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CompositesWorld

Thermoplastic pipes: DISPLACING METALS IN THE DEEP SEA

MARCH 2019

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Thermoplastic composite pipe (TCP) is more easily transported and installed in deep-sea oil and gas applications than conventional metal pipe. Spooled here is 1.2 km of 6.7 ksi m-pipe from Magma Global. See p. 16.

Source / Magma Global

FOCUS ON DESIGN

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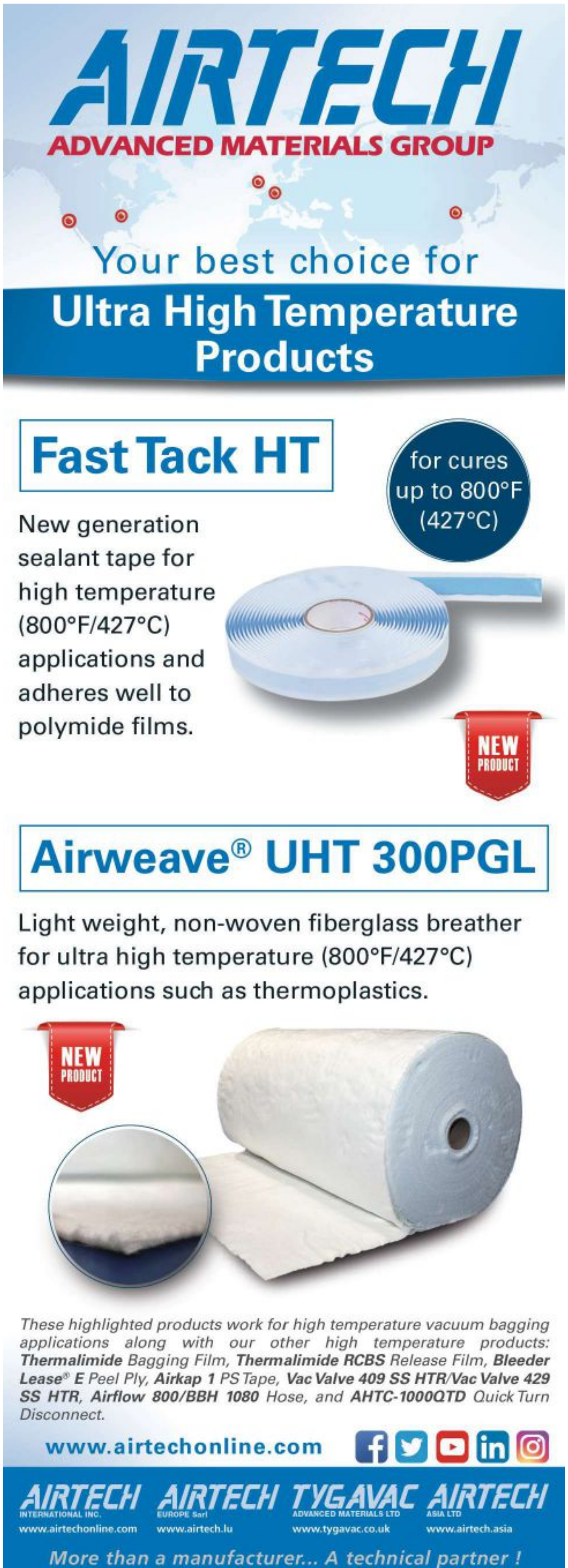

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PUBLISHER	Ryan Delahanty rdelahanty@gardnerweb.com
EDITOR-IN-CHIEF	Jeff Sloan jeff@compositesworld.com
SENIOR EDITOR	Ginger Gardiner ggardiner@compositesworld.com
SENIOR EDITOR	Scott Francis sfrancis@compositesworld.com
ASSISTANT EDITOR	Hannah Mason hmason@compositesworld.com
DIRECTOR, STRATEGIC INITIATIVES AND EVENTS	Scott Stephenson sstephenson@compositesworld.com
ADVERTISING PRODUCTION MANAGER	Becky Taggert btaggert@gardnerweb.com
GRAPHIC DESIGNER	Susan Kraus skraus@gardnerweb.com
MARKETING MANAGER	Chris Saulnier csaulnier@gardnerweb.com

CW CONTRIBUTING WRITERS

Sara Black	sara@compositesworld.com
Dale Brosius	dale@compositesworld.com
Michael LeGault	mlegault@compositesworld.com
Peggy Malnati	peggy@compositesworld.com
Karen Mason	kmason@compositesworld.com

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EASTERN US SALES OFFICE	Barbara Businger / REGIONAL MANAGER barb@compositesworld.com
MOUNTAIN, WEST	Michael Schwartz / REGIONAL MANAGER mschwartz@gardnerweb.com
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HEADQUARTERS

6915 Valley Ave., Cincinnati, OH 45244-3029

Phone 513-527-8800 Fax 513-527-8801

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» My (immediate) family owns four cars. The oldest was manufactured in 2004. The youngest was manufactured in 2010. Three of them are hovering at or near 250,000 miles. Each of our cars, given its age and rate of use, is in decent if not great condition, but several are clearly near the end of their lives. When that end comes, the Sloan family will be in the market for a new vehicle.

Would you like carbon fiber with that car?

Because our youngest vehicle is nine years old (and in possession of son #2), our exposure to new vehicles and new-vehicle technology is limited. That said, whenever I rent a vehicle during my travels, I appreciate the opportunity to assess makes, models, styles, comfort and features. These extended test drives give me a chance to evaluate everything from power to handling to sound system quality. Because of this, I have, over the years, become sensitive to the rate of vehicle feature evolution.

Sound systems, for example, have morphed quickly from glorified radios and CD players to high-fidelity sound and video systems that seamlessly meld with our phones to provide a host of directional, music, podcast and communication options. Safety systems also have enjoyed rapid evolution, with a proliferation of airbags designed to provide passenger protection from nearly any impact.

Conversely, some aspects of vehicle technology have evolved more slowly. For example, materials use in the cars I typically rent are substantially unchanged. And overall fuel efficiency, although improving, is not where I had hoped/thought it would be as we prepare to enter the third decade of the 21st century.

All of this (and more) came to mind in January when I visited the North American International Auto Show (NAIAS) in Detroit, where the latest in vehicle technology is poked and prodded. I usually come to this show with the intent of assessing how obviously composites are being integrated into new vehicles. But as I roamed the floor and drifted from vehicle to vehicle, seeing very few composites, I was struck by something.

The big advantage of composites for automotive use — particularly carbon fiber — is weight savings, which engenders better fuel efficiency and reduced emissions. But in looking at the vehicles on exhibit in Detroit, and in looking at *any* marketing for *any* vehicle, reduced vehicle weight or reduced emissions are rarely if ever selling points. Nowhere at the auto show did I see a sign declaring, "Now with carbon fiber to increase efficiency!" or "Reduce your CO_2 footprint with this lightweight beauty!" Even fuel efficiency often gets short shrift.

This is not to say that there were no composites at the show. They could be found, usually on high-end cars and usually with attention-getting clearcoat finish, in spoilers, wheels and side view mirrors. But even the *largest* carbon fiber structure at the show, the CarbonPro bed of the GMC *Sierra Denali* pickup truck, was found not on the exhibit hall floor, but in the hallway in the booth of Continental Structural Plastics, which makes the bed. On top of all of that, the two carmakers that have been the most aggressive in developing autocomposites, BMW and Audi, did not exhibit at NAIAS this year.

The composites industry faces a difficult challenge within the automotive industry: There are many arguments to be made to automotive OEMs in favor of composites use in cars and trucks, but there are very few arguments that can be made to *car buyers* in favor of composites use in cars and trucks. The features that draw consumers to a given vehicle are often aesthetic and tactile — designed to drive an *emotional* appeal. Composites, although eminently practical, do not feed that emotion.

I think it's fair to say that affordable composites use in autostructures is not yet overwhelmingly and emotionally compelling to consumers, and without that "pull," OEMs are unlikely to demand substantial increase in composites use. We can, however, make the *practicality* of composites use in autostructures impossible to ignore, and that's where our future may lie — so that customers, like the Sloan family, are *compelled* to consider the advantages that composites bring to the market.

JEFF SLOAN — Editor-In-Chief

Can the aerospace industry regain its ability to “try”?

» The new year kicked off with a little-noticed headline from the *South China Morning Post*: “China’s Chang’e 4 spacecraft to try historic landing on far side of moon between ‘January 1 and 3.’” Indeed, on Jan. 3, the People’s Republic of China successfully completed the “try” with the first soft landing of a craft on the far side of the moon. Imagine how this event has captured the minds of young Chinese students — the wonder of their government making this attempt and the national pride of a successful mission. I am particularly stirred by the use of the word “try” in the periodical’s headline. It makes me wonder: Do we as a nation still try? Are risks allowed in our world today?

Let’s travel back 50 years to 1969, the zenith of America’s space age. The year was preceded by the Christmas orbit of *Apollo 8* around the far side of the moon. A scant seven months later, July 20, 1969, saw man’s first step on that very same surface. For those of us experiencing our formative years — and for me personally — the Mercury, Gemini and Apollo programs shaped not only a sense of national pride (and the importance to serve) but nearly all of my future interest in a career centered around science, technology, mathematics and engineering. Imagine the vision, the effort, the technical development that occurred from John Glenn’s first orbit of the Earth and that first step, seven years and seven months later. In 2019, we barely complete the technical specifications of a new aircraft system in that same period of time.

> While our progress is remarkable, the timeline applied to these projects is less than inspirational.

In my opinion, the Apollo program and the great challenge that was laid before us as a nation then was our last great “try.” Today, despite the computing power on our desktops, the material technologies that are so much more matured (and themselves a product of our space program), the engineering simulation that is so well vetted and the availability of capital, it now takes generations to accomplish something Yuri, Alan and John did nearly 60 years ago. I am only left to wonder what the world would be like today if the same level of acceptable risk we employ today were applied to the voyages of the great explorers, the building of the transcontinental rail system, industrialization, the Wright brothers and the travails of the Greatest Generation (which includes the original seven Mercury astronauts).

Recently, I had the opportunity to visit Spirit AeroSystems, which manufactures the forward fuselage section of the Boeing 787. Despite my being an industry professional who understands the evolution of automated fiber placement (AFP) in the vernacular of our business, I could not help but feel — standing before the massive AFP machine placing fiber tow on the cockpit of this massive and beautiful vehicle — the same inspiration for this industry that I felt as a nine-year-old boy.

In 1969, the technology of advanced composite materials, particularly carbon fiber-reinforced materials, was at its infancy. The understanding of the mechanics of both static failure and mechanisms of wear-out due to cyclic loading were just being explored. A lack of manufacturing experience and the fear of inconsistency in bonded structures gave rise to an industry vernacular that includes “chicken rivets” and “redundant structure.” But it was the likes of Steve Tsai, Chris Chamis, Nick Pagano, J. C. Halpin, Jim Whitney and so many others that rapidly evolved our understanding of these materials and shed light on the science of anisotropy. Today, using computing capability combined with the knowledge those leaders developed, we have built a deep and broad ability to apply composite material systems to nearly all industries, including my precious aerospace industry.

Since my entry as a professional in the winter of 1984 as a lieutenant in the U.S. Air Force, I have had the opportunity to work on countless applications for composites on a variety of platforms. My disappointment at the slow pace of deployment in production, however, left me jaded. For example, the Advanced Technology Fighter (ATF) slated for my organization’s care (AF-ALC McClellan AFB) would take 20 years to enter service, delayed by contracts, legal ramifications and countless levels of test and development.

On the other hand, today, we could not imagine *not* using composite materials technology to build the pressure vessels that house the solid or liquid propellant that lift our space vehicles to new worlds and deploy the satellites that make up so much of daily life. Also, not by surprise, today’s “space race” is led by commercial industry. The likes of SpaceX, Virgin Galactic and Blue Origin are now expanding manned space flight in search of the untapped potential of “space tourism.”

While the progress we have seen in the past five decades is remarkable, one cannot help but admit that the timeline applied to these projects is far less than inspirational. It’s unfortunate, in my opinion, that our leadership has chosen not to lead the world in singular grand challenges such as a race to inhabit or colonize Mars, to seek energy independence from fossil fuels or to explore the deepest reaches of our oceans to unlock secrets of climate change. Or, for that matter, to capture the minds of today’s young students and allow them to imagine what, left unencumbered, may be accomplished if only they could “try.” CW

ABOUT THE AUTHOR

Steve Nolet is senior director for Innovation & Technology at TPI Composites in Scottsdale, Ariz., U.S. In this role, he manages the research and development activities of the company’s production of utility-scale wind turbine blades as well as transportation and automotive markets.

2019 North American International Auto Show: An unclear future for autocomposites?

The North American International Auto Show (NAIAS) has been held at Cobo Hall in downtown Detroit, Mich., U.S., every January since 1989. Prior to then, it was simply the Detroit Auto Show, but became one of the big "international" shows 30 years ago, setting itself up as equal in importance with shows in Frankfurt, Paris, Tokyo and Geneva. Automakers unveil new models and suppliers promote advanced technologies for future vehicles. Over the course of two weeks, commencing with media days followed by industry and public days, more than 750,000 people come to see the latest from most of the world's automakers.

I've been to many of these over the past 30 years, sometimes on the public days with my kids and other times on media or industry days before the public opening. I'm always fascinated how, during industry days, engineers from one OEM carefully inspect how other OEMs execute certain features and functionalities, some crawling under the car with a mirror, or checking body panels with a magnet to see which might be steel, aluminum, or even composite. I go to seek inspiration, perhaps for a column, or to just check the pulse on how composites are making progress in this industry.

Overall, I came away from 2019 NAIAS with more questions than answers.

There's an old saying that goes, "Sometimes you're more conspicuous by your absence than by your presence." That was definitely the case in 2019, as major German automakers BMW, Mercedes-Benz and Porsche, as well as Italian high-end marques like Lamborghini, Ferrari and Maserati all elected to skip this year's NAIAS. This led to a lot of speculation that the Consumer Electronics Show (CES) in Las Vegas the week before had an impact. Both BMW and Mercedes had large presences at CES, focusing on electrification, mobility and infotainment, with BMW showing the iNext concept and Mercedes rolling out the 2020 CLA Coupé and all-electric EQC vehicles. Listen, Detroit weather can be a bit inhospitable in January, but it's still North America's most significant auto show. Sensing a shift, the organizers of the NAIAS are moving the 2020 show to June, still in Detroit, allowing the addition of large outdoor displays and opportunities to engage media and public interactively. It will be interesting to see how this plays out.

Despite the reduced OEM participation, composites were still on display at NAIAS. Baffling to some, GM elected not to display the new *Sierra* pickup with the carbon fiber/nylon composite CarbonPro box, although it is due to go on sale mid-2019. Tier 1 supplier Teijin Continental Structural Plastics (Auburn Hills, Mich.) displayed the CarbonPro box in the main foyer of Cobo, so at least folks could see what is coming. GM did display one version of the C7 Corvette, which has a carbon fiber hood, but the company elected not to unveil the forthcoming C8 version, which is anticipated to be a mid-engine version (a la Ferrari and Lamborghini). GM says there will be a separate unveiling in spring/summer 2019. We can only speculate the extent to which carbon fiber components will be featured in that vehicle.

True to previous announcements concentrating on the truck and SUV market going forward, Ford displayed only one four-door sedan, a *Fusion*. Ford did display the carbon fiber-intensive Ford GT supercar, available in limited volume, and made a big splash with the introduction of the 2020 Mustang *Shelby GT500*, which will be available later in 2019. With a 700-horsepower, 5.2-liter supercharged engine, it is Ford's most powerful car ever. The base model includes a carbon fiber driveshaft and what appears to be an SMC hood. On display was the version with the carbon fiber track package, with exposed carbon fiber in the front splitter, rear wing and fully carbon fiber wheels, the latter supplied by Carbon Revolution (Geelong, Australia).

The JEC Group (Paris, France) hosted a large pavilion in the Cobo foyer during media and industry days, featuring production carbon fiber and fiberglass parts on various vehicles, including a thermoplastic liftgate debuting on the new Acura RDX and produced by Magna Exteriors (Aurora, Ontario, Canada). Traffic was brisk, especially during industry days, which is good, as it exposed more engineers to the potential of composites.

Overall, I came away from 2019 NAIAS with more questions than answers. We are currently in a market where autonomy, electrification and infotainment are dominant themes in the automotive industry. The need to improve fuel economy and emissions is still there, but the path forward is less clear. Maybe the June 2020 NAIAS will provide some insight into the future of composites in this market. We know it will be warmer. Here's to hoping it will be more vibrant as well. CW

ABOUT THE AUTHOR

Dale Brosius is the chief commercialization officer for the Institute for Advanced Composites Manufacturing Innovation (IACMI), a DOE-sponsored public-private partnership targeting high-volume applications of composites in energy-related industries including vehicles and wind. He is also head of his own consulting company, which serves clients in the global composites industry. His career has included positions at US-based firms Dow Chemical Co. (Midland, MI), Fiberite (Tempe, AZ) and successor Cytec Industries Inc. (Woodland Park, NJ), and Bankstown Airport, NSW, Australia-based Quickstep Holdings. He served as chair of the Society of Plastics Engineers Composites and Thermoset Divisions. Brosius has a BS in chemical engineering from Texas A&M University and an MBA.

Design engineering of tailored preforms

» Many new technologies have been developed recently to reduce the cycle time and cost of composites, with the aim of increasing composites' use in automotive, industrial and consumer goods applications. One of the most promising areas of development is in automated production lines that cut and place thermoplastic prepreg tape to form tailored blanks, and then convert these into parts using compression molding and injection overmolding. Companies active in this development include Airborne (The Hague, Netherlands), Van Wees UD and Crossply Technology (Tilburg, Netherlands) and the French engineering and advanced manufacturing R&T organization Cetim (Nantes, France). The latter unveiled its Quilted Stratum Process (QSP)[1] in 2015. QSP can produce complex-shaped parts with a production line pulse-time of 40-90 seconds. For example, using QSP, an omega-shaped profile molded into an L-shaped beam integrates 13 patches of 1.5-, 2- and 3-millimeter thick organosheet (woven fabric thermoplastic prepreg) and UD tape into a 6-millimeter-thick part with a cycle time of less than 77 seconds per part.

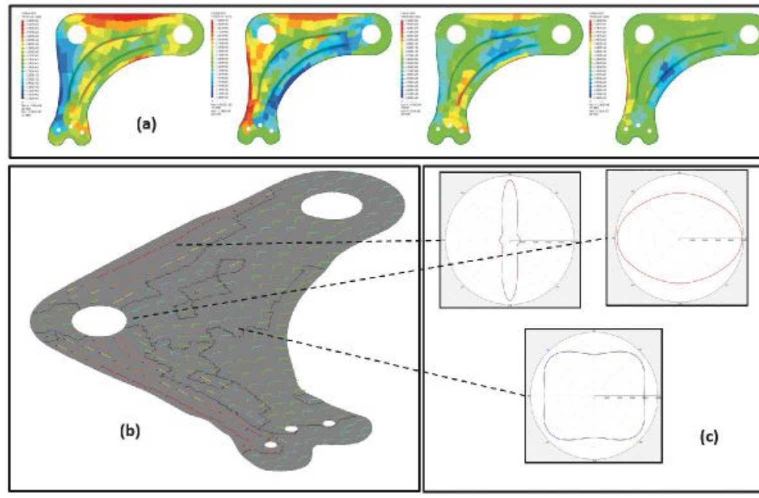

FIG. 1 Structural optimization results

A variety of displays are possible for QSD structural optimization results including (a) direct variable fields, (b) main direction stiffness and (c) stiffness polar plots. Source | Cetim

However, to take advantage of automation technology such as QSP, engineers must develop design and optimization methods that can evaluate many theoretical combinations of partial plies and the corresponding variation in the number, thickness, position and composition of plies (for example, reinforcement type and fiber orientation). With this in mind, Cetim has combined its experience in composites structural analysis, nondestructive testing (NDT) and manufacturing with the expertise of ONERA (The French Aerospace Lab) in advanced optimization methods used for years in the aerospace industry. The result is QSD, a tool now available in Altair Engineering's (Troy, Mich., U.S.) HyperWorks computer-aided engineering (CAE) software. It is basically an optimization add-on that helps to design composite parts made using tape- and organosheet-based processes and to control their cost, including how to reuse production scrap for zero-waste, closed-loop manufacturing.

Four-step process

The QSD methodology comprises four steps: structural optimization, shaping analysis, layup identification and design-to-cost analysis. Each of these helps the designer to quickly test what can be done with the input materials and to make the right decisions regarding mechanical and manufacturing constraints to control part cost. The QSD add-on was developed with Altair to make it directly usable by all HyperWorks OptiStruct users in a well-known environment. These users can take advantage of QSD without developing new finite element models, using their already developed internal know-how with the Altair software.

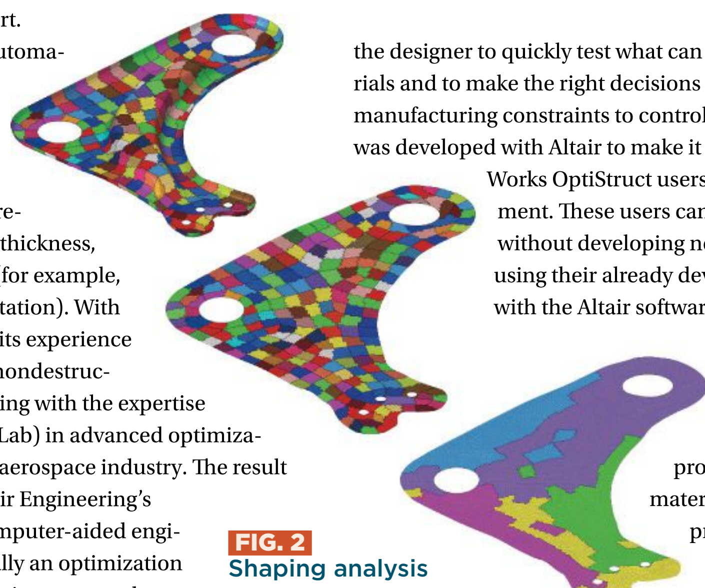

FIG. 2 Shaping analysis

QSD shaping analysis first flattens the part shape, then uses a clustering algorithm to partition the part into zones, and finally simplifies those zones — in this case, from 300 down to five — improving manufacturability.

Source | Cetim

Structural optimization

In the first step of QSD's process, thermoplastic tape materials are selected and their properties — including strength, modulus and other standard parameters — are input from the designer's selected database or by Altair's Multiscale Designer database of anisotropic thermoplastic composite materials and their micromechanical models. QSD uses this database and HyperWorks Optistruct to complete a "stiffness matching" optimization. Because some of the results from this analysis are not easily envisioned (for example, anisotropic stiffness), QSD provides a variety of ways to interact with the complex but rich data, including direct variable fields or interpreted results such as the main stiffness directions or a stiffness polar plot (Fig. 1). All of these displays define the same mechanical response but offer tailored views according to the user-selected preferences. The goal is to help designers understand and visualize the path forward for achieving the desired part performance. This step is where thickness and mass can be optimized, the latter typically reduced by up to 50 percent versus metal parts.

Shaping analysis

The next step helps designers make essential compromises by first flattening the part — converting from 3D shape to 2D sheet — with the Drape Estimator tool and then performing an automatic partition of this sheet by using a clustering algorithm. The goal is to make evaluation of the link between flat preform and final part simpler and faster. The automotive wishbone shown in Fig. 2 was originally split into 300 zones, based on the finite element mesh and results from OptiStruct, but that number was reduced to five zones by QSD.

The designer can then straighten and smooth the edges of each zone to minimize waste in the corresponding cut plies. This is a key step, improving manufacturing feasibility in order to control cost. This step is also interesting because the designer can evaluate the influence of ply and shape simplification on the part's mechanical performance. If compromises are to be made between mechanical performance and part manufacturability/scrap/cost, this step provides the data for that evaluation.

Layup identification

The aim in this step is to determine the best local layup for each zone by selecting from a QSD stacking database, or ply library, which can be enriched by user-specific data. The QSD tool helps the designer to sketch the part's plies and then test to find the best layup strategy by evaluating the part's response via mechanical criteria (for example, local displacement, buckling factor or eigenfrequency).

Design to cost analysis

In this final step, designers can evaluate the part's material cost, including scrap waste, and its manufacturing cost due to cutting and assembly of plies. Indeed, the number of plies and the material waste per ply are primary cost drivers. A quick evaluation of waste will soon be available in QSD, enabling estimated values during early design iterations. For final iterations, each ply can be exported to perform a detailed nesting analysis on whatever software the user prefers. Parameters for the part's cost evaluation formula may also be customized by the designer if needed. Thus, the designer may evaluate various layup strategies and compare their waste, manufacturability, cost and mechanical performance.

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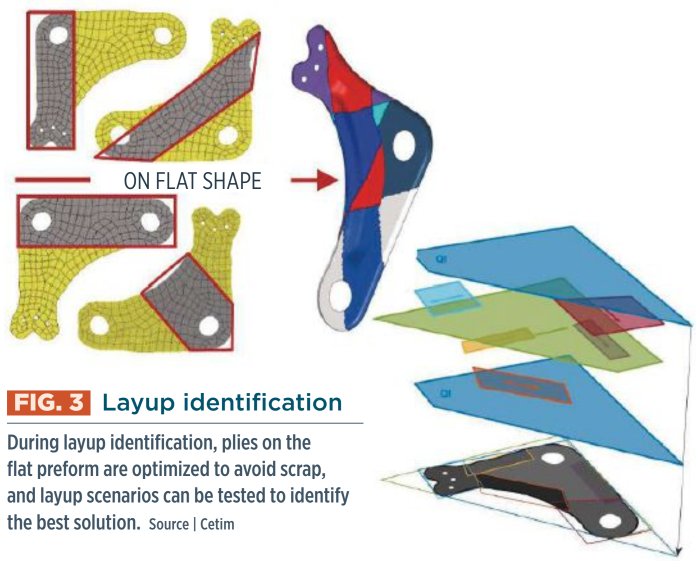


FIG. 3 Layup identification

During layup identification, plies on the flat preform are optimized to avoid scrap, and layup scenarios can be tested to identify the best solution. Source | Cetim

Note that QSD enables evaluating the use of all kinds of semi-products such as tape and woven or cross-ply organosheet. It can also evaluate recycled materials, such as nonwoven mats made from recycled carbon fiber by Carbon Conversions, ELG Carbon Fibre and others, or thermoformable sheet made from thermoplastic scraps using Cetim's Thermosaïc technology or other similar processes. Of course, the mechanical properties of such materials would be needed, but once determined, they could be easily input into the QSD modules, including the final ply library/stacking database. In this way, scrap from this part is used back in this part for zero-waste, closed-loop manufacturing — an ideal goal for all composites manufacturing with regard to sustainability.

Tool for increased use of composites

QSD is suitable for the first steps of the design process because it fits not just with Cetim's QSP process, but with all processes used to create tailored preforms, regardless of the degree of automation (for example, automated tape placement, automated cutting and hand layup). It is designed to help engineers optimize their parts and avoid bad design choices early in the design workflow. CW

REFERENCE:

[1] "A novel design method for the fast and cost-effective manufacture of composite parts employing the Quilted Stratum Process" François-Xavier Irisarri, Terence Macquart, Cédric Julien, Denis Espinassou.

ABOUT THE AUTHOR

Denis Espinassou is a mechanical engineer and project leader on QSD. He joined Cetim, the French mechanical institute, in 2010 as a specialist of design and optimization of long fiber thermoplastic composites structures. He's also in charge of product development through prototype manufacturing and mechanical validation.

Index sees gradual start to 2019 with slow new orders growth

January 2019 — 53.0

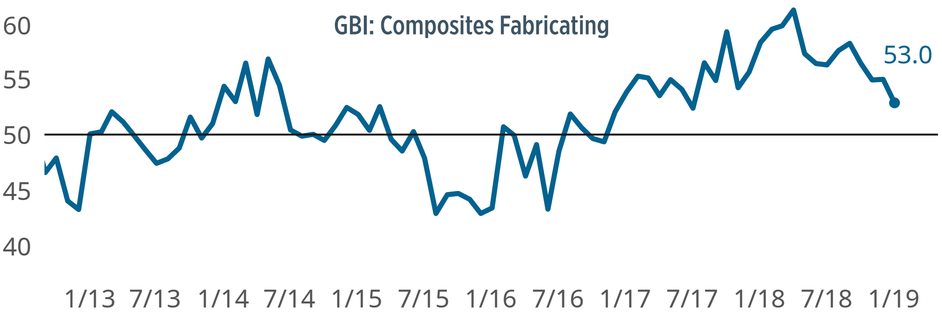
» The January GBI: Composites Index moved lower from the prior month to 53.0. The latest reading continues a slowing growth trend in the Index first established in the second quarter of 2018. The latest reading is 9.7 percent lower compared to the same month one-year ago — near the time that the Index was headed to a new all-time high in early 2018. Gardner Intelligence's review of the underlying data indicates that the Index was propelled higher during the month by production and supplier deliveries. The Index, calculated as an average, was pulled lower by new orders, employment, exports and backlogs. Backlogs was the only component to contract in January; the last time backlogs contracted was December 2017.

January marks only the second time in nearly a year that the reading for supplier deliveries was not the leading component of the Index. The supplier deliveries component has regularly been the fastest growing component of the Index since early 2018 when new orders and production readings peaked at all-time record highs. This trend suggests that the composites supply chain diligently expanded throughout 2018 in order to keep up with heightened composite orders.

According to the latest data, production expanded quickly at the start of the year while new orders growth simultaneously slowed. The combined effects of these conditions resulted in the sharpest contractionary reading in backlogs in over two years. Exports, which have experienced several recent months of contraction, did not mitigate the lower backlog reading.

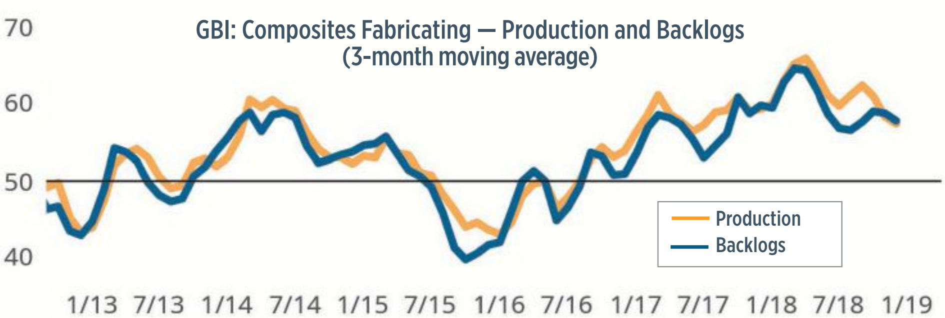
ABOUT THE AUTHOR

Michael Guckes is the chief economist for Gardner Intelligence, a division of Gardner Business Media (Cincinnati, Ohio, U.S.). He has performed economic analysis, modeling and forecasting work for nearly 20 years in a wide range of industries. Guckes received his BA in political science and economics from Kenyon College and his MBA from Ohio State University. **mguckes@gardnerweb.com**



Twenty-five consecutive months of expansion

A surprise jump in production growth combined with ongoing supplier delivery expansion were key supports in the Index's 25th consecutive month of expansion, the longest in recorded history.



January's strong production increase interrupts backlog's growth trend

A relatively greater expansion in production than new orders at the start of 2019 resulted in a significant contraction in the Index's backlog component. Slowing expansion in supplier deliveries gave way to production as the fastest expanding component of the Index in January.

Expanding production of aerospace wing skins, new partnerships in thermoplastic overmolding, student research into robotic fabrication of carbon fiber and more.

AEROSPACE

IAI launches new production line for F-35 wing skins

Israel Aerospace Industries (IAI, Lod, Israel) has launched a new production line for composite skins for the F-35 wings. The line was established following Lockheed Martin's (Bethesda, Md., U.S.) decision to expand the skins' production and its selection of IAI as the subcontractor responsible for the manufacturing.

The IAI board approved the construction of the new production line in 2015. The 20-year program is expected to yield revenues of hundreds of millions of dollars, with shipments begun earlier this year. The first shipments will be of some 700 kits with potential for additional orders at a later stage.

The skins are being manufactured using automated fiber placement (AFP), which must meet strict dimension and thickness parameters to give the aircraft its stealth capability.

IAI's new production line uses AFP to make composites wing skins. Source | Lockheed Martin

According to IAI, the establishment of the new production line constitutes a significant improvement of the company's automation and robotics capabilities, allowing it to become a key player in the military and commercial aerostructures field.

AEROSPACE

SGL Carbon and Airbus Helicopters to intensify collaboration

Source | SGL Carbon

Airbus Helicopters Germany (Donauwörth, Germany) and SGL Carbon (Wiesbaden, Germany) have agreed on a framework contract extending their cooperation to develop applications in the helicopter sector and further intensifying their partnership. The companies have been working together for years in the processing of composite materials for aircraft doors of the Airbus Group (Toulouse, France), and they have recently defined the framework conditions in a joint agreement that regulates the basic provision and further development of innovative carbon fiber and glass fiber materials. A first project currently in preparation will focus on the delivery of structural parts for Airbus helicopters.

AUTOMOTIVE

NCC and Surface Generation partner to demonstrate thermoplastic overmolding capabilities


Source | National Composites Centre

The National Composites Centre (NCC, Bristol, U.K.) is currently supporting Surface Generation Ltd. (Rutland, U.K.) in the application of its PtFS technology with a thermoplastic composites injection overmolding process. The two companies have worked together to produce a number of carbon fiber-reinforced/PA6 automotive demonstrators that will be assessed by an automotive OEM. Each manufactured component weighs 1.2 kilograms and comprises four continuous carbon fiber-reinforced/PA6 composite inserts overmolded with short carbon fiber-filled PA6.

"PtFS technology provides a variety of benefits for injection molding," says Sean Cooper, principal research engineer for High Volume Manufacturing at the NCC.

According to Cooper, "The ability to keep the average tool temperature higher than usual during the injection phase of the process can reduce the clamping force and injection pressures required for mold filling. The zonal temperature control is exploited to ensure an optimum joint is achieved between the inserts and the overmolding material. Enhanced thermal control also facilitates manufacturing for variable thickness injection moldings."

The NCC's overmolding equipment and the related facility cost was funded by the Aerospace Technology Institute (ATI, Cranfield, Bedfordshire, U.K.) and West of England Combined Authority (WECA, Bristol, U.K.). The NCC overmolding cell supplied by Engel (Schwertberg, Austria) features a horizontal 1,700-ton press, which supports injection barrel temperatures ranging to 420°C, pressures ranging to 2,000 bar and a shot volume up to 6,400 cubic centimeters. In addition to the acquisition of the overmolding cell, the NCC has also invested £690,000 of its High Value Manufacturing Catapult (HVM Catapult) funding into a capability development project to further apply fundamental research across design, simulation, structural analysis, manufacturing and physical/mechanical testing of high-performance overmolded structures.

CW MONTH IN REVIEW

Notes about newsworthy events recently covered on the *CW* website. For more information about an item, key its link into your browser. Up-to-the-minute news | www.compositesworld.com/news/list

New additive manufacturing platform prints transparent glass structures
The 3D printing platform aims to introduce industrial-scale production capabilities for molten glass.
1/2/19 | short.compositesworld.com/AM_glass

Graphene consortium produces graphene-enhanced composite leading edge
Resin used to produce the leading edge showed increased mechanical and thermal properties upon graphene addition, including a decreased fracture speed.
1/4/19 | short.compositesworld.com/leadingedg

Hexagon unveils production software business
Vero Software, FASys and SPRING Technologies combine under the Hexagon brand.
1/7/19 | short.compositesworld.com/H_software

FACC delivers 1000th outer flaps shipset for Airbus A321
The outer flaps of the Airbus A321 are manufactured from carbon fiber-reinforced plastic (CFRP) and glass fiber-reinforced plastic (GFRP).
1/10/19 | short.compositesworld.com/Airbus1000

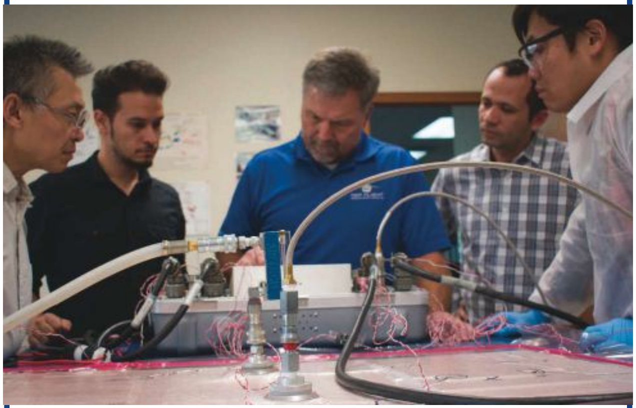
AMRC adds 3D permeability measurement bench
The system can measure the permeability of a dry reinforcement, important for learning how liquid resin will behave when injected in infusion and RTM processes.
1/10/19 | short.compositesworld.com/3D_AMRC

Bell Helicopter unveils air taxi design at CES 2019
The air taxi is powered by a hybrid-electric propulsion system from Safran and features Bell's signature powered lift concept incorporating six tilting ducted fans.
1/11/19 | short.compositesworld.com/Bell_taxi

TPI to open India-based wind blade manufacturing facility, signs supply agreement with Vestas
New manufacturing hub based in the Chennai region will provide composite wind blades from four manufacturing lines for India and export markets.
1/14/19 | short.compositesworld.com/Wind_India

Boom Supersonic gets funding for Mach-2.2 airliner
Boom is assembling a subscale prototype of its supersonic airliner to demonstrate the craft's aerodynamics, advanced composite materials and propulsion system in flight.
1/14/19 | short.compositesworld.com/Mach_fund

AMRC and Prodrive partner to advance manufacturing of recyclable composite components
The companies have been collaborating on Prodrive's P2T process, which is used to manufacture recyclable composite components that can satisfy end-of-life requirements without compromise in the performance of the original parts.
1/18/19 | short.compositesworld.com/AMRC_Pro



ARCHITECTURE

LeMond Composites and Yale School of Architecture explore carbon fiber robotic fabrication

LeMond Composites (Oak Ridge, Tenn., U.S.) has partnered with the Yale School of Architecture (YSoA, New Haven, Conn., U.S.) to explore new methods of computing and manufacturing structures using advanced carbon fiber technologies.

A new seminar at the architecture school entitled “Computational Composite Form: computational design & carbon fiber robotic fabrication” was led by YSoA Professor Ezio Blasetti. The YSoA students built computational tools and material prototypes using the robotic tools of the YSoA fabrication studio. The student projects tested manufacturing strategies and material properties of carbon fiber.

Founded by Tour de France champion Greg LeMond, LeMond Composites seeks to offer solutions for high-volume, low-cost carbon fiber. LeMond claims its new manufacturing process will enable reduced carbon fiber prices and expand global production capacity, with the goal of making carbon fiber more accessible for the next generation of designers and builders. The partnership between YSoA and LeMond will continue as students continue to develop their work into 2019.

Students present advanced carbon fiber manufacturing projects at the Yale School of Architecture. Source | LeMond Composites

Professor Ezio Blasetti (center) leads the advanced carbon fiber manufacturing seminar at the Yale School of architecture. Pictured here with Geoff LeMond (left) and Greg LeMond (right).

Source | LeMond Composites

Thermoplastic composite pipe on the rise in the deep sea

Demonstrators, pilot programs and qualification efforts are paying off as thermoplastic composite pipe (TCP) makers take orders for deep-sea oil and gas applications.

By Karen Mason / Contributing Writer

» Visit the news pages of the Airborne Oil & Gas (AOG, IJmuiden, Netherlands) and Magma Global Ltd. (Portsmouth, U.K.) websites and you'll come away with the impression that 2018 was a watershed year for these two leading manufacturers of thermoplastic composite pipe (TCP) for deep-sea applications. But don't be surprised if 2019 news about this burgeoning market for composites eclipses that of the preceding year.

Lightweight and spoolable

Flexible and light, TCP is much more easily transported and installed in deep-sea applications than conventional metal pipe. Spooled here is 1.2 km of 6.7 ksi m-pipe, made by Magma Global. Source | Magma Global

A few notable achievements of 2018 for AOG: In June, the company commenced a qualification program for carbon fiber/polyvinylidene difluoride (PVDF) risers (pipes connecting subsea production systems and surface production vessels) for a major operator in South America. AOG worked in collaboration with Subsea 7 (Luxembourg), a major offshore installation contractor, on this project. In August, after an extensive five-year qualification program followed by the world's first pilot installation on hydrocarbon (full well bore) service of a glass fiber/high-density polyethylene (HDPE) flowline (pipe that connects the well head to further processing equipment; see "Oil & gas subsea pipe terms," p. 18), Petronas (Kuala Lumpur, Malaysia) recognized AOG's TCP flowline as having achieved technology readiness level 6 (beta prototype verification). "And we expect to reach TRL 7 [pilot system demonstration] in 2019," reports Martin Van Onna, AOG CCO. Along with these successful qualifications and pilot programs, AOG reports a growing commercial track record, especially with its glass fiber/HDPE TCP.

As for Magma, 2018 was equally eventful. In March, Tullow Ghana awarded a contract to Magma for a 2.5-kilometer flowline for its development of Tweneboa, Enyenra, Ntomme (TEN) offshore fields. In May, working with Ocyan (Rio de Janeiro, Brazil), an offshore services company, Magma completed and received third-party validation of a Composite Multi-Bore Hybrid Riser (CMHR) design that employs Magma's carbon fiber/polyetheretherketone (PEEK) m-pipe. Magma and Ocyan are bidding the CMHR for deep-water developments in Brazil. Magma announced in August that a joint initiative with Equinor (Stavanger, Norway) had secured £10.5 million in funding from Innovate UK, a government funding organization, to qualify an all-Magma solution for jumpers (pipes that connect flowlines and/or subsea facilities). Finally, in November, the Energy Institute (London, U.K.) bestowed its 2018 Award for Innovation to Magma for its m-pipe, citing the pipe's ability to solve the challenges of oil and gas production in deepwater reserves, as well as its ability to be reused.

In 2019, AOG and Magma have plans for increased production capacity as they serve the composites market. "Especially in the second half of last year," Van Onna affirms, "the demand is growing so fast that we really need to grow very, very quickly."

TCP appeal

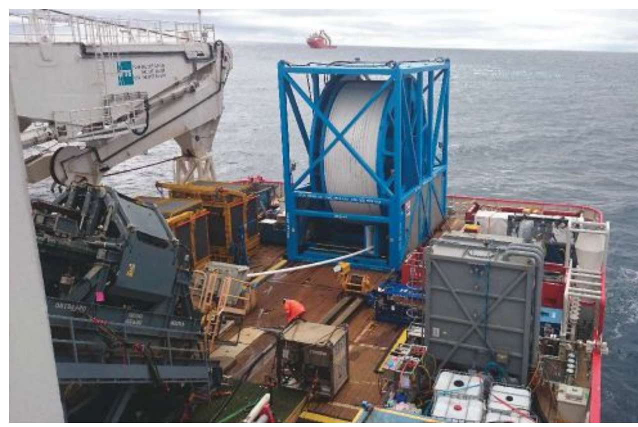
Underscoring this rapid growth is the relatively brief history of TCP deployment in deep-sea oil and gas applications. Note that TCP is distinct from reinforced thermoplastic pipe — RTP — which has been around since the 1990s. RTP consists of a thermoplastic liner overwrapped with *unbonded* aramid or glass fiber composites, then coated with thermoplastic. It is used in lower pressure and less demanding temperature applications compared to the fully bonded TCP. Although TCP consists of a similar set of materials, it is suited to higher pressures and a greater temperature range for two reasons. First, some TCP uses higher performing thermoplastic resins, such as PEEK, and/or higher strength reinforcement like carbon fiber. Second, TCP layers are *bonded* to each other through a melt-fuse manufacturing process, which yields higher performance properties than RTP made from the same materials.

Only 11 years ago, Van Onna recounts, *no* TCP had been deployed in deep-sea applications. Then in 2009, AOG developed and deployed the first offshore TCP downline (used to pump fluids down to the seabed for injection into subsea pipelines or subsea wellheads). The company built a full-scale TCP production site in 2012. By 2018, AOG had increased production capacity to include three production lines as well as manufacturing capability that includes glass fiber/HDPE for applications up to 65°C/50°F and 5 ksi; carbon fiber/polyamide 12 for applications up to 80°C/180°F and 10 ksi; and carbon fiber/PVDF for applications up to 121°C/250°F and 15 ksi.

In the meantime, Magma was founded in 2009 and began deploying its m-pipe in 2012, opening its production site in Portsmouth, U.K. in 2016. At the company's five-year anniversary »

Technology ready

An extensive qualification and pilot program has resulted in AOG's carbon fiber/polyvinylidene difluoride (PVDF) gaining acceptance for demanding flowline applications. Source | Airborne Oil & Gas



Ease of installation

Spooled 2.5-inch diameter TCP downline illustrates the ease of installation on the high seas. Source | Airborne Oil & Gas

Automated production

Described as a "fully automated robotic 3D laser print process," Magma's production line is centered on automatic tape laying with in-situ laser fusing. Source | Magma Global

Local production

Magma's in-country manufacturing module (ICMM) is designed to bring m-pipe production to a locale near the subsea application, easing logistics and cost of installation. Source | Magma Global

celebration, CEO Martin Jones commented, "The aviation industry is a good precedent where the use of carbon fiber is now standard. It is now also happening in oil and gas. We are currently engaged with all of the major operators."

The growing adoption of TCP stems from its numerous cost-saving advantages over conventional pipe. For example, despite higher cost of materials, AOG's highest performance carbon fiber/PVDF in a flowline application generates a reported 30 percent savings on as-installed cost compared to metal flowlines. Similarly, a Calash (London, U.K.) commercial review of m-pipe versus steel in a single-line offset riser (SLOR) application estimated an as-installed cost savings of 11 percent. These savings result from several TCP properties that make transportation, preparation (for example, terminating pipes with end fittings) and installation considerably less expensive than performing these tasks with pipes made from other materials.

As is often the case with composites, the first such property is light weight — TCP weighs as little as one-tenth the weight of steel pipe — but the combination of light weight and flexibility of the pipe makes for a critical advantage: the pipe can be spooled on relatively small drums and subsea pallets. Because of this, smaller vessels can transport and install long spans of TCP — a logistical and economic boon in more remote offshore locations (for example, off the West African coast), where deployment of conventional heavy-lift vessels is a costly proposition. Another cost-saving advantage created by the melt-fusing capacity of TCP is that the pipe can be terminated and end fittings installed onsite.

TCP offers high strength, flexibility and ease of termination, giving it the best qualities of conventional metal pipe (strong but rigid) and flexible pipe made from unbonded layers of helically applied metal wires and extruded thermoplastics (flexible but heavy, and very costly to terminate onsite). TCP is fully capable of efficiently handling the demanding pressures and temperatures of subsea applications — both from external conditions and from the internal conditions created by the fluids moving through them. TCP's thermoplastic liner also offers high flowrates due to its low coefficient of friction. Two other key TCP properties — corrosion and fatigue resistance — make TCPs highly durable, even as energy companies are more frequently pumping sour (that is, acidic) crude oil found deeper underground.

Accelerating pipe production

Preparing to meet accelerating demand, AOG is one year into a three-year program designed to increase the company's production capacity by a factor of five. "We are implementing more than 10 individual measures that all lead to increased production capacity," Van Onna says.

TCP is produced at AOG in three continuous steps. First, a thermoplastic liner is extruded. Next, automatic tape laying (ATL) with in-situ consolidation winds anywhere from a few to 100 layers of the fiber-reinforced thermoplastic tape, with each layer melt-fused onto preceding layers. Lastly, the pipe is run through a coating extrusion die. This is not regular coextrusion, Van Onna explains. "We melt the outside composite layer and pressure-form the coating onto the laminate. The result is a pipe with high shear strength between the coating and laminate, which enables our clients to terminate our TCP anywhere, while maintaining a high-strength, durable and protective coating."

AOG is adding winding stations, an obvious way to increase capacity, but it is also increasing extrusion and winding speeds. The company has integrated a proprietary automatic inspection system on the production line, which ensures consistent characteristics and properties even as production speed is increased.

SIDE STORY

Oil and gas subsea pipe terms

- Downline: used to pump fluids down to the seabed for injection into subsea pipelines or subsea wellheads
- Flowline: connects the well head to further processing equipment
- Jumper: connects flowlines and/or subsea facilities
- Riser: connects subsea facilities to a floating surface rig

Magma's production process bears a resemblance to AOG's. Magma m-pipe consists of about 25 percent carbon fiber, 25 percent S2 glass fiber and 50 percent PEEK. Magma refers to its manufacturing process as a "fully automated robotic 3D laser print process." It consists of extrusion of a smooth-bore inner pipe precursor made from PEEK onto which an ATL process uses a laser to fuse alternating layers of glass fiber/PEEK and carbon fiber/PEEK tapes. Magma selected PEEK, which the company acquires from Victrex (Lancashire, U.K.), because of its very high fatigue capacity. Toray Industries (Tokyo, Japan) supplies the reinforcements used in m-pipe. Magma is keeping up with production demands not only with its internal Portsmouth, U.K., production line but with mobile in-country manufacturing modules (ICMM), the first of which is also operating in Portsmouth. Magma anticipates deploying more ICMMs, since the company favors local production, both logistically and financially, especially for riser applications.

Commercial success soon

Importantly, the development of TCP has been accompanied by the creation of a formal standard for design and qualification of TCP in subsea applications. The road to this standard has been painstaking, Van Onna says, but the result is a document and guideline that engenders among energy professionals a great confidence in the product's long-term performance, as well as its expected cost in use. Such confidence, one can imagine, is critical in a highly regulated and closely watched industry like offshore oil and gas production, where pipe failure is simply unacceptable. The standard, Van Onna explains, covers the qualification of the base materials as well as the design method and, of course, the production technology. AOG has been able to demonstrate that its TCP base materials and production quality are equal to those of benchmark, autoclave-cured composite structures like those used in aerospace.

AOG's approach to qualification, Van Onna continues, was to "run separate qualification for all our base materials. Then we design and manufacture pipe of any size using those qualified materials." Achieving qualification and climbing through TRL levels, TCP is now poised for a mass volume of products beginning in 2019, Van Onna believes. CW

LEARN MORE

Read this article online | short.compositesworld.com/TCPdeepsea

ABOUT THE AUTHOR

CW contributing writer Karen Mason focused academically on materials science and has been researching and writing about composites technology for more than 25 years.
kmason@compositesworld.com

Moving continuous-fiber 3D printing into production

With patents proliferating and production applications emerging, 3D printing with continuous fiber reinforcement is poised for significant market growth.

By Karen Mason / Contributing Writer

Highly complex structures

The continuous fiber-reinforced print technology developed by the University of South Carolina's McNair Center and partners is designed to produce highly complex and unique structures. Source | McNair Center

» For an industry accustomed to years-long (if not decades-long) development cycles for new components, composites fabricators may find the timeline for a bicycle frame at Arevo (Milpitas, Calif., U.S.) quite remarkable. Wiener Mondesir, Arevo chief technical officer, reports that the company rolled out a demonstrator frame made from continuous carbon fiber/polyetheretherketone (PEEK) in May 2018; was approached by *every* major U.S. bicycle OEM shortly after; and launched into bike frame production in its new 20,000-square-foot facility in February 2019 — a span of just nine months. The bicycle industry is perhaps even more astounded: an Arevo frame for a battery-assisted "ebike" advanced from design to prototype in just 18 days, compared to 18 months for traditional composite bike frames.

The key to this short development cycle? Continuous fiber-reinforced 3D printing.

Though Arevo's experience is unlikely to become the new normal for development cycles of all composite components, it augurs well both for the composites industry and for innovators like Arevo that are advancing this new technology. *CW* has been following these developments since 2014, yet news from stakeholders suggests that the next one to two years may see accelerated growth in R&D, prototyping, small-batch and — yes — commercial production applications. *CW* gathered the latest updates from continuous fiber-reinforced 3D printers around the world, including contributors from university research facilities, entrepreneurs and small start-ups, and established composites companies.

Interestingly, efforts in continuous fiber-reinforced 3D printing seem to be diverging in two primary directions: those pursuing high-volume applications, and those servicing prototype and small-batch parts with especially challenging features such as highly complex geometries or critical performance characteristics that require extremely accurate manufacture. Whether these two market paths are accompanied by two distinct technology paths is a point of debate, as revealed in some of the opinions expressed here.

Volume production

Arevo's swift move into commercial production volumes is powered by the company's direct energy deposition (DED) process, which prints components from thermoplastic towpreg. Comprising an industrial robot, a printhead with laser heating and a rotating build platform, the Arevo DED work cell is reportedly capable of accelerating production speed 100-fold compared to previous continuous fiber-reinforced 3D printing.

Arevo's current focus is on both consumer products, evidenced by the most recently introduced bike frame for a new line of electric bikes; and on aerospace applications, toward which Airbus Ventures has recently invested in Arevo's efforts.

The eight robotic work cells that have begun producing bike frames in Arevo's new facility are each able to produce one frame per day, including the printing itself as well as post-processing (for example, drilling holes) and pre-sanding for painting. Mondesir

predicts a speedy ramp-up, with three times faster cycle time within the first year of production. To accomplish this, Arevo is working to implement "parallelizing," that is, running multiple printheads per robot and/or multiple robots per work cell. The company is also investigating larger feedstock (large tow). As with other manufacturing technologies, a balance will have to be struck between the slower cycle times but feature-rich, complex geometries possible with small tow, and the higher production speeds but steerage limitations of large tow.

To maintain quality and repeatability throughout the ramp-up, Arevo has implemented in-situ inspection and machine learning to control process parameters in real time. The printer is fitted with numerous sensors — measuring height, pressure, distortion, etc. — and the system's software uses data from these sensors to adjust process parameters as needed. "As we run the robot faster, we make sure that deposition rate, heating, consolidation and other parameters match baseline," Mondesir explains. "In-situ inspection is the way to go. We build a digital model of the process, then iterate and improve. Allowables and data for a host of thermoplastics are now known."

Another company working toward mass production with a continuous fiber-reinforced 3D printing process is Orbital Composites (Silicon Valley, Calif., U.S.) — though CEO Cole Nielsen is pushing away from the "3D printing" moniker, noting that there has been "too much hype for '3D printing'; the fact is, you can't print just *anything*." He prefers to focus on the next generation of customers' products rather than the additive manufacturing technology itself. Built for the demands of the end product, Orbital's modular robot printers can vary greatly.

Orbital is devoting its R&D efforts to optimizing print technology for standard, lower cost materials.

The trajectory for this technology? "We want to be able to print a million of one object," Nielsen says. With this goal, Orbital is focused not just on the flexibility of 3D printing but also on its reliability, repeatability and layman usability.

Like Arevo's technology, Orbital's modular, coaxial extrusion end effectors, parallel robotics and out-of-autoclave processes boast production speeds up to 100 times faster than what was possible with previous continuous fiber-reinforced additive manufacturing. The extrusion nozzle feeds fiber through its central bore and the matrix material through the surrounding annular nozzle. Parallel robotics accelerate production velocity through teamwork.

Continuous fiber and hybrid applications

9T Labs' CarbonKit extends existing 3D printer capabilities to continuous carbon fiber applications. A sampling of components includes (pictured left to right) an 8-cm diameter mini-drone frame consisting of neat polymer interior with carbon fiber-reinforced face sheets; a 10-cm diameter CFRP clamp along with a carbon fiber/polyamide organo sheet with local continuous fiber reinforcement; and a full carbon fiber-reinforced wing (chord length of ribs approximately 20 cm).

Source | 9T Labs

Orbital's technology development philosophy is "material agnosticism." Ideally, the company wants to design the specific end effectors and print cells around the material a customer has already selected, Nielsen says, noting that aerospace material developments may have been specified five or 10 years before deployment. Orbital's technology is designed to adapt to nearly any composite material: plastic, ceramic or metal matrix, including thermosets, thermoplastics and silicon carbide; dry, bindered fiber ranging from 3K to 48K tow; and with the capacity to incorporate copper or aluminum wire, nanomaterials, conductive inks or other options that help to achieve a multifunctional structure.

Importantly, Orbital's system works effectively with commodity materials — a necessary capability to be cost-competitive in high-volume applications. "We want changes happening on the tool side, not the material side," says Amolak Badesha, Orbital COO. "We would rather have a very complex tool and low-cost materials than the other way around." Unlike companies that are producing specialty — and more costly — materials optimized for their print technology, Orbital is devoting its R&D efforts to optimizing the print technology for standard, lower cost materials. As the company nears public disclosure of some major projects, »

3D-printed carbon fiber bike frame

Arevo's "ebike" is the world's first battery-assisted bicycle using a 3D-printed carbon fiber frame. Arevo partnered with Oechsler (Ansbach, Germany) to leverage Oechsler's Drivematic three-speed automatic gearbox with the Arevo frame. Source | Arevo

the Orbital team is optimistic about this potential for large-scale applications.

Across the Atlantic, 9T Labs (Zurich, Switzerland) in February began beta testing of its CarbonKit, which is designed to make existing 3D printers capable of continuous fiber printing. An undisclosed serial production application, also in the works, is expected to make around 30,000 parts per year. A spinoff from the Swiss Federal Institute of Technology Zurich (ETH Zurich), 9T Labs has a goal of using 3D printing to make carbon fiber-reinforced composites more accessible for industrial serial production, says co-founder Martin Eichenhofer. "We provide the CarbonKit so engineers at R&D departments, students at universities or makers at home can experience the new possibilities and advantages of 3D printing with continuous fibers at competitive entry-level pricing. This is because we see the mass adoption as crucial to finding real industrial-use cases."

The CarbonKit employs knowledge gained from the continuous lattice fabrication (CLF) process that Eichenhofer developed as a Ph.D. student at ETH Zurich. Intended for use with industry-grade, inexpensive material as feedstock, the system pultrudes composite rods, which then travel through a pulling unit and into a thermally regulated extrusion head. The system, he says, can work with a range of thermoplastic matrix systems and produces fiber volume content upwards of 50 percent. Another important feature is the ability to scale the extrusion cross-sectional area, so that the system can accommodate high-resolution applications with small tow, as well as big area additive manufacturing with large tow.

An R&D/prototyping focus

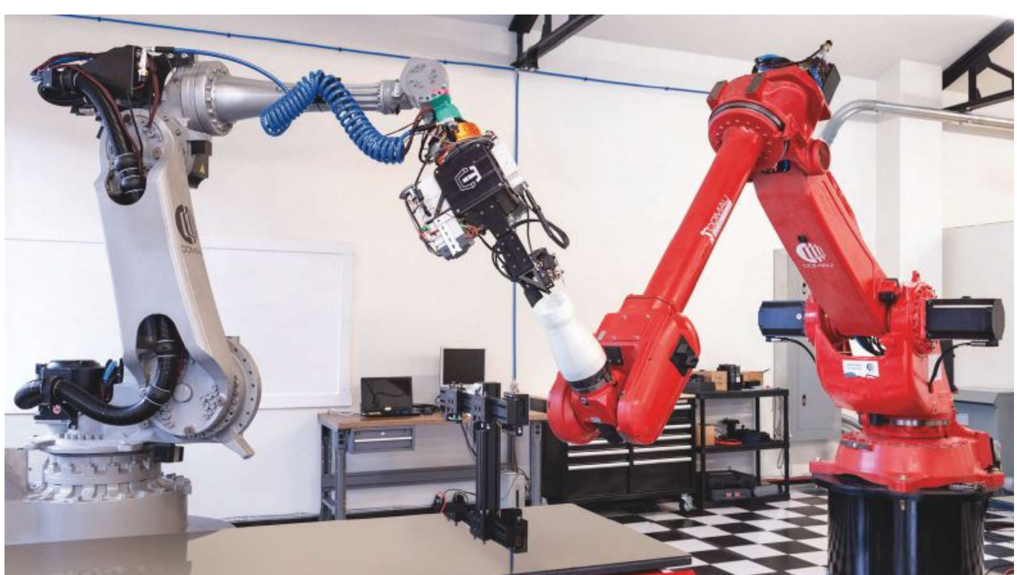
On the other end of the market spectrum, researchers at the University of South Carolina's Ronald E. McNair Center for Aerospace Innovation and Research (Columbia, S.C., U.S.) have collaborated with TIGHITCO (Atlanta, Ga., U.S.) and Ingersoll Machine Tools (IMT, Rockford, Ill., U.S.) to develop continuous fiber-reinforced 3D printing for highly specialized and demanding applications. The technology is a fused filament fabrication (FFF) approach for which the team has developed a thermoplastic composite filament and a robotic 3D print system (patents pending). The system, which will be produced by IMT, provides seven degrees of freedom using a Siemens-controlled industrial robotic platform equipped with a continuous fiber deposition end effector. "One of the biggest things we want is to remain leaders in part accuracy," says Arturs Bergs, TIGHITCO project engineer (who works onsite at the McNair Center). "Rather than large beads and large patterns with significant post-processing, we want to print with minimal post-processing."

The McNair team believes that the technology is well-suited for three application trajectories. First is low-volume manufacturing in aerospace or automotive applications; for example, this

Advancing the process

Continuous Composites, which patented its continuous fiber-reinforced 3D printing process in 2012, is adding capabilities, including dual robot operations.

Source | Continuous Composites



includes applications where only one of a particular high-strength component is needed per vehicle, making a mold or mandrel difficult to cost-justify. Second is highly complex structures, such as stiffened grids, for which other manufacturing methods are unable to produce the required strength- and stiffness-to-weight ratios. Third is overprinting, a technique in which a component is inserted during the print cycle and is thus fully embedded within the printed part. Examples include printing around a threaded insert instead of adding it through a post-print process; or embedding RFID chips or electronic sensors within a printed part. Overprinting thus may enable part consolidation. Michel van Tooren, McNair Center professor and senior member, explains: "An automated fiber placement [AFP] fuselage has a minimal level of integration, with many smaller parts bolted on. The brilliance of this technology is that if you make a composite component with thermoplastics, you remelt each time to add new parts through overprinting." Eliminating rivets, fasteners and bonding adhesives could advance these structures significantly.

Integral manufacturing

Continuous fiber 3D printing can print multiple structures and sub-structures as a single component, like this aircraft spar with an embedded gusset. Printed with Continuous Composites' CF3D process, it is later skinned with a hand layup of a carbon fiber composite.

Source | Continuous Composites

A pioneer of continuous fiber-reinforced 3D printing, holding the earliest patents on the process worldwide (2012), is Continuous Composites (Coeur d'Alene, Idaho, U.S.). CEO Tyler Alvarado holds an optimistic view of long-term market penetration for the company's trademarked CF3D technology and foresees a day when it will be used to print entire aircraft or automotive structures on demand — whether 10 or 10,000 parts. "The economics of CF3D will democratize composites into a variety of new industries and applications," Alvarado believes.

Using snap-cure thermoset resins (though also amenable to thermoplastics), CF3D impregnates the reinforcing fiber within the printhead and cures the composite immediately after material deposition. Thermosets enable the process to perform high-speed printing unsupported in free space. CF3D is achieving 50-60 percent fiber volume, and Continuous Composites is continuing to advance the process in numerous ways. Some of the most significant recent developments include more automated toolpath generation; automated tool changing to enable high-resolution »

■ Large-scale printing

The CFAM Prime printer is designed to produce continuous fiber-reinforced components on a continuous 24-hour unattended production cycle. Its build volume of 2m x 4m x 1.5m is reportedly the largest in Europe. Source | CEAD

single-channel and high-deposition multi-channel printing on the same part; improved accuracy and precision of robots; and development of materials with greater mechanical properties.

Like Arevo, Continuous Composites is not waiting for the aerospace and automotive markets to materialize. Instead, Alvarado anticipates near-term commercial application in industries that can "self qualify," such as DOD, experimental aircraft, marine, construction, sporting goods and Formula 1 automotive.

A technology reportedly similar to Continuous Composites' CF3D, and which has reached the early adoption and development phase (technology readiness level 5), is the continuous fiber manufacturing (CFM) process from moi composites (Milan, Italy). Established in early 2018, the company is another university spinoff, building on work done at +LAB laboratory of the Politecnico di Milano (Milan, Italy).

Moi's CFM technology was developed to solve the challenge of 3D printing with thermoset resins. The process has successfully printed continuous glass fiber-reinforced composites with epoxy, acrylic and vinyl ester. UV is the predominant cure process used with moi's print technology, but the process is also amenable to other cure and post-cure mechanisms — necessary for carbon fiber applications because carbon's opaqueness and black color interfere with UV curing, reports moi co-founder Michelle Tonizzo.

Short-run focus

Another European venture expected to launch production applications in the near term, CEAD Group (Delft, Netherlands), introduced its large-scale CFAM (Continuous Fiber Additive Manufacturing) Prime 3D printer in November 2018. While initial CFAM Prime applications will build prototypes, CEAD business development director Charléne van Wingerden believes the system to be especially beneficial for large, complex products in small quantities, where short lead times and the elimination of molds make it a highly efficient manufacturing process.

CFAM Prime is a complete, enclosed printer built on a Siemens CNC system base. With a build volume of 2 by 4 by 1.5 meters, it is reportedly the largest 3D printer available in Europe. The printer has an average output of 15 kg/hr and can run for 24 hours without an operator present. It features a smart heating/cooling system that monitors the process with thermal cameras and adjusts as needed in real time. A range of thermoplastics can be used on CFAM Prime. To create continuous fiber-reinforced composites, CEAD first pre-impregnates continuous glass or carbon fiber with the desired thermoplastic. The printhead then combines the continuous fiber with melted thermoplastic granules, which may also include a percentage of chopped fiber.

CFAM Prime's first two customers are Royal Roos (Rotterdam, Netherlands), a marine engineering company, and Poly Products (Werkendam, Netherlands), which specializes in fiber-reinforced plastics for construction. Royal Roos is considering projects such as gangways, for which unreinforced or chopped fiber 3D printing could not produce the needed strength and light weight. Poly Products expects to make façade cladding pieces, trim lines for cargo ships and various train applications as its initial CFAM Prime projects.

Startup Anisoprint (Moscow, Russia) also has an eye toward short-run production applications. Like CEAD and others, Anisoprint prepregs the reinforcing filament before feeding it into the printer, but this technology has a twist: the filament is prepregged with a specially formulated, proprietary thermoset and is then *fully cured,* and the matrix resin typically is a thermoplastic. Other composite print experts have expressed some skepticism, given the brittleness of a typical cured thermoset filament. Anisoprint CEO Fedor Antonov says, "The fully cured filament is stiff at room temperature but in a rubbery state when heated." The thermoset polymer more easily wets out the individual monofilaments than thermoplastics, he continues, and it provides better adhesion.

Anisoprint's first 3D printer is the Composer, a desktop composite fiber co-extrusion (CFC) unit. The dual matrix system is compatible with thermoplastic processing temperatures up to 270°C. In addition to several customers reviewing prototypes, one current small-batch production customer is Supreme Motors, which is using a Composer to fabricate parts and fixtures for its "UNA wheel" wheelchair electric drive unit. Once it ramps up production, the company expects to print a few thousand parts per year. Anisoprint also plans to bring an industrial model, a robotic cell-based machine, to the market within the next two years.

Volume *and* small-run production?

Known as a pioneer in continuous fiber-reinforced 3D printing, Markforged (Watertown, Mass., U.S.) has established a solid customer base for its X7 printer, which is currently applied primarily to small-run production; but Jon Reilly, MarkForged VP of products, anticipates technological development to converge for small-run and volume production. Noting that the current market for continuous fiber 3D printing is in high-value, low-volume parts, Reilly expects the target market to grow toward relatively high-volume, low-value parts as printer manufacturers reduce printing and material costs. "3D print companies that don't invest for scale will lose out," he believes. Yet with few exceptions for ultra-specialized parts, he predicts that print technology made for volume will still possess the capabilities needed for highly detailed, complex components, because complexity is generally addressed in the software.

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MarkForged's continuous fiber system uses proprietary towpreg made with a specially developed thermoplastic resin, and it uses two printheads, one for the matrix resin and the other for the towpreg. Technology improvement efforts are focused on reliability and repeatability, Reilly says. The company also is working toward an entirely closed-loop process and developing additional features such as fully integrated material tracing and comprehensive automatic reporting.

A key market for Markforged is the printing of fixtures and components for traditional production-line tooling. Compared to machined aluminum components, Reilly reports, "Ours are just as strong but lighter. They don't mar the part like a metal component can. And they are ready the same day." Customers in this market have reported an impressive return on investment of one to three months.

Software standardization needed

Nearly every team reported that they were developing proprietary software, primarily because the needed software does not exist commercially. "We wrote our own software for tool path planning because we couldn't find one with continuous tool paths," McNair Center's De Backer affirms. Alvarado notes that Continuous Composites wanted to generate tool paths in a more automated fashion than traditional slicing software would provide. As with most software development, though, it seems likely that a standard for tool path generation software will emerge.

In the meantime, activity on the software, hardware and material fronts will likely continue at a brisk pace for the foreseeable future. Innovators and entrepreneurs continue to dominate the continuous fiber-reinforced 3D printing market, and it should be some time before a shakeout and industry consolidation occurs. CW

ABOUT THE AUTHOR

CW contributing writer Karen Mason focused academically on materials science and has been researching and writing about composites technology for more than 25 years.
kmason@compositesworld.com

Building confidence in recycled carbon fiber

Recycled carbon fiber is proving, increasingly, to be a cost-effective, environmentally sustainable composite solution for automotive and other high-volume applications.

By Amanda Jacob / Contributing Writer

Recycled or hybrid nonwovens

Nonwoven mats, either 100 percent recycled carbon fiber or hybrid blends with thermoplastic fibers, can be compression molded or processed as prepreg or sheet molding compound.

Source | ELG Carbon Fibre

» Carbon fiber composites are valued for their potential to provide more sustainable transportation solutions for reduced carbon emissions during use, yet the production and end-of-life phases of their lifecycle reveal a greater environmental impact than the metals they typically replace. Current carbon fiber composites production methods result in significant waste, little of which is recycled. As carbon fiber composites use continues to grow and sustainability strategies push for "zero-waste-to-landfill," routes to reclaiming and reusing this expensive resource are becoming more critical. It's not an easy business to develop, but a small number of companies around the world have set out to tackle the technical and commercial challenges involved in establishing carbon fiber recycling operations. Among these companies is ELG Carbon Fibre (Coseley, U.K.), which runs a 1,500-metric tonne capacity plant in the U.K. and is now gearing up for global expansion.

ELG's first Technical Workshop, held at the University of Warwick (Coventry, U.K.) in 2018, brought together a number of the company's academic partners and customers to share the latest research findings, to exchange experiences and to discuss knowledge gaps and potential road blocks to market growth.

"There is extensive, ongoing research into recycled carbon fiber, but the individual projects tend to be siloed," notes Frazer Barnes, managing director of ELG Carbon Fibre. "We want to share the breadth of technical work and practical knowledge we now have available to build confidence in the marketplace."

Why use recycled carbon fiber?

ELG sets out three main drivers for use of recycled carbon fiber (rCF): cost, security of supply and environmental sustainability. The cost proposition centers on making lightweight carbon fiber composites more affordable. ELG's reclaimed carbon fibers are said to have similar mechanical properties to the original fibers, usually retaining at least 90 percent of their tensile strength with no change in modulus. The fiber price is typically 40 percent less than industrial grades of virgin fiber. Recycled fiber can therefore provide similar weight-saving benefits to virgin fiber at substantially reduced part cost, making it attractive for automotive lightweighting applications (Fig. 1).

The use of rCF could also mitigate shortage of virgin fiber supply. As carbon fiber demand increases, manufacturers are scheduling capacity expansions, but some analysts predict a gap between supply and demand of about 24,000 metric tonnes by 2022. With current composites manufacturing techniques, waste »

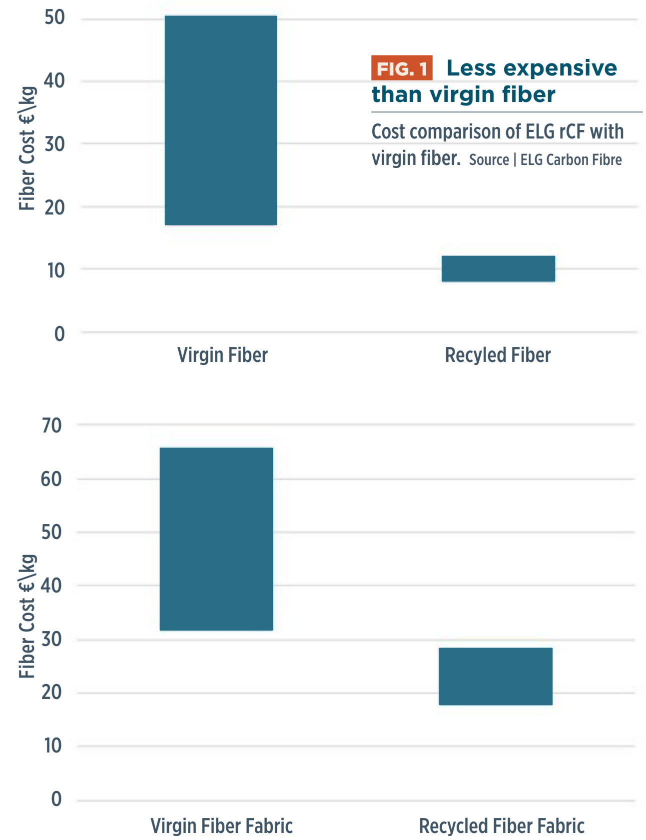

FIG. 1 Less expensive than virgin fiber

Cost comparison of ELG rCF with virgin fiber. Source | ELG Carbon Fibre

FIG. 2 iStream Superlight

Gordon Murray Design's latest iStream variant, Superlight, employs an aluminum thin-wall tubular frame and recycled carbon fiber sandwich panels for a weight savings of up to 50 percent.

Source | Gordon Murray Design

can amount to around 30 percent of production volumes, resulting in approximately 24,000 metric tonnes of carbon fiber waste globally from manufacturing operations each year. By 2021, this figure could grow to about 32,000 metric tonnes. Fiber recovered from waste could fill the supply gap *and* potentially be used to help grow the overall carbon fiber market.

The third driver for use of rCF, says ELG, relates to legislation and the reduced environmental impact of recycled fiber compared with virgin fiber. As governments around the world take action to minimize landfilling, the disposal of carbon fiber waste via this route is subject to increasing regulation and cost. Legislation such as Europe's End-of Life Vehicle Directive is also setting recycling and reuse targets for end-of-life products. rCF can help the composites industry reduce waste bound for landfills and boost reuse levels.

Recycled fiber also improves the lifecycle analysis (LCA) of carbon fiber composite parts. According to an LCA on ELG rCF conducted by Fraunhofer Institute for Environmental, Safety and Energy Technology (UMSICHT, Oberhausen, Germany), recycled carbon fiber has significantly less global warming potential than virgin fiber.

As LCAs gain importance in the materials selection process, the use of rCF (even in conjunction with virgin fiber) makes for a strong argument for switching to composites from metals. In automotive applications, for example, incorporation of rCF could significantly reduce the "break-even" mileage at which the composite design starts to deliver a better LCA than steel.

A new market for a new material

Over the past five years, ELG has introduced its Carbiso range of products, targeting automotive and other high-volume manufacturing sectors. It has taken time to get to this point, involving significant investment in industrialization of the reclaiming process, development of conversion technologies, materials and performance characterization, and applications development. ELG attributes this progress to the backing of metals recycling specialist ELG Haniel GmbH (Duisburg, Germany), which acquired the Coseley operation (Milled Carbon Ltd) in September 2011.

ELG believes it has solved the challenge of reclaiming high-quality fiber, cost effectively and on an industrial scale, via its modified pyrolysis process. The furnace at its U.K. site can process up to 5 metric tonnes of material per day. In order to ensure products deliver a consistent level of performance, the company tests fiber properties on receipt and when recovered, followed by classification of the recycled fibers depending on the type of waste and their mechanical properties. Quality management systems ensure that waste is fully traceable through the subsequent processes. But this is only part of the story. The conversion of the reclaimed fiber into useable products, at industrial-scale quantities, has been a huge learning curve, resulting in a long product development line. The recycled fibers emerge in the form of a "fluffy" 3D structure of entangled, short, unsized fibers of varied length, which cannot be processed in the same way as virgin fiber. Milled fiber formed an initial base for ELG's business, but the company commenced additional product development programs in 2013, targeting products for cost-effective, high-volume manufacturing processes. Its portfolio now comprises milled fibers (80-100 micrometers long) suitable for coatings and compounds, chopped and pelletized fibers (3-100 millimeters) for thermoset and thermoplastic molding compounds, and, its staple automotive line — nonwoven mats (fiber length 60-90 millimeters, 100-500 gsm). These are available in widths up to 2.7 meters and are suitable for compression molding and the manufacture of intermediate products such as prepreg and sheet molding compound (SMC). ELG also produces hybrid mats, in which the recycled fiber is commingled thermoplastic fibers designed for fast press molding applications.

> The biggest challenge with recycled carbon fiber is the ongoing process of applications development.

The biggest challenge, according to ELG, has been the ongoing process of applications development. "Recycled carbon fiber is not a straight substitution for virgin fiber," explains Barnes. "We're making a very different product form, which requires different processes, and different design. We're not trying to substitute an existing material; we're trying to create a market for a new material."

Rethinking automotive manufacturing

Gordon Murray Design (Shalford, U.K.) was an early adopter of ELG's rCF. The company was established in 2007 to develop iStream, a rethink of the traditional automotive manufacturing » process, designed to make lightweight composites design affordable for mainstream vehicles (see Fig. 2, p. 28).

The iStream architecture starts with a frame consisting of simple, low-cost tubular metal members (the iFrame), to which components such as the powertrain, suspension, seats and crash structures are attached. The frame is stabilized by bonding in 14 to 20 rigid composite sandwich panels (iPanels), depending on the type and size of the vehicle, which typically serve as the inner floor, side walls and front and rear bulkheads. According to Gordon Murray Design, this iStream structure delivers valuable weight savings over the conventional stamped steel manufacturing process — up to 200 kilograms on a typical super-mini.

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Read this article online | short.compositesworld.com/recycledCF

Read about Boeing's partnership with ELG | short.compositesworld.com/boeing_ELG

Read about Mitsubishi's partnership with ELG | short.compositesworld.com/Mit_ELG

Originally, the composite panels were manufactured using glass fiber reinforcement. The potential for further weight reduction using carbon fiber, together with its strong marketing appeal, led to the introduction of iStream Carbon in October 2015, in which the glass fiber is replaced with carbon fiber. Virgin carbon fiber proved too expensive for the iStream business case, and Gordon Murray Design saw ELG's rCF as a route to cost reduction. A two-year research program funded by Innovate UK (the U.K. government's innovation agency) followed, which demonstrated the applicability of ELG's nonwoven mat for iStream.

At the start of this project, the biggest concern regarding rCF for Andy Smith, Gordon Murray Design's director of research & development, related to control of the waste feedstock for the recycling process (which could potentially include many different grades of carbon fiber) to ensure consistent mechanical properties in the nonwoven. ELG's subsequent refinement of its supplier base and implementation of fiber classification procedures resolved this.

From a practical point of view, Smith was uncertain if the recycled nonwoven would be robust enough for handling and processing, how well it would infuse and whether the needed fiber volume fraction (FVF) would be achievable. For the glass fiber iStream panels, an FVF of about 40 percent was obtained, but with the rCF the figure was below 20 percent — although the rCF panels were still said to outperform the glass iPanels overall. Improving FVF was a major focus of the research program, and Gordon Murray Design continues to pursue this with ELG. Going forward, Smith is positive about the prospects for rCF in automotive.

Moving forward

Recently, partnerships between ELG and Boeing Co. (Chicago, Ill., U.S.) and Mitsubishi Corp. (MC, Tokyo, Japan) have expanded the company's ability to grow into further markets. In December 2018, Boeing and ELG signed a five-year agreement whereby Boeing will supply cured and uncured carbon fiber composites to ELG for conversion into secondary manufacturing products. Also in December, ELG announced that Mitsubishi Corp. has entered a shareholder agreement for 25 percent of shares in the company. Mitsubishi Corp. will be able to use its global network to promote the sales and marketing of ELG's rCF.

Barnes emphasizes that there is no doubt that sustainability is starting to become a more important consideration for customers. This bodes well for the rCF market. "Levels of activity and the number of customers buying product are increasing month on month," he says. "According to our analyses, in five years the potential market demand will grow very heavily, and we see our business growing several times over in that time." CW

ABOUT THE AUTHOR

Located in Oxford, U.K., Amanda Jacob is a journalist and marketing communications consultant with more than 20 years of experience in the composites industry.

Thermoplastic overmolded thermosets, 2-minute cycle, one cell

Adhesive-free, functionalized hybrid composites enabled by industry-first, integrated molding cell.

By Ginger Gardiner / Senior Editor

Thermoplastic-*thermoset* hybrid production

A section of the BMW *i3* Life Module floor panel demonstrates a serial production hybrid composite molding cell that uses a central swivel platen to accommodate both thermoset prepreg compression molding, and thermoplastic overmolding while photonics provide essential part referencing and more.

Source | AZL at RWTH Aachen University, Arges

» Automated preforming of thermoplastic tapes and subsequent hybrid molding — thermoforming and injection overmolding ribs, clips and bosses onto part surfaces — have been heralded as the future for composites manufacturing in high-volume applications such as automotive. But what if it was possible to combine the toughness of thermoplastics and functionality of injection molded features with the high performance of carbon fiber-reinforced epoxy parts?

This is what the three-year project OPTO-Light, which ended in 2018, set out to answer. It was funded by Germany's Federal Ministry of Education and Research (BMBF) as part of its strategy to develop photonics — light-based technology such as lasers — for mass production of lightweight constructions. The project was awarded to the Aachen Center for Integrative Light Construction (AZL) at RWTH Aachen University (Aachen, Germany), which provides a single campus for companies to collaborate with eight research institutes to develop lightweight materials, production technologies and applications.

OPTO-Light's obvious achievement is combining the high stiffness, light weight and low creep of epoxy-based carbon fiber-reinforced plastic (CFRP) with the high freedom of design and short cycle times of thermoplastic overmolding. But this is just one of myriad potential composites industry disruptors the project has achieved, including:

- Development of laser pretreatment for joining thermoplastic to 3D thermoset surfaces;
- Integration of three technologies — reaction polymer processing, laser processing and overmolding — into a single, fast-cycle-time manufacturing cell;

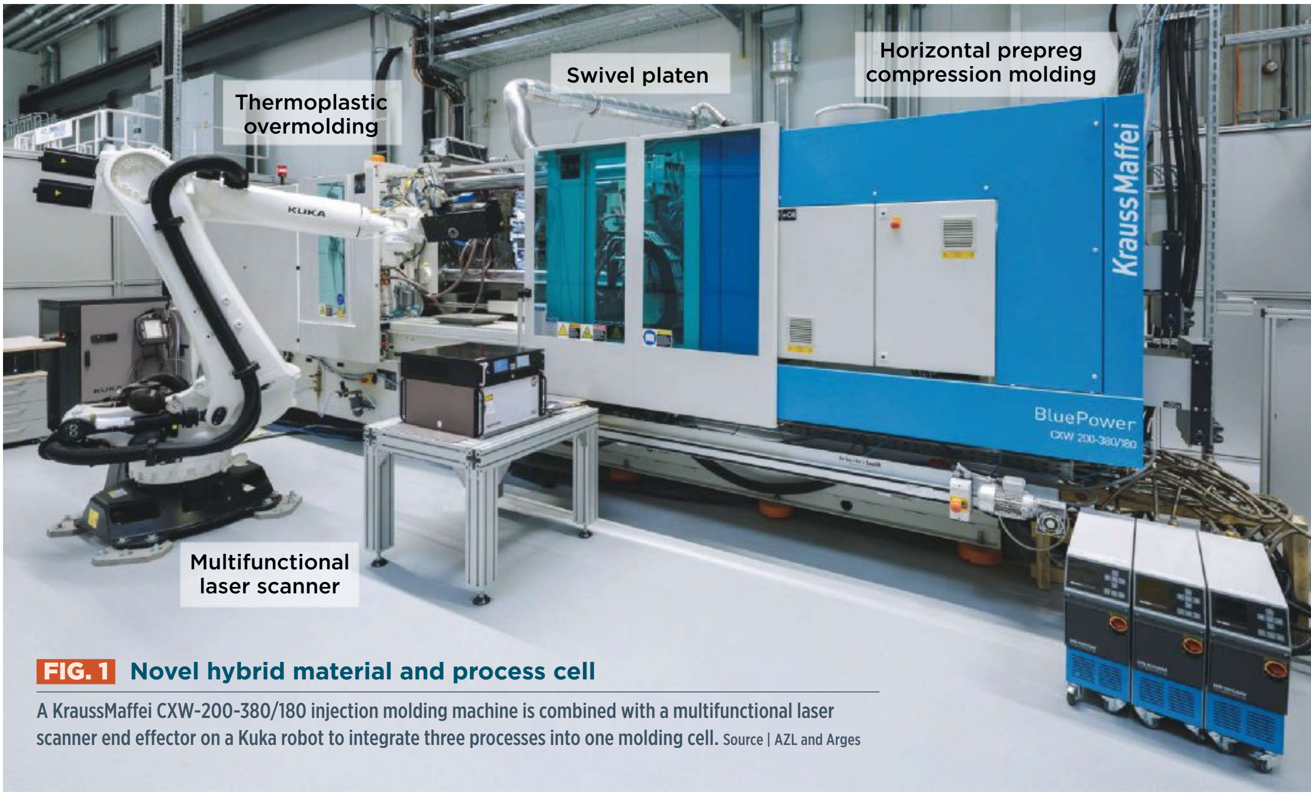


FIG. 1 Novel hybrid material and process cell

A KraussMaffei CXW-200-380/180 injection molding machine is combined with a multifunctional laser scanner end effector on a Kuka robot to integrate three processes into one molding cell. Source | AZL and Arges

- Horizontal prepreg compression molding (HPCM) where materials are affixed vertically for processing in a standard injection molding machine;
- Development of a single rotating mold that integrates all requirements for prepreg compression molding and thermoplastic overmolding;
- Optical part referencing methodology for critical alignment of laser pretreatment and overmolding along a freeform 3D surface;
- Demonstration of this process to produce a 3D structural portion of the floor panel for the BMW *i3* electric vehicle's Life Module with a 2-minute cycle time.

Indeed, the project's April 2018 final report asserts that this technology can reduce automotive CFRP part cost by up to 30 percent versus current production using wet compression molding and adhesive bonding of single onserts for clips.

Thermoplastic to thermoset partners

Why join thermoplastic overmolding to a thermoset composite part? "Thermoset CFRP components made with epoxy resin offer the best characteristics for car body applications," asserts AZL research engineer Richard Schares. Overmolding thermoplastic composite ribs increases the part's design stiffness (section modulus), thus reducing the amount of carbon fiber required. "Using a rib thickness equal to that of the CFRP shell, the specific bending stiffness of the OPTO-Light demonstration part can be tripled," he adds. Overmolding can further reduce part cost by providing molded-in attachment clips or bosses for screws while simultaneously providing isolation to prevent galvanic corrosion between the carbon fiber and metallic fasteners.

Thus the objective was defined, but the issue was how to combine both materials in a single molding cell. Schares explains how the industry partners were selected. "BMW had the most experience with serial production of CFRP parts. KraussMaffei was very proactive in creating combination technologies, such as its ColorForm multi-component injection molding machine and FiberForm hybrid molding machine."

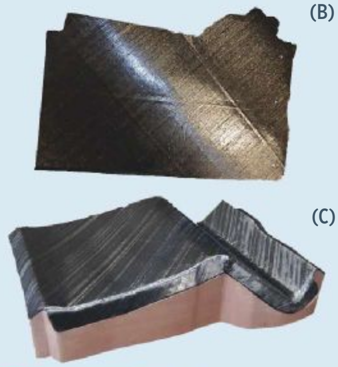
The OPTO-Light demonstration part was a 470-millimeter-long by 317-millimeter-wide by 130-millimeter-deep portion of the BMW *i3* Life Module floor, including the end wall at the wheel well. "The load cases of this component require good stiffness and strength characteristics in case of a crash," Schares explains. "We also wanted complexity of shape and draping to prove out the horizontal prepreg compression molding, laser ablation and overmolding along a free-form surface."

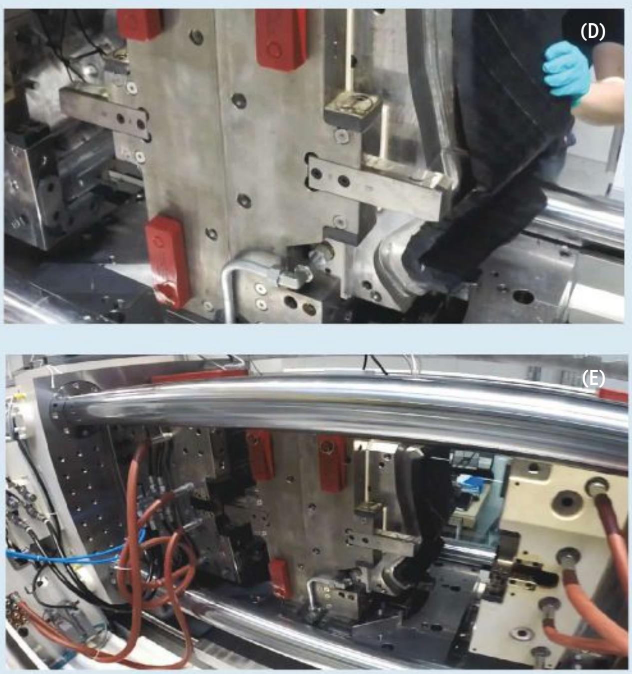
Why photonics?

Germany has funded a long-term strategy to continue developing photonics technology because of the key role it plays in the current global digital transformation of manufacturing. The composites industry should take note, because photonics enable not only advanced processing such as automated fiber placement, laser »

(A)

Prepreg
SGL Group SIGRAFIL 50K CF/hot melt E420 epoxy
Voith Composites Zoltek 50K CF (60% vf)/ Hexion EPIKOTE epoxy
Hexcel M77 HiMax 50K CF/hot melt fast-cure epoxy





1 Prepreg compression molding
Three evaluated carbon fiber/epoxy prepreg tapes (A) are converted into blanks (B), preforms (C) and placed into the OPTO-Light molding cell (D). Each preform is cured into a CFRP shell during Horizontal Prepreg Compression Molding (E). Source | AZL

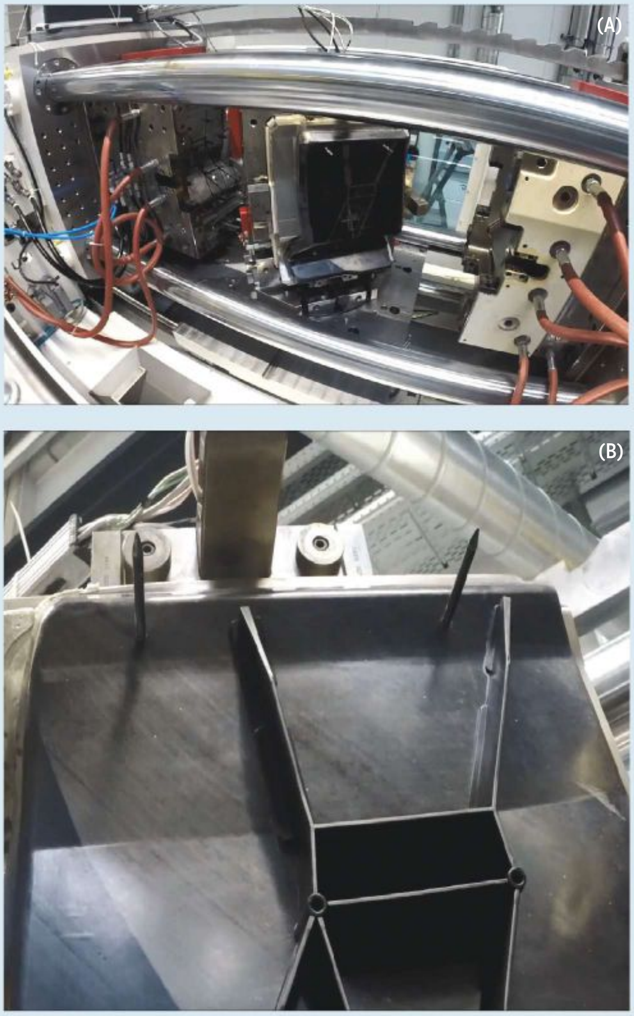
2 Laser beam treatment
The cured shell is rotated on the swivel platen and the multifunctional laser scanner performs part referencing (A). Laser ablation removes the topmost 10-meter-thick layer of epoxy resin in preparation for overmolding (B).
Source | AZL

welding of thermoplastics, precision machining and various 3D printing processes, but also sensor and visual communication for metrology, process monitoring and inline inspection. In OPTO-Light, a near infrared (NIR) laser was used to pretreat surfaces for overmolding; in addition, a variety of laser-based sensors provided data for process control and inline quality assurance (QA).

The final four OPTO-Light partners are German photonic systems suppliers. The first, Arges (Wackersdorf), is an expert in 3D scanners used for laser machining. “It typically develops innovative laser scan systems, positioning and deflecting laser beams in industrial materials processing and medical applications,” says Schares. “An Arges double-beam unit was developed for ablation and heating. Precitec (Gaggenau) supplied the interferometric sensor for measuring distance used during ablation and part referencing throughout the process. Sensortherm (Sulzbach) provided the pyrometer (temperature sensor) that aided process control, and Carl Zeiss Optotechnik (formerly Steinbichler, Neubeuern) contributed the T-scan laser scanner for QA. “It measures part geometry and detects potential deformation,” explains Schares. “It will show defects, such as the overmolded rib not completely bonded to the CFRP shell.” All of these systems are integrated into the *multifunctional laser scanner* (Fig. 1, p. 33), which is mounted on the end of a six-axis Kuka (Augsburg, Germany) robotic arm.

HP-RTM to prepreg tape

The initial idea was to make the epoxy CFRP parts using C-RTM, a kind of high-pressure resin transfer molding (HP-RTM) also known



3 Overmolding PA6
The pretreated shell rotates on the swivel platen (to face left) for back injection molding with short glass fiber/reinforced PA6 compound (A). The finished part features overmolding precisely along the laser pretreated paths (B) that were outlined in the laser treatment step (2A). Source | AZL

as gap impregnation, developed by the IKV Institute of Plastics Processing. However, during this time, automated tape-based processes began to challenge liquid molding of noncrimp fabric (NCF), offering a reported 30 percent reduction in cutting scrap. Snap-cure liquid epoxy resins were also expanded into prepreg materials, making compression molding attractive, with a potential cycle time of one to two minutes.

Three unidirectional prepregs were evaluated for the demonstrator's shell. These were converted into net-shaped, 2D tailored blanks using Broetje-Automation's (Rastede, Germany) STAXX tape placement cell.

The molded CFRP shells would then be overmolded with 30-percent short glass fiber-reinforced polyamide 6 (GF/PA6) using Lanxess (Cologne, Germany) Durethan BKV 30 H2.0 901510.

A KraussMaffei CXW-200-380/180 SpinForm injection molding machine was chosen as the foundation for the OPTO-Light manufacturing cell and installed at AZL. It features swivel platen technology developed to enable multi-component injection molding.

The mold attached to the swiveling platen was used to form two different molding cavities for two different processes — epoxy prepreg compression molding and thermoplastic injection overmolding. "No one has created such a tool before," Schares points out. BMW and KraussMaffei spent many weeks finalizing all of the requirements for both processes, including tolerances due to different temperature zones, turning accuracy and sealing for the thermoset resin, as well as the standard details for injection molding tools.

Laser ablation and part referencing

The epoxy CFRP shell resulting from the compression molding process was treated prior to thermoplastic overmolding to achieve sufficient join strength between the disparate materials. Laser ablation offers an environmentally friendly, single-step process compared to mechanical or chemical pretreatment and enables a precise ablation depth and path, well-suited for joining ribs to parts along 3D surfaces. The ablation method entails exposing the carbon fibers by locally removing the topmost 10-micron-thick layer of epoxy resin. This cleans the surface and produces a microstructure that allows the overmolding compound to wet and infiltrate the exposed fibers.

The multifunctional laser scanner emits a laser beam with a wavelength of 1.064 nanometers in nanosecond pulses. "You need high intensity, and pulsing achieves this most efficiently," Schares explains. "We tried a continuous wave laser, but it introduces too much thermal stress into the composite laminate below the joining zones, reducing the fiber-epoxy adhesion. Finding a process-suitable beam source that can be used for remote-processing in an industrial environment was not easy."

Because the overmolded ribs must match the pretreated areas, the ablation process requires high positioning accuracy. Subsequent placement of the overmolded glass fiber/PA6 composite material is strictly defined by the mold tool. Thus, a necessary part referencing methodology was developed by AZL. "The offset between the pretreated geometry and overmolded compound should be less than 300 microns. Thus, accuracy for the central point of the laser scan field (tool center point) must be within 150 microns relative to the reference point. This was achieved, as well as a cycle time of less than two minutes for the laser pretreatment. "Very important was the preliminary work by Fraunhofer Institute for Production Technology (IPT) to develop path generation for the robot and laser beam — this was not trivial," says Schares. The system did indeed prove its mettle — test results showed a shear strength of 27 MPa between the GF/PA6 overmold and epoxy CFRP substrate.

Shorter process routes

Even as the benefits of the initial process were being documented, the OPTO-Light team realized it was possible to eliminate the laser »

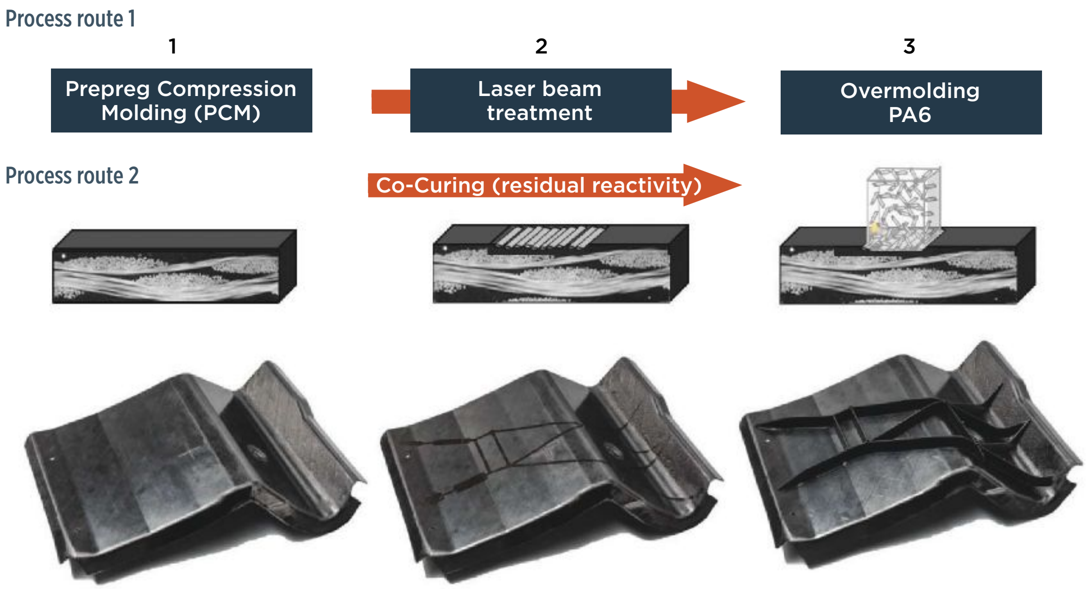


FIG. 2 One manufacturing cell, multiple process routes

OPTO-Light has developed different process routes for achieving epoxy CFRP parts functionalized via thermoplastic overmolding. Both process route 1, using laser ablation, and process route 2, which eliminates the laser in favor of co-curing, have been validated via 50 demonstrator parts.

Source | AZL

ablation treatment. The resulting two-step process would only partially cure the epoxy prepreg shell and use remaining reactivity in the epoxy resin to achieve attachment with the thermoplastic overmolding. Three potential mechanisms exist for bonding between uncured epoxy and PA6:

- Covalent bonding between reactive epoxy rings and PA amine groups;
- Hydrogen bonds with amine's hydrogen as donator and epoxy's oxygen as acceptor;
- Semi-interpenetrating networks by diffusion effects, possible by high-temperature mobility of the PA molecular chains.

The advantage of this two-step process, says Schares, "is that you can skip the pretreatment, but the required process control is much more challenging and the surface quality is not as high-gloss. However, further reduction in part cost by simplification of production is very attractive."

The key to this process route is process monitoring. "You must look inside the prepreg compression molding process because knowledge about the state of cure must be sure in order to achieve a good join with the thermoplastic overmolding," he explains. This cure state monitoring was achieved by using in-mold pressure and temperature sensors, as well as in-mold direct current resistivity (DCR) and dielectrical analysis (DEA) sensors.

DCR and DEA are well-established for cure monitoring in composites. In OPTO-Light, the DCR/DEA process control comprises an Optimold system from Synthesites Innovative Technologies (Piraeus, Greece) including a durable 16-millimeter DCR sensor and Optiview software. Optimold monitors the resin's electrical resistance and temperature up to 210°C and pressure of 90 bar with a sampling rate of 1 Hz. The DEA288 Epsilon analytic device from Netzsch Gerätebau (Selb, Germany) includes a 4-millimeter ceramic monotrode and Proteus software. Kistler Instruments (Winterthur, Switzerland) DataFlow software for injection molding optimization is another key component.

The process, beginning with fixation of the prepreg preform inside the mold and ending with ejection from the injection overmolding cavity, is described by the DCR/DEA sensor signals. These data are crucial for determining the optimum cure time in compression molding before the pivot to injection molding for cure completion and overmolding. The sensors help to characterize the material during processing for optimal part quality. In the future, the process may be adaptive and intelligent, with process pivoting triggered by the DEA and DCR sensor signals.

Initial tests show a pull-off strength of 9 N/mm^2 and an even higher shear strength for the epoxy-PA6 join using this second, shorter OPTO-Light process route. Work is ongoing to improve this join strength, including further use of process monitoring. The team is also exploring a one-step process in which horizontal prepreg compression molding is no longer a separate process, but is instead achieved simultaneously with overmolding.

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Read this article online | short.compositesworld.com/TPovermold

Watch a video of the OPTO-Light integrated process | https://youtu.be/b9HmgnuGQY0

Read more about AZL online | short.compositesworld.com/AZL

Hybridization for future disruption

OPTO-Light's potential for disruption was recognized with the AVK Innovation Award for the research and science category in 2017. The project's 2018 final report asserts that for composites to achieve cost parity with metal in series automotive production, it is necessary not only to maximize the integration of functions in parts but also the integration of the processes used to manufacture those parts. OPTO-Light has developed an array of technologies, including photonics-based metrology, surface treatment and thermoplastic/thermoset molding, that enable both. These technologies also open the door to further hybrid processes, such as laser processing to augment injection molding. "By integrating the developed laser tool in the molding cell, you now have the possibility to perform laser ablation, cutting, pretreatment or heating before, between or after polymer processes inside the injection molding machine," explains Schares. "This enlarges the functionality of future parts."

The idea of combining multiple manufacturing processes into a single work cell is gaining momentum in composites. For example, many of the CNC machine manufacturers now offer cells that combine additive manufacturing and subtractive CNC machining. MF Tech (Argentan, France) has combined *3D filament winding* and CNC machining, and co-founder Emanuel Flouvat confirms further hybridization, with robots able to switch out end effectors to an ultrasonic or laser welder for joining thermoplastics, or an automated fiber placement head to apply local patches of unidirectional tape. "By integrating a robot-guided laser system, the 'tool box' for the definition of further inline combination technologies is extended," says Schares. This is another significant step forward in this advance toward automated, multi-process composites manufacturing that will no doubt soon integrate electronics into finished parts.

The final lesson OPTO-Light offers in hybridization is in its partnership. "The most interesting challenge in managing this project was how to take all of the different partners, each with their unique expertise — for example, photonics, reaction polymers, injection molding, metrology — and have them develop and advance a common understanding of the effects of each operation in order to make this single process chain successful," says Schares. He stresses the importance of the expertise and support contributed by five partner institutes — IKV injection molding, IKV reaction polymers, ISF for welding and joining, Fraunhofer IPT for laser integration and Fraunhofer ILT for alternative laser sources. "This project demonstrated the ability of such interdisciplinary development to efficiently solve technical challenges for reduced-cost composites production," says Schares. It has also laid the groundwork for even further disruptive innovation. CW

ABOUT THE AUTHOR

CW senior editor Ginger Gardiner has an engineering/materials background and more than 20 years of experience in the composites industry.
ginger@compositesworld.com

COMBINING MATERIALS FOR BETTER BICYCLES

Bicycle manufacturer HIA Velo combines composite materials to make its products more durable.

Source: HIA Velo

Bicycle manufacturer HIA Velo (Little Rock, Ark., U.S.), founded in 2016, makes carbon fiber bikes in the U.S. (HIA means Handmade in America), without relying on the typical business model of overseas manufacturing. The company recently introduced the brand name Allied Cycle Works, as well as its *Alfa* bicycle models.

Sam Pickman, HIA Velo's director of engineering, who came to the company from Specialized Bicycle Components, says, "Designing and making carbon fiber bikes involves compromises that you try to overcome. You must balance stiffness and handling with rideability, comfort and durability." Allied Cycle Works' *Alfa* frames are typically made with six plies of Mitsubishi Chemical Carbon Fiber & Composites Inc.'s (Irvine, Calif., U.S.) unidirectional carbon fiber prepreg, both 130-gsm standard modulus carbon and 110-gsm intermediate modulus carbon, prepregged with Mitsubishi's Newport 301 epoxy resin and supplied in 1-meter-wide rolls. Pickman also reports that the company is investigating 114-gsm TeXtreme spread-tow woven material supplied by Oxeon (Boras, Sweden), as an alternative to unidirectional prepreg.

Pickman acknowledges, however, that lightweight carbon fiber frame tubes can be damaged when riders crash, particularly during racing: "And typically the damage is unseen, so riders get back on, and the unseen damage causes the frame to unexpectedly come apart." To add durability to its frames, HIA Velo worked with Innegra Technologies (Greenville, S.C., U.S.) to incorporate Innegra S high-modulus polypropylene fabrics, sized for compatibility with epoxy resin, to discrete areas of the *Alfa* bike frames to improve frame durability. "The woven biaxial Innegra provides flex — it is very ductile and damps vibrations, so it increases ride comfort. And it's tough and absorbs impact, so we use it in frame areas that are potentially damage-prone," Pickman says. Those areas include the seat stays, the top tube where the handlebars could impact the tube and the fork crown.

The company typically incorporates the Innegra plies in the center of the tube layup, encapsulated by carbon fiber plies, with the Innegra often forming the innermost ply of the tube. "The polypropylene adds weight without stiffness," Pickman explains. "We have to pick and choose where to have the flex and ductility." CW

Composites Events

March 4-5, 2019 — Detroit, Mich., U.S.
Graphene Automotive 2019
usa.graphene-automotive-conference.com

March 6-8, 2019 — Rome, Italy
5th Annual World Congress of Smart Materials: 2019
bitcongress.com

March 11, 2019 — Paris, France
SAMPE Europe Summit 19
sampe-europe.org

March 12-14, 2019 — Paris, France
JEC World 2019
jeccomposites.com

March 21, 2019 — Belfast, U.K.
Joining of Composites Conference
ktn-uk.co.uk/events

March 24-28, 2019 — Nashville, Tenn., U.S.
NACE Corrosion 2019
nacecorrosion.org

April 7-10, 2019 — Charleston, S.C., U.S.
TRFA Annual Meeting
trfa.org/meeting

April 8-10, 2019 — Rosemont, Ill., U.S.
North American Pultrusion Conference
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April 8-11, 2019 — Colorado Springs, Colo., U.S.
35th Space Symposium
spacesymposium.org

April 9-11, 2019 — Detroit, Mich., U.S.
SAE 2019 World Congress & Exhibition
10times.com/sae-world-congress

April 10-11, 2019 — Amsterdam, Netherlands
CompIC 2019
compositesinconstruction.com

April 23-25, 2019 — Moscow, Russia
Composite-Expo-2019
composite-expo.com

April 29-May 2, 2019 — Long Beach, Calif., U.S.
AeroDef 2019
aerodefevent.com

April 29-May 2, 2019 — Chicago, Ill., U.S.
AUVSI XPONENTIAL 2019
xponential.org

May 6-8, 2019 — Beijing, China
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sampechina.org

May 20-23, 2019 — Houston, Texas, U.S.
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windpowerexpo.org

May 20-23, 2019 — Charlotte, N.C., U.S.
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June 12-13, 2019 — Stade, Germany
CFK-Valley Stade Convention 2019
CFK-Valley.com

June 17-23, 2019 — Paris, France
Paris Air Show
siae.fr/en/

June 19-20, 2019 — Chicago, Ill., U.S.
JEC Chicago 2019
jec-chicago.events

July 3, 2019 — Vigo, Spain
MATCOMP19
matcomp19.com

Aug. 11-16, 2019 — Melbourne, Australia
ICCM22 — The 22nd International Conference on Composite Materials
iccm22.com

Aug. 27-29, 2019 — Austin, Texas, U.S.
Additive Manufacturing Conference and Expo
additiveconference.com

Sept. 4-6, 2019 — Novi, Mich., U.S.
SPE Automotive Composites Conference and Exhibition (ACCE)
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CW **Sept. 23-26, 2019 — Anaheim, Calif., U.S.**
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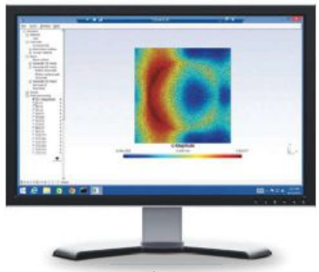

Source | AnalySwift

AnalySwift LLC (West Jordan, Utah, U.S.), a provider of high-fidelity modeling software for composites and other advanced materials, has launched its Academic Partner Program, through which it will offer universities no-cost licenses for its SwiftComp and VABS tools for academic research. Academic licenses of VABS and SwiftComp have always been available to universities for purchase, but the new program offers the licenses at no cost. The composite simulation programs are commonly used in aerospace and mechanical engineering programs, with emerging applications in other areas, such as civil engineering, medical devices and life sciences. analyswift.com

Source | L&L Special Furnace Co. Inc.

» FURNACES & OVENS

Retort furnace for de-bindering ceramic composites

L&L Special Furnace Co. Inc. (Aston, Pa., U.S.), designer of special industrial furnaces, ovens, kilns, quench tanks and heat-treating systems, has announced the development of a large retort box furnace for de-bindering ceramic matrix composite (CMC) prepreg materials. It is also suitable for powder metals processing and hot isostatic processing. The furnace, Model XLC3648, has a work zone of 29" wide by 29" high by 35" deep. It has a temperature uniformity of ±20°F at 1,100°F using six zones of temperature control, with biasing to balance any temperature gradients. According to L&L, the furnace is constructed of low-mass insulation that allows for quicker cooldown times. The XLC3648 also has a venturi blower to aid in cooling, controlled by a Eurotherm program control with over-temperature protection. A programmable flow panel manages the nitrogen flow throughout the process. llfurnace.com

» TEMPERATURE CONTROL

Expanded line of silicone heating blankets

Source | BriskHeat

BriskHeat Corp. (Columbus, Ohio, U.S.), provider of flexible heating, insulating and temperature control solutions, has announced additions and improvements to its silicone heating blanket line. BriskHeat now offers five silicone heater lines with a range of custom choices. Options range from heavy-duty silicone heaters to ultra-thin etched foil heaters to hazardous-area-rated heaters. According to BriskHeat, features include built-in temperature control, custom cut-outs and configurability to nearly any shape, size and power. For composites fabrication applications, silicone blankets are most often used to concentrate cure heat in a particular area, especially for parts too large to fit in a curing oven, or for parts where heat must be selectively applied. BriskHeat's silicone heating blankets can be controlled by products such as the ACR3 Hot Bonder or MPC2 Multipoint Control Panel. Both of these devices are capable of a slow temperature ramp, soak and cool down — for composite repair or composites production. Silicone blankets can also be used to preheat tools after prepreg layup, or to cure adhesives during bonding processes. briskheat.com

» ADDITIVE MANUFACTURING

New melt core enables larger bead size for large-format 3D printer

Thermwood Corp. (Dale, Ind., U.S.) has completed initial testing of a larger melt core for its LSAM (Large Scale Additive Manufacturing) systems. A melt core consists of a feed housing, extruder and polymer melt pump; its size dictates how fast material can be printed. The new 60-mm melt core has been tested with different polymers and reportedly has achieved print rates of 480-570 lb/hr. (The standard 40-mm melt core has a maximum output of 190-210 lb/hr., depending on the polymer being printed.) Thermwood says the higher output capability enables the printing of layers with 250 ft. or more bead length with most polymers. Further, the higher print rate of the new melt core, even when processing high-temperature materials, allows the print bead to be oriented along the length of the tool, even for tools that are as long as the machine table itself. Thermwood reports that the larger melt core may not be desirable for all applications, noting that many tools and molds are too small for efficient printing with the larger core. If a user needs the ability to generate small and large parts on the same machine, the melt cores can be changed in less than a shift. thermwood.com

Source | Thermwood Corp.

» FILAMENT WINDING

Revamped filament winding machinery lineup


Source | Entec

Engineering Technology Corp. (Entec, Salt Lake City, Utah, U.S.) reports that it has reorganized its line of filament winding equipment into primary products, each offering different combinations of maximum mandrel weight, maximum mandrel length, mandrel diameter, number of spindles, number of axes and speed.

The most basic unit is the SS filament winder, designed for R&D or educational use. It can be used with wet winding or towpreg delivery and has a maximum mandrel weight of 23 kg, maximum mandrel length of 2,000 mm, mandrel diameter of 23-305 mm, one spindle and two axes. The SS+, for small production environments, features an integrated cabinet and table. It has the same specifications as the SS except for a 25-205-mm diameter mandrel and three or four axes.

The SM, for medium envelope part production, has a maximum mandrel weight of 340 kg, maximum mandrel length of 5,000 mm, mandrel diameter of 25-610 mm, one spindle and two to four axes. The SM+, for medium envelope part production at high volumes, has a maximum mandrel weight of 454 kg, maximum mandrel length of 6,000 mm, mandrel diameter of 25-914 mm, one to eight spindles and two to five axes.

The CXG, for winding compressed natural gas (CNG) or compressed hydrogen gas (CHG) tanks, is designed for high-volume manufacturing and features a dual-drive carriage. It has a maximum mandrel weight of 454 kg, maximum mandrel length of 5,000 mm, mandrel diameter of 25-406 mm, three to five spindles and four axes.

The SL and SL+ are large-format winders designed for aerospace and oil and gas applications. They offer a maximum mandrel weight of more than 2,268 kg, maximum mandrel length of more than 5,000 mm, mandrel diameter of 25-2032 mm, one spindle and two to six axes. **entec.com**

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ADVERTISING INDEX

SHOWCASE

■ Recycled CFRP for personal transport

BMW's Personal Mover Concept attempts to redefine personal transportation with an electric, tilt-proof vehicle built primarily from repurposed CFRP and designed to carry one person and light cargo. Source | BMW AG

Micro transportation: BMW personal mover concept

Recycled composites, additive manufacturing and 3D printing enhance form, function of fun-to-drive personal transport.

By Peggy Malnati / Contributing Writer

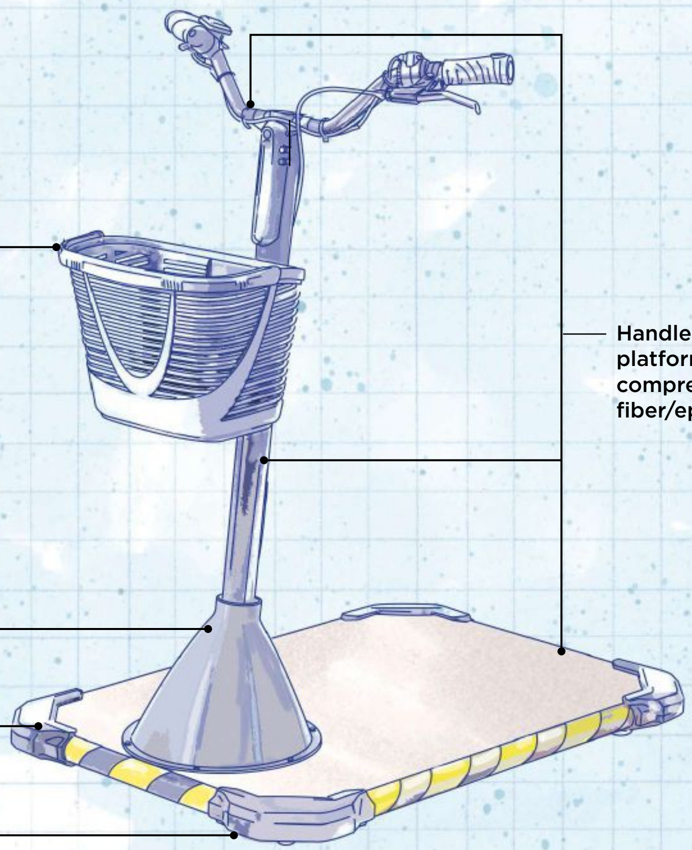
» BMW Group (Munich, Germany) is once again redefining transportation, this time with its Personal Mover Concept, an electrically powered mobile platform designed to carry a person and light cargo over short distances within operating sites as diverse as manufacturing facilities, airports or even theme parks. The unit, which is versatile, maneuverable, tilt-proof and clean-powered, can be used inside or outside of buildings and, most importantly, has been designed to be fun yet safe to drive.

The genesis of this project was the realization that many of the automaker's plants and logistics centers are sprawling campuses where employees can walk up to 12 km/day while carrying small parts and other work materials as part of their jobs. To make it easier and more efficient for employees to move around, BMW experts drawn from the Research & Technology House in Garching, Germany, and the central aftersales logistics network at Dingolfing, Germany, took up the challenge to create a mobility solution for their colleagues at other BMW facilities.

"Makerthon"

The team began the project by randomly surveying employees at multiple sites and recording their needs. In parallel, other team members conducted environmental analyses, reviewed site-safety guidelines and considered legal issues. When combined, results from these studies presented the team with a list of demanding requirements that the new transport device would need to meet, including:

- safety and stability with no chance of overturning,
- ease of operation for most users,
- low cost to produce,
- light weight,



DESIGN RESULTS | **BMW Personal Mover Concept**

- Repurposed carbon fiber and epoxy resin from BMW vehicle production is used in wet compression molding to produce the handlebars, steering rod and platform.
- 3D-printed 2K (2-part) epoxy plus plasticizers are used to produce bumpers for each corner of the platform. The material is post-mold cured via UV laser.
- Additive manufacturing of polylactic acid polymer is used to produce the protective cone, handlebar mount and basket to carry small items.

Illustration / **Karl Reque**

- space to include lights, horn and bell, plus two independent brakes,
- and a fun riding experience.

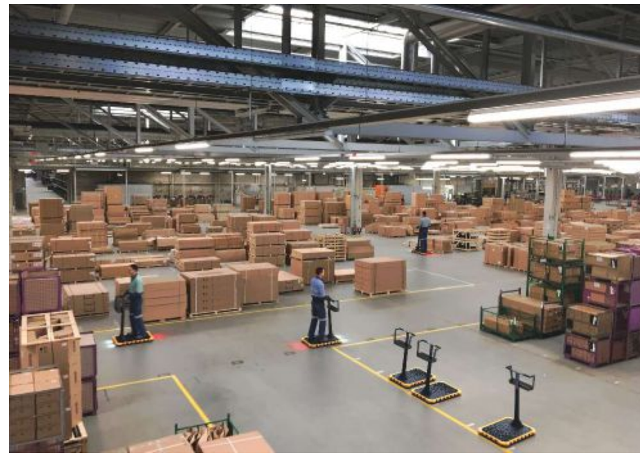
An evaluation of existing options did not provide satisfactory solutions that met the requirements. The team concluded that only a custom design developed in-house would work.

To encourage the team to quickly develop creative and unconventional ideas, a BMW design-thinking format called "Think Make Start" was employed. This involved use of agile methods to develop and evaluate ideas and prototypes in a sort of "makerthon," a process originally developed by UnternehmerTUM.com and the Technical University of Munich (both Munich, Germany) for developing new products in only one or two week-long sessions. It was from this process that preliminary concepts for the Personal Mover emerged. Initial ideas did meet all of the preliminary project requirements but, according to the company, were deemed "to need too much technical and financial effort for simple and straightforward implementation."

"Based loosely on the motto, '*fail fast*,' we put our heads together after the makerthon and radically overhauled the concept," recalls Stephan Augustin, BMW special projects team leader for research, new technologies and innovations.

"Using the 'MakerSpace' — a high-tech workshop for inventors and researchers that is open to the public on site at UnternehmerTUM — we created as simple a prototype as possible with the help of dedicated BMW apprentices," adds Rainer Daude, BMW project director for mobility concepts.

"That prototype met all the project's main requirements and, unlike our initial concepts, it can be implemented much more quickly, easily and inexpensively with the expertise we already have in-house," Augustin adds. »



■ **Designed for safety**

Intended for use by employees in BMW's large facilities, the Personal Mover, though built to be quiet and fast, is not permitted to exceed 12 km/hr and has features like LED lights and a bell to help operators alert those close to the vehicle's path.

Source | BMW AG

■ **The design space**

The BMW team used the "MakerSpace" at UnternehmerTUM to develop the original ideas for the Personal Mover Concept. Pictured are three members of the team, from left to right: Stephan Augustin, BMW special projects team leader for research, new technologies and innovations; Alexander Brössler, apprentice at BMW Group Plant Munich; and Rainer Daude, BMW project director for mobility concepts.

Source | BMW AG

■ **Redesigning personal transport**

As conceived via the design process, the Personal Mover's body features a 60 by 80-centimeter platform. Two skateboard wheels are fixed under the rear corners and two more wheels, each capable of rotating 360 degrees, are positioned under the front corners for stability. A fifth and larger drive wheel is positioned at the front under the handlebars and steering rod. The drive wheel, which provides acceleration, braking and steering, penetrates through the platform and is covered by a protective cone. Source | BMW AG

From concept to reality

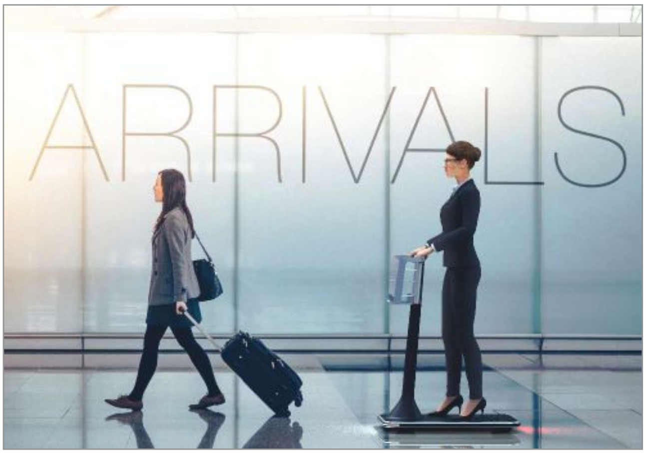
As conceived via the design process, the Personal Mover's body features a platform on which a person can stand comfortably and still transport some light objects. Two skateboard wheels are fixed under the rear corners and two more wheels, each capable of rotating 360 degrees, are positioned under the front corners for stability. This 360-degree wheel geometry helps keep the device highly maneuverable while also ensuring that — even when making tight corners — the unit doesn't tip over. A fifth, larger drive wheel is positioned at the front under the handlebars and steering rod. The drive wheel, which provides acceleration, braking and steering, penetrates through the platform and is covered by a protective cone. Use of a larger wheel here provides better grip and performance. The handlebar itself houses the unit's entire electrical system and battery and is directly connected to the drive wheel, which enables the driver to pivot the handlebars 90 degrees to left or right, permitting the unit to turn on a tight 1.2-meter radius.

All operator interfaces are mounted to the handlebar grips. Buttons on the display unit turn the vehicle on or off, select the driving mode, turn the lights on or off, and provide a check-battery indicator. On the right side, a thumb throttle regulates speed, while on the left side are a brake and a "dead-man's" control button, which must be pressed for acceleration and will quickly stop the unit should the operator's hand leave the handlebar for whatever reason. Because of the Personal Mover's quiet electric drivetrain, a bell is mounted to the handlebars so the operator can warn those walking in the vehicle's path.

Much like the company's *i3* battery-electric vehicle (BEV), the Personal Mover is designed to use regenerative braking, which feeds kinetic energy back into the battery for recharging during

The final stages

The Personal Mover is currently undergoing final design reviews and changes prior to roll-out at BMW sites worldwide. One of the first uses is likely to be at FIZ Future, BMW's Research & Innovation Centre (FIZ) in Northern Munich, which is set to open this year and provide workspace for 26,000 people and approximately 1 million square meters of floorspace. Source | BMW AG



Thinking beyond BMW

Beyond its own use, BMW indicates that the company is in discussions about possibly extending use of the Personal Mover Concept outside BMW locations to airports, exhibition centers, shopping centers and more.

Source | BMW AG

braking. The electric drive accelerates to a maximum speed of 25 km/hr, although the units will not be permitted to exceed 12 km/hr at any BMW facility. Under normal use, the battery cells have a guaranteed range of 20-30 kilometers without a recharge. Recharging takes two to three hours and can be done via a household electrical outlet thanks to a power adapter. Occupational safety guidelines stipulate that permanent daytime running lights operate when the vehicle is in use, so it's outfitted with a front light-emitting diode (LED) mounted on the handlebars and two rear LEDs, which are integrated with bumpers on the rear of the platform to ensure good visibility.

The steering rod, handlebars and body platform are made of repurposed carbon fiber-reinforced plastic (CFRP) scrap reclaimed from *i3*, *i8* and *M-Series* models produced at BMW's Lightweight & Engineering Center in Landshut, Germany. New parts are produced via dry preforms that are infused with epoxy resin during wet compression molding. Bumpers mounted at each corner of the body platform are produced using 2K (2-part) epoxy resin plus plasticizers via the Polyjet process on a printer produced by Stratasys Ltd. (Eden Prairie, Minn., U.S.) and then post-cured with a UV laser. This 3D printing process makes it possible to simultaneously build up both a hard, structural part as well as a soft outer skin to reduce damage during low-speed impacts. A small handlebar-mounted basket, the handlebar mount and the protective cone that covers the lower portion of the handlebar and drive wheel where both penetrate through the platform body are all produced via additive manufacturing processes — using polylactic acid (PLA) polymer either via fused-deposition modeling (FDM) or fused-filament fabrication (FFF) on printers from Ultimaker B.V. (Geldermalsen, Netherlands).

> The steering rod, handlebars and body platform are made of repurposed CFRP scrap.

In its current form, the Personal Mover Concept is 60 centimeters wide, 80 centimeters long, 110 centimeters high (at the top of the handlebars) and weighs 20 kilograms.

Future steps

Initially, five prototype Personal Mover Concept units were produced and presented at a global BMW aftersale logistics meeting. Not surprisingly, it was well received.

The device — which is undergoing final design reviews and changes — will first be deployed at FIZ Future, BMW's Research & Innovation Centre (FIZ) in Northern Munich, which at 1-million square meters, is already BMW's largest facility and is undergoing another expansion. Beyond that, plans are to roll out the Personal Mover to other BMW sites worldwide. There is even discussion about the possibility of extending use outside BMW locations to airports, exhibition centers, major shopping centers and more. CW

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ABOUT THE AUTHOR

Contributing writer Peggy Malnati covers the automotive and infrastructure beats for *CW* and provides communications services for plastics- and composites-industry clients.
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