement of fiber orientations. Local areas may be in tension or compression.

AniForm software [D1] has proven an effective tool to model ply movements and assess fabrication conditions in the virtual domain (Ref D2 and Fig. 8). Thermoplastic composites undergo significant thermo-mechanical changes as they cool down to ambient from their processing temperature (above melting temperatures), solidify and crystallize. This affects the anisotropic coefficient of thermal expansion (CTE), polymer volumetric change, viscosity and viscoelastic behavior in the solid state. Some processes are isothermal while others are highly non-isothermal. These changes affect the dimensional characteristics (spring-in), crystallization and other characteristics. Modeling of these processes is advancing and commercial software packages are now available [D3]. A key aspect of modeling is having suitable data cards with temperature-dependent and anisotropic properties.

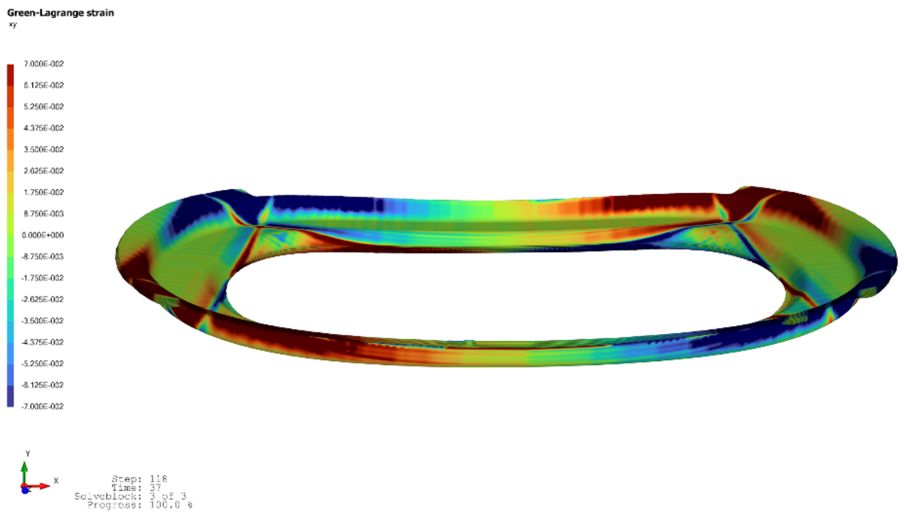


Fig. 8. AniForm analysis of part forming (Ref D2).

SWOT: Competitive materials and technologies, sustainability

Thermoplastic Materials

The opportunities for TPCs rely on the inherent material strengths: reprocessability, a range of properties (toughness, solvent corrosion resistance, low moisture absorption, hot/wet performance and flame, smoke and toxicity (FST)) and suitability for automated, multistep processes capable of improving rates and costs of thermoplastics compared to thermosets and metallics.

In contrast, further investment to generate data, models, design and processing expertise is needed to close the knowledge gap and expand the choice of materials relative to incumbent thermosets and metals. The higher cost and limited number of high-performance reinforcing fibers and polymers hinder the adoption of TPCs and limit their ability to be widely used in high-volume applications. The cost and risk level for TPCs is still higher than for their metallic and thermoset counterparts. Further development of lightweight metallic alloys and next-generation, snap-cure, toughened and low-FST thermosets and epoxies will narrow the gap and reduce the competitive advantage of thermoplastic composites. The greater potential for repairability, recyclability and circular economy solutions is central to TPC's competitive advantage.

Thermoplastic Fabrications Technologies

Layup, consolidation, co-consolidation, joining and post-molding operations enable design complexity, ease of assembly, flexibility, automation and reduced labor for TPCs. These characteristics are ideal for high-volume and high-performance markets where efficiency and assembly rates are critical and for function integration in new and legacy components.

In addition to the gap in skillsets and limited material choice, barriers to TPC adoption include capital investment and supply chain conservatism. Compared to thermosets, flexibility in processing and storage is counterbalanced by the need for pre- and post-processing stages for semi-crystalline TPCs. The knowledge gap includes process control strategies to minimize manufacturing defects and improve design fidelity (volume changes, recrystallization, CTE mismatch, etc.). Out-of-autoclave (OOA) thermoset processes are competitive for current volumes and large structures, and improved processes for metallics compete for high-performance applications. These factors may slow thermoplastic technology adoption. One key advantage of thermoplastic technologies is their potential towards sustainability, moving towards a trend of decreasing the carbon footprint of the destined applications.

SWOT Analysis

The goal of the SWOT analysis is to analyze the competitive position of thermoplastic composites and associated technologies. In addition, peer-reviewed references and review papers are included, reflecting the scientific relevance of the main aspects considered in the analysis. The assumptions to conduct this analysis are summarized in Table 1.

Table 1: Assumptions taken into consideration in the SWOT analysis

Thermoplastic Composite Materials vs. Thermoset and Metal Alternatives	Thermoplastic Process Technologies vs. Competitive Technologies
• High-performance polymers considered (amorphous and semi-crystalline) • Focused on continuous and long fiber-reinforced thermoplastic composites • Short fibers only considered as part of additional multi-step processes (e.g., overmolding)	• Injection molding and welding processes considered as part of multistep processes applied to continuous fiber composites. • Additive manufacturing process is out of scope.

The SWOT analysis is summarized in Table 2 for Materials and Table 3 for Process Technologies.

Table 2: SWOT analysis of thermoplastic materials

SWOT ANALYSIS | THERMOPLASTIC MATERIALS	
STRENGTHS	**WEAKNESSES**
• Enable short cycle processes (e.g., minutes) • Range of properties available: toughness, solvent corrosion resistance, low moisture absorption, hot-wet properties and FST • Enabler of multi-step processing and thicker structures • Low volatile organic compound (VOC) emissions • No shelf life or pot life concerns. • Greater potential for recyclability	• Limited data, modelling, design and processing knowledge/expertise. • Limited choice and higher cost of materials: resins and fiber sizing. • Lower temperature resistance (no crosslinking). • Challenges on adhesion and paint compatibility (semi-crystalline).
OPPORTUNITIES	**THREATS**
• Enable short cycle processes (e.g., minutes) • Range of properties available: toughness, solvent corrosion resistance, low moisture absorption, hot-wet properties and FST • Enabler of multi-step processing and thicker structures • Low volatile organic compound (VOC) emissions • No shelf life or pot life concerns. • Greater potential for recyclability	• Limited data, modelling, design and processing knowledge/expertise. • Limited choice and higher cost of materials: resins and fiber sizing. • Lower temperature resistance (no crosslinking). • Challenges on adhesion and paint compatibility (semi-crystalline).

(Kumar, Phanden and Thakur, 2021), (Barroeta Robles et al., 2022), (Thiruchitrambalam et al., 2020), (Ramon, Sguazzo and Moreira, 2018), (Zhi et al., 2022), (Arquier et al., 2022), (Condé-Wolter et al., 2023), (Ahmed et al., 2006), (van Rijswijk and Bersee, 2007), (Hürkamp et al., 2021), (Joppich, Menrath and Henning, 2017), (Bernatas et al., 2021), (Red, 2014)

Table 3: SWOT analysis of thermoplastic process technologies

SWOT ANALYSIS | THERMOPLASTIC MATERIALS

STRENGTHS	WEAKNESSES
• Enabler of higher design complexity and ease of assembly • Variety of welding processes, post-molding operations and multi-step processes available • Variety of short cycle time processes available • Automated manufacturing for increased cost efficiencies, flexible throughput rates and reduced labor and cycle times	• Possible need for capital investment, skillset and process knowledge development • Pace of technology development defined by material options, design data available and need for qualification is some sectors • Additional processes and equipment may be required to preheat, soften and condition material prior to processing • Non-linear CTE, crystallinity and volume change in laminates may require different control approaches for semicrystalline polymers
OPPORTUNITIES	**THREATS**
• High-volume and high-performance markets, including mass customization (additive manufacturing carbon fiber reinforced composites) • Function integration and in-situ, dustless assembly • Sustainability: low energy consumption, repair and end-of-life/downcycling technologies • Replacement of legacy parts as production rates increase and processes mature	• Incumbent technologies with lower price point for current production volumes • OOA thermoset technologies well suited for large structures • Design and supply chain conservatism (aerospace) may lead to slow adoption of new thermoplastic technologies • New forming and processing technology for lightweight metallic alloys

(Leach, 2022), (Martín et al., 2023), (Proy et al., 2021), (Chen et al., 2021), (Golzar, Sinke and Abouhamzeh, 2022), (Zhang and Xu, 2022), (Li et al., 2022), (Collinson et al., 2022), (van Grootel et al., 2020), (Witik et al., 2012)

Materials: Polymers, material forms

[1] Yao S-S, Jin F-L, Rhee KY, Hui D, Park S-J. Recent advances in carbon-fiber-reinforced thermoplastic composites: A review. Composites Part B: Engineering 2018;142:241–50. https://doi.org/10.1016/j.compositesb.2017.12.007.

[2] Strong AB. Plastics: Materials and Processing. Pearson Prentice Hall; 2006.

[3] Oshima S, Higuchi R, Kato M, Minakuchi S, Yokozeki T, Aoki T. Cooling rate-dependent mechanical properties of polyphenylene sulfide (PPS) and carbon fiber reinforced PPS (CF/PPS). Composites Part A: Applied Science and Manufacturing 2022:107250. https://doi.org/10.1016/j.compositesa.2022.107250.

[4] Mitschang P, Blinzler M, Wöginger A. Processing technologies for continuous fibre reinforced thermoplastics with novel polymer blends. Composites Science and Technology 2003;63:2099–110. https://doi.org/10.1016/S0266-3538(03)00107-6.

[5] Yousefpour A, Hojjati M, Immarigeon J-P. Fusion Bonding/Welding of Thermoplastic Composites. Journal of Thermoplastic Composite Materials 2004;17:303–41. https://doi.org/10.1177/0892705704045187.

[6] Avenet J, Cender TA, Le Corre S, Bailleul J-L, Levy A. Experimental correlation of rheological relaxation and interface healing times in welding thermoplastic PEKK composites. Composites Part A: Applied Science and Manufacturing 2021;149:106489. https://doi.org/10.1016/j.compositesa.2021.106489.

[7] Ahmed TJ, Stavrov D, Bersee HEN, Beukers A. Induction welding of thermoplastic composites an overview. Composites Part A: Applied Science and Manufacturing 2006;37:1638–51. https://doi.org/10.1016/j.compositesa.2005.10.009.

[8] Kemmish DJ, Leach DC. Poly(aryl ether ketone) matrix resins and composites, International Encyclopedia of Composite Materials' Ed. Lee S, Nicolais L, Borzacchiello A, Encyclopedia of Composites, 2nd Edition, Wiley May, 2012.

[9] Chen G, Mohanty AK, Misra M. Progress in research and applications of Polyphenylene Sulfide blends and composites with carbons. Composites Part B: Engineering 2021;209:108553. https://doi.org/10.1016/j.compositesb.2020.108553.

Assembly, repair and inspection
Assembly:

- Yousefpour, A., Hojjati, M., & Immarigeon, J. P. (2004). Fusion bonding/welding of thermoplastic composites. *Journal of Thermoplastic Composite Materials*, 17(4), 303-341.
- Costa, A. P. D., Botelho, E. C., Costa, M. L., Narita, N. E., & Tarpani, J. R. (2012). A review of welding technologies for thermoplastic composites in aerospace applications. *Journal of Aerospace Technology and Management*, 4, 255-265.
- Thermoplastic composites welding advances for more sustainable airframes. https://www.compositesworld.com/articles/thermoplastic-composites-welding-advances-for-more-sustainable-airframes, September 28, 2022.
- Thermoplastic composites welding: Process control, certification, crack arresters and surface prep. https://www.compositesworld.com/articles/thermoplastic-composites-welding-process-control-certification-crack-arresters-and-surface-prep, September 30, 2022.

Repair:
Overview (also including list of references on the subject):

- J. Barroeta Robles et al. Repair of thermoplastic composites: An overview. *Advanced Manufacturing: Polymer and Composite Sciences*. 2022

Initiatives and other players:

- Retpair Project with Clean Sky 2 : http://www.retpairproject.eu/the-project/project, January 2021. Accessed on November 30th, 2022
- Flexible, induction-based heating for thermoplastic composite part repair. https://www.compositesworld.com/articles/flexible-induction-based-heating-for-thermoplastic-composite-part-repair. August 2022. Accessed on November 30th, 2022.

Inspection:

- G650 TPC induction welded elevator (post-production inspection):
- A.B. Jaap Willem van Ingen, F.S. Martijn van Wijngaarden, Development of the Gulfstream G650 Induction, Sampe Seattle 2010. (2010) 2012.
- Non-Destructive Evaluation (NDE) of Thermoplastic Composites
- A.A. Hassen, H. Taheri, U.K. Vaidya, Non-destructive investigation of thermoplastic reinforced composites, Compos. Part B Eng. 97 (2016) 244–254. https://doi.org/10.1016/J.COMPOSITESB.2016.05.006.
- R. Szymański, Non-Destructive Testing of Thermoplastic Carbon Composite Structures, Trans. Aerosp. Res. 2020 (2020) 34–52. https://doi.org/10.2478/tar-2020-0003.

In-process inspection of the welding process

- J. Pandher, M. Van Tooren, M. Davis, J. Fant, in-Process Monitoring of Induction Welding of Thermoplastic Composites Based on Fiber Optics, (n.d.) 1–12.

Post-process inspection of the welding process

- R. Ochoa, Pedro; Roger, Groves; Benedictus, Full-scale testing of an ultrasonic guided wave based structural health monitoring system for a thermoplastic composite aircraft primary structure, Delft, 2018.

In-process and post-process inspection, AFP

- Danezis, D. Williams, A.A. Skordos, In-process nip point temperature estimation in automated tape placement based on analytical solution and remote thermal measurements, J. Thermoplast. Compos. Mater. 0 (2022) 1–27. https://doi.org/10.1177/08927057221122095.
- A.R. Chadwick, M. Willmeroth, Use of in-process monitoring and ultrasound to detect defects in thermoplastic AFP-produced parts, ICCM Int. Conf. Compos. Mater. 2019-August (2019).

Design and modelling

D1. Composite forming simulations | AniForm

D2. Postera R, Leach D C, Fabrication and Evaluation of a Commercial Aircraft Window Frame, Proc 6th International Conference Thermoplastic Composites (ITHEC), Bremen, 12-13 October 2022.

D3. COMPRO Simulation Software | Convergent

Market and applications

Aerospace:

https://www.grandviewresearch.com/industry-analysis/thermoplastic-composites-market-report

Oil &Gas:

https://www.compositesworld.com/articles/composites-extend-service-of-corrosion-prone-oil-and-gas-pipelines

Sports and Recreation:

https://arevo.com/applications?lang=en
https://www.oribicomposites.com/parts-gallery/

SWOT: Competitive materials and technologies, sustainability

- Ahmed, T.J., Stavrov, D., Bersee, H.E.N. and Beukers, A. (2006). Induction welding of thermoplastic composites—an overview. Composites Part A: Applied Science and Manufacturing, 37(10), pp.1638–1651. doi:https://doi.org/10.1016/j.compositesa.2005.10.009.
- Arquier, R., Iliopoulos, I., Régnier, G. and Miquelard-Garnier, G. (2022). Consolidation of continuous-carbon-fiber-reinforced PAEK composites: a review. Materials Today Communications, 32, p.104036. doi:https://doi.org/10.1016/j.mtcomm.2022.104036.
- Barroeta Robles, J., Dubé, M., Hubert, P. and Yousefpour, A. (2022). Repair of thermoplastic composites: an overview. Advanced Manufacturing: Polymer & Composites Science, 8(2), pp.68–96. doi:https://doi.org/10.1080/20550340.2022.2057137.
- Bernatas, R., Dagreou, S., Despax-Ferreres, A. and Barasinski, A. (2021). Recycling of fiber reinforced composites with a focus on thermoplastic composites. Cleaner Engineering and Technology, 5, p.100272. doi:https://doi.org/10.1016/j.clet.2021.100272.
- Chen, H., Li, S., Wang, J. and Ding, A. (2021). A focused review on the thermo-stamping process and simulation progresses of continuous fibre reinforced thermoplastic composites. Composites Part B: Engineering, 224, p.109196. doi:https://doi.org/10.1016/j.compositesb.2021.109196.
- Collinson, M., Bower, M., Swait, T.J., Atkins, C., Hayes, S. and Nuhiji, B. (2022). Novel composite curing methods for sustainable manufacture: A review. Composites Part C: Open Access, 9, p.100293. doi:https://doi.org/10.1016/j.jcomc.2022.100293.
- Condé-Wolter, J., Ruf, M.G., Liebsch, A., Lebelt, T., Koch, I., Drechsler, K. and Gude, M. (2023). Hydrogen permeability of thermoplastic composites and liner systems for future mobility applications. Composites Part A: Applied Science and Manufacturing, 167, p.107446. doi:https://doi.org/10.1016/j.compositesa.2023.107446.
- Golzar, M., Sinke, J. and Abouhamzeh, M. (2022). Novel thermomechanical characterization for shrinkage evolution of unidirectional semi-crystalline thermoplastic prepregs (PPS/CF) in melt, rubbery and glassy states. Composites Part A: Applied Science and Manufacturing, 156, p.106879. doi:https://doi.org/10.1016/j.compositesa.2022.106879.
- Hürkamp, A., Lorenz, R., Ossowski, T., Behrens, B.-A. and Dröder, K. (2021). Simulation-based digital twin for the manufacturing of thermoplastic composites. Procedia CIRP, 100, pp.1–6. doi:https://doi.org/10.1016/j.procir.2021.05.001.
- Joppich, T., Menrath, A. and Henning, F. (2017). Advanced Molds and Methods for the Fundamental Analysis of Process Induced Interface Bonding Properties of Hybrid, Thermoplastic Composites. Procedia CIRP, 66, pp.137–142. doi:https://doi.org/10.1016/j.procir.2017.03.275.
- Kumar, D., Phanden, R.K. and Thakur, L. (2021). A review on environment friendly and lightweight Magnesium-Based metal matrix composites and alloys. Materials Today: Proceedings, [online] 38, pp.359–364. doi:https://doi.org/10.1016/j.matpr.2020.07.424.
- Leach, D, (2022). Thermoplastic Composites: Opportunities and Challenges", Materials Innovation and Advanced Technology Leadership Forum, Huntington Beach, CA 2022.
- Li, Y., Xiao, Y., Yu, L., Ji, K. and Li, D. (2022). A review on the tooling technologies for composites manufacturing of aerospace structures: materials, structures and processes. Composites Part A: Applied Science and Manufacturing, 154, p.106762. doi:https://doi.org/10.1016/j.compositesa.2021.106762.
- Martín, I., Fernández, K., Cuenca, J., Sánchez, C., Anaya, S. and Élices, R. (2023). Design and manufacture of a reinforced fuselage structure through automatic laying-up and in-situ consolidation with co-consolidation of skin and stringers using thermoplastic composite materials. Heliyon, 9(1), p.e12728. doi:https://doi.org/10.1016/j.heliyon.2022.e12728.

- Proy, J., Massa, F., Notta-Cuvier, D., Lauro, F., Tison, T. and Spingler, G. (2021). Integrating fibers and injection molding process variability in short-natural-fiber-reinforced thermoplastics behavior: A review. Materials Today Communications, 29, p.102785. doi:https://doi.org/10.1016/j.mtcomm.2021.102785.
- Ramon, E., Sguazzo, C. and Moreira, P. (2018). A Review of Recent Research on Bio-Based Epoxy Systems for Engineering Applications and Potentialities in the Aviation Sector. Aerospace, 5(4), p.110. doi:https://doi.org/10.3390/aerospace5040110.
- Red, C. (2014) "Thermoplastics in Aerospace Composites Outlook, 2014-2023", Composites World. Published September 1, 2014. https://www.compositesworld.com/articles/the-outlook-for-thermoplastics-in-aerospace-composites-2014-2023
- Thiruchitrambalam, M., Bubesh Kumar, D., Shanmugam, D. and Jawaid, M. (2020). A review on PEEK composites – Manufacturing methods, properties and applications. Materials Today: Proceedings, 33, pp.1085–1092. doi:https://doi.org/10.1016/j.matpr.2020.07.124.
- van Grootel, A., Chang, J., Wardle, B.L. and Olivetti, E. (2020). Manufacturing variability drives significant environmental and economic impact: The case of carbon fiber reinforced polymer composites in the aerospace industry. Journal of Cleaner Production, [online] 261, p.121087. doi:https://doi.org/10.1016/j.jclepro.2020.121087.
- van Rijswijk, K. and Bersee, H.E.N. (2007). Reactive processing of textile fiber-reinforced thermoplastic composites – An overview. Composites Part A: Applied Science and Manufacturing, 38(3), pp.666–681. doi:https://doi.org/10.1016/j.compositesa.2006.05.007.
- Witik, R.A., Gaille, F., Teuscher, R., Ringwald, H., Michaud, V. and Månson, J.-A.E. (2012). Economic and environmental assessment of alternative production methods for composite aircraft components. Journal of Cleaner Production, 29-30, pp.91–102. doi:https://doi.org/10.1016/j.jclepro.2012.02.028.
- Zhang, W. and Xu, J. (2022). Advanced lightweight materials for Automobiles: A review. Materials & Design, [online] 221, p.110994. doi:https://doi.org/10.1016/j.matdes.2022.110994.
- Zhi, M., Yang, X., Fan, R., Yue, S., Zheng, L., Liu, Q. and He, Y. (2022). A comprehensive review of reactive flame-retardant epoxy resin: fundamentals, recent developments, and perspectives. Polymer Degradation and Stability, 201, p.109976. doi:https://doi.org/10.1016/j.polymdegradstab.2022.109976.

Space Applications

Chris Fleming
Principal Engineer
SI Staff, M&P Engineering
Virgin Galactic (Former)
Chair

LaNetra Tate
Director, Engineering Execution,
Operations, and Planning
Ball Aerospace (Former)
Vice Chair

Ali Mansouri
Senior Engineer
Virgin Galactic
Secretary

Li Tan
Professor of Materials
Engineering and Chemistry
University of Nebraska, Lincoln
Member

Moutushi Dey
Member

Susan Ruth
Retired M&P Engineer
SAMPE Past President
Member

Paul Wienhold
Principal Professional Staff
Johns Hopkins University
Applied Physics Laboratory
Past Vice Chair

sampe
North America

TC 7
SPACE APPLICATIONS

Executive Summary

The SAMPE Space Applications Technical Committee addresses the application of advanced materials and processes for to space applications. Two main areas are of interest include expendable launch vehicles and spacecraft. On the horizon, we expect new materials and processes to deliver reusable launch vehicles along with field-operation capabilities, exo-body landers and rovers, and the realization of human habitation and colonization in space.

While there are many considerations involved in designing and delivering space-qualified materials that are mission specific, material selection is usually the first to start. It is generally driven by the ability to get to space (mostly minimum mass) followed by anticipated performance in space environments and planned lifetime in that environment. Our knowledge of the environments is still evolving. Some of the evolution is related to design and operation, while others are related to the operational environment.

Process selection is another critical step driven in part by the materials/technology selected and the business case. A business case includes cost/unit, production rate or production per unit time. Nonrecurring costs such as new facilities and equipment may be a part of the business case too.

Materials and processes specific to space flight are a blend of unique opportunities coupled with classic engineering – from ground support equipment augmented to contain specialty fuels and oxidizers to laminates and adhesives that can withstand the strenuous requirements of launch, space travel, and reentry. This report highlights some of these and also provides a brief overview of specific applications, markets, and key players that occupy this domain.

Selection of materials and processes driven by unique environments

Requirements drivers

The flight profiles of spacecraft drive the materials selection requirements. Fig. 1 is a schematic representation of the general trajectories of a spacecraft for orbital+ and sub-orbital space missions. Orbital+ missions are varied in scope and path, but most spacecraft on such missions end up traveling around the Earth's surface at a distance beyond the Karman Line, e.g., approximately 160 to 2,000 km. Other orbital missions use their Earth orbits to slingshot themselves to other planetary bodies, or into deep space.

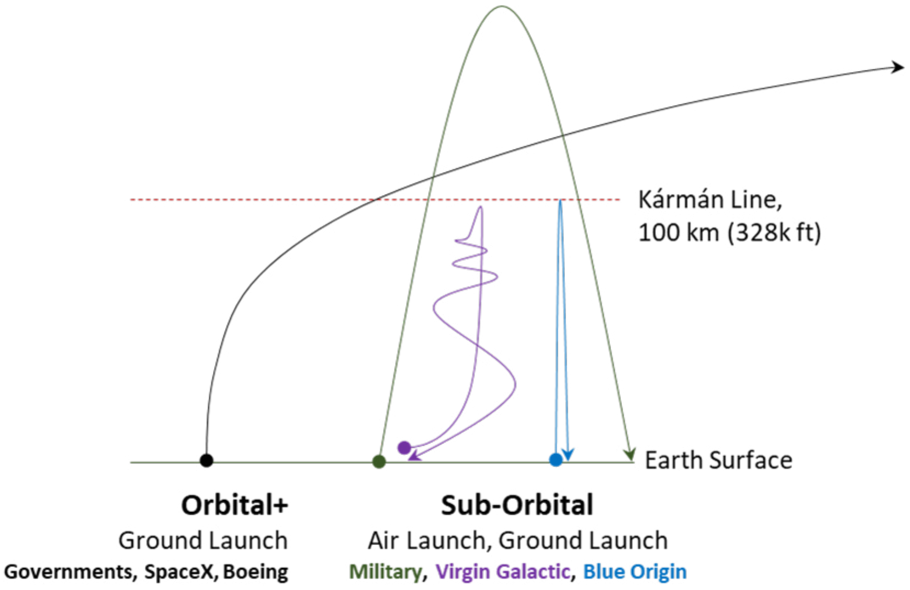


Fig. 1. Two general trajectories for spacecraft. Orbital+ refers to ground-launched spacecraft that orbit the earth or other planetary bodies. Sub-orbital refers to space flights that apogee 200-400 km AGL, or near the Karman Line.

Sub-orbital missions are currently pursued by the government/military and space tourism companies with the primary goals of delivering passengers or cargo on a ballistic path.

Environmental extremes and mass are primary foci of material selection and design for space flight.

Environmental factors

Many challenges exist when selecting materials for spacecraft to carry the mission and complete the flight profile. In choosing the right material for any component in a spacecraft assembly, mass and environment are always considered. The following sections note some of the challenges associated with each stage of mission and highlight a few mission-relevant influences for material selection.

Earth

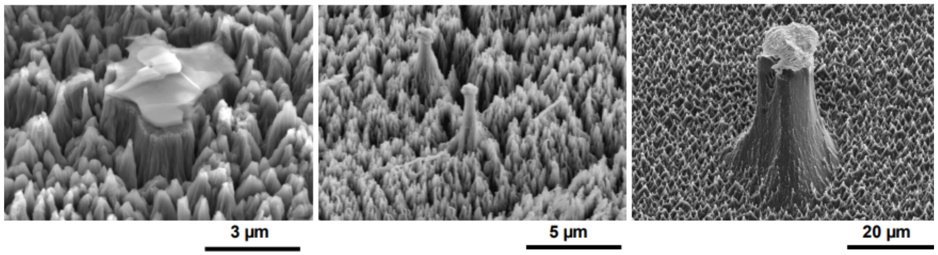
- Manufacturing- and assembly-induced cracks, residual stresses, internal defects, stress corrosion cracking, or contamination of structural materials, electronic components, and propulsion systems
- Transport-induced interfacial contamination, corrosion or structural damage
- High RH-induced moisture condensation at the launch site
- Chemical- (cleaning agents, propellants, and oxidizers) induced polymeric degradation and metal corrosion, SCC, hydrogen embrittlement.
- Fueling-induced exposure of oxidizer to fuel-sensitive materials.

Lift off/launch

- High-intensity vibrations (5-200 Hz, NASA)
- Mechanical impacts
- Thermal flux
- Environmental uncertainty, e.g., lightening/bird strikes

Low Earth orbit (200-700 km)

- Exposure to fluxes of atomic oxygen (3PO) (disassociated by radiation, this varies by altitude and solar activities)
  - Regularly leads to degradation and erosion of materials and coatings (rate can be determined through ground test) [5]
  - AO oxidizes metals (particularly silver and osmium)
  - Interaction with plasma can lead to a build-up of surface charge, which can damage avionics, lead to single-event upsets
  - This is a common cause of failure in satellites (NASA RP-1390). Can use static dissipative materials or conductive coatings to take off surface charge such as indium tin oxide coated thin films
  - Can even lead to degradation of the aluminum anodized layer



a. EOIM III Pyrolytic graphite b. EOIM IIII Kapton H c. LDEF Teflon FEP

Fig. 2. SEM images of protected mesas of pyrolytic graphite, polyimide Kapton, and Teflon FEP exposed to directed LEO atomic oxygen [5].

- Dynamic temperatures (repeated orbital temperature variation (±100˚C)
- Ultrahigh vacuum (~5 x 10^{-10} Torr)

See Fig. 2 for Pressure and temperature profiles through launch.

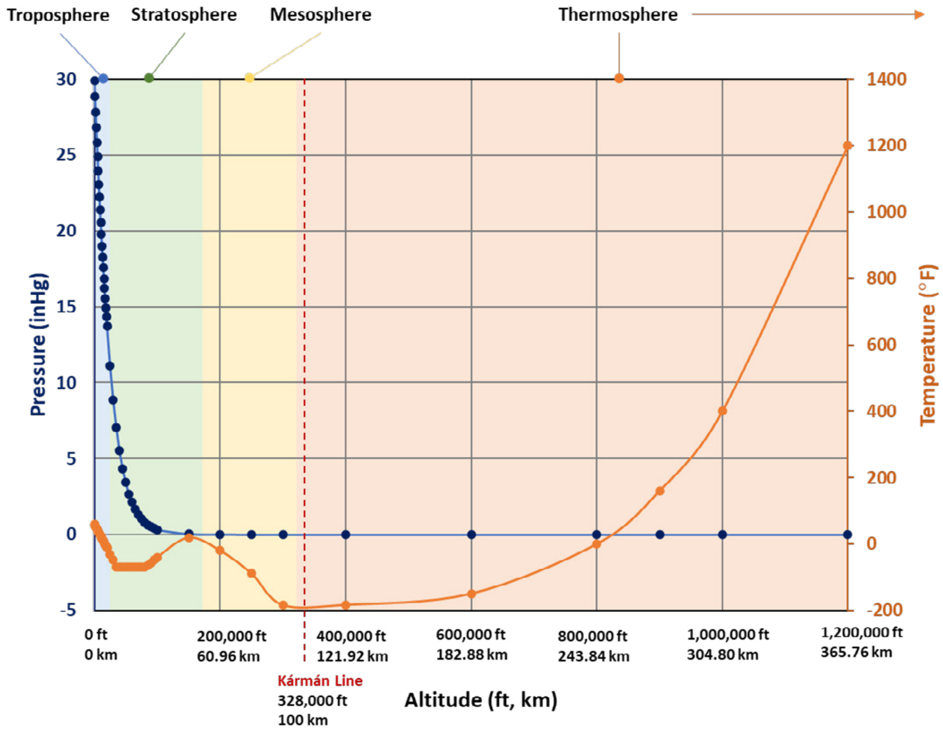


Fig. 2. Pressure and temperature with altitude/atmospheric region.

Human-occupied environments

- Corrosion, biological growth, fire and wear due to breathable air, water, organic materials and human activities
- Considerable mass added to mission for human life support and sustainment
- Toxicity and flammability concerns for humans
  - "Ignition sources can never be eliminated. Propagation paths must be eliminated" (ref.)

Vacuum (7.5 x 10-16 Torr, interplanetary)

- Impacted structural, electrical, thermal and optical properties due to desorption of chemisorbed water from ceramic oxides
- Loss of lubrication or blockage of rotating components due to outgassing of lubricants
  - Example: The Solar Alpha Rotary Joint on the International Space Station bearing failure (~2007) due to poor understanding of tribological interaction
  - Solid lubricants (molybdenum disulfide, tungsten disulfide, niobium diselenide, Teflon, nylon) generally a better choice than liquid lubricants (with higher volatility and limited temperature range)
- Clouded screens or lenses on scientific instruments due to condensation of outgassed species

Solar/cosmic radiation-induced materials degradation

- Degradation of surface treatments (adherence issues due to microcracks, flaking off, peel off, color change)
- Irreversible changes in appearance, chemical, physical or mechanical properties due to cross-linking and chain scission of polymers
- Greater radiation than those in low Earth orbit when traveling in or out of Van Allen Belts
- Changes in electrical properties because high-energy particles displace Si atoms from proper crystal lattice locations, creating new defects (can be an issue for solar panels)
- Thermal stress and cracking
  - In orbit around Earth, materials are exposed to frequent fluctuations between -180 C and 180 C
  - Beyond orbit can face even higher fluctuations (other moons, planets)

Orbital collisions

- High-velocity impacts with micrometeoroids and artificial orbital debris (MMOD)
  - While large MMOD objects are tracked, many are too small to track
- Orbital debris
  - Whipple shields are a common method of protection; they break up the impacting particle into smaller pieces; usually aluminum, but copper and composite materials have also been used
  - In some cases (like ISS), combine a Whipple shield with thermal protection to have a blanket of Kevlar and Nextel between the Whipple shield bumper and pressure wall
- Danger of micrometeoroids beyond Earth orbit not known

Re-entry

- Extreme high temperature (up to 2800˚C or 5070˚F) and atmospheric dynamic pressure
  - Heatshield material needs to sustain the peak heat flux and stagnation pressure during reentry
  - Mechanical strength, density, entry angle, and the shape of the heatshield (i.e. blunt-body, sphere-cone, biconic, or non-axisymmetric) are also important.
  - The aerothermodynamic heat fluxes (plasma) and friction with the atmosphere will lead to extremely high erosion and corrosion
- Weight vs uncertainty of performance
- For reusable vehicles: multiple re-entries, low re-work
  - Silica ceramic tiles/ceramic matrix composites are common reusable materials; ablatives are common one-time use materials
- Silica ceramic tiles are fragile and need a coating to be waterproof

Space markets

Satellites

From security to weather to communications to scientific investigation, and tourism, orbital platforms are strategic outposts for measurement, observation and defense.

Tourism

Orbital and suborbital.

Near Earth and outer space exploration

While currently the domain of government or government-backed entities, private companies have long-term goals to extend their reach beyond orbital outposts and communities.

Space materials and process change drivers

From the major known players to small specialty suppliers, there are thousands of companies involved in the materials and process aspect of the space industry around the world. The Space Foundation estimates that the space economy was worth $469 billion in 2021. Table 1 lists the larger, established space-related companies and some of the newer start-ups that are creating change in the industry.

Emerging Applications and Markets

Manufacturing in space

There has been limited research about differences between terrestrial and space manufacturing. Existing research shows that:

- In microgravity, surface tension dominates manufacturing in ways different than on Earth, creating challenges in the formation of porosity, function of lubricants, the ability to manage small particles from machining, fretting, and wear

Table 1. Companies Driving Change and Their Foci

Company	Company Focus
SpaceX	Launch vehicles (orbital, lunar), satellites
Planet Lab	Satellite Constellation
Relativity Space	3D Print launch vehicles
ABL Space Systems	Transportable launch systems (can be moved via shipping containers)
Astroscale	Orbital sustainability (clean up satellites in low earth orbit at end of life)
Rocket Lab	Launch vehicles
Axiom Space	Commercial Space Station
Blue Origin	Suborbital tourism, Launch (suborbital, orbital)
Evolution Space	Nanostartup Launch
Firefly	Launch vehicles
Form logic	Precision manufacturing for space applications
Launcher	Launch vehicles
OneWeb	Broadband satellite internet
Sierra Space	Commercial space platform (private space station?)
Space Forge	Develop on orbit fabrication technology (semiconductors & alloys in microgravity)
Spin Launch	Novel launch technology (‘mass accelerator’)
Virgin Orbit	Horizontal launch of satellites at commercial flight altitude
Virgin Galactic	Suborbital tourism
Astra	Launch vehicles
Northrup Grunman	Launch Vehicles, Spacecraft, Satellites
Boeing	Launch Vehicles, Spacecraft, Satellites
Lockheed Martin	Launch Vehicles, Spacecraft, Satellites
United Launch Alliance	Launch Vehicles

- Thermal transfer within a structure is very different than processing norms on Earth (because there is no gravity-driven convection, which dominates systems on Earth); this removes some obstacles for thermal control of processes, but also leads to very different phase transformation, precipitate evolution, flow stress dependence
- Materials property data (whether for metals, polymers or composites) may be considerably different in space manufacturing based on environmental and manufacturing constraints
- Other challenges include radiation, no electrical ground and atmospheric oxygen corrosion
- This ultimately leads to a complete departure from traditional understanding (at standard temperatures, pressure, and gravity) and a need for new equilibrium conditions (and associated materials processes)

Competitive materials

The materials innovation gap is staggering in the composites industry. Larger, well-established companies have a significant advantage over their smaller and newer competitors. For example, there are thermoplastics currently in use that outpace high-temperature thermosets in both temperature and toughness, but are unavailable for general purchase by small start-ups.

While smaller companies can use the newest composites systems, they come at a cost. Allowables development programs are expensive in scope for even standard composites of average fiber and resin construction. Even for well-known composite material systems, the cost to qualify that system through a company's process can run well over $2-3 million. The cost of integrating the newest material systems is even more financially taxing as the materials are more expensive and the process upgrades are considerable. The added cost of internal, specialized R&D is even higher.

Material selection

Materials are generally chosen based on their mechanical strength, low outgassing properties, low density, low dielectric loss, high-temperature resistance capability and other criteria as required by the end-use application. Polymeric materials can be modified with fillers, additives and nanomaterials to provide customized functional properties to meet the end-use requirements.

The list below is a very generalized categorization of thermoplastics, thermosets and other polymeric materials used in space applications.

Thermoplastics

Thermoplastics are a material of choice for many applications due to their recyclability and their ability to be processed rapidly. Thermoplastics like polyarYletherketone (PAEK), polyetheretherketone (PEEK) can be used for on ground as well as for off-Earth applications. Thermoplastics like polyamide, Vespel, ABS and nylon, reinforced with glass fibers, are primarily used as insulating materials in cryogenic boundary conditions. Thermoplastics like UHMW polyethylene can be used for thermal heat switch applications.

Thermosets

Thermosets are also good candidates for space applications, but due to their inherent brittleness, they are generally modified with thermoplastics and/or other additives to circumvent their brittleness. Epoxies modified with thermoplastics like polyetherimide (PEI), polybutylene terephthalate (PBT), polycarbonate (PC) and other fillers can be used for cryogenic applications. Thermosets like cyanate esters are also very promising in space applications because of their excellent thermal and dimensional stability, resistance to micro cracks, low moisture absorption and low dielectric loss. Cyanate esters can be blended with other thermosets like epoxies for use in space applications.

Another promising material for space application is polytetrafluoroethylene (PTFE). PTFE is used as a solid lubricant due to its low coefficient of friction. Solid lubricants are extensively used in spacecraft where liquid lubricants are ineffective. The use of PTFE is well known in niche space application like ball bearing cages, solid lubricating films, bushings in the solar sail for the Near

Earth Asteroid scout [1,2] and unbonded lubricant coating [3]. Like all other polymers, PTFE can be modified with other additives [4] to meet the end use requirements and can be applied in other space applications.

---

1. Sobey, A.R.; Lockett, T.R. Design and Development of NEA Scout Solar Sail Deployer Mechanism. In Proceedings of the 43rd Aerospace Mechanisms Symposium, Santa Clara, CA, USA, 4–6 May 2016.

2. Miyoshi, K. *Solid Lubricants and Coatings for Extreme Environments: State-of-the-Art Survey*; NASA/TM—2007-214668; NASA: Cleveland, OH, USA, 2007).

3. Jeffrey R. Lince, Effective application of solid lubricants in spacecraft mechanisms, Lubricants 2020, 8(7), 74).

4. Tasuku Onodera, Jun Nunoshige, Kenji Kawasaki, Structure and Function of Transfer Film Formed From PTFE/PEEK Polymer Blend, *The Journal of Physical Chemistry* C 121 (27), 14589-14596, 2017.

5. Bruce A. Banks, Kim K. de Groh, and Sharon K. Miller, *Low Earth Orbital Atomic Oxygen Interactions With Spacecraft Materials*, NASA/TM-2004-213400

> Whether you are a subject matter expert or simply interested in the topics, there is a place for you at SAMPE.

Jeff Sloan
Brand VP
CompositesWorld

Special thank you to Jeff Sloan for his editing of this report.

sampe
North America

nasampe.org

CONTACT
Raj Manchanda | CTO
Raj@sampe.org