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HIGH-PERFORMANCE Composites

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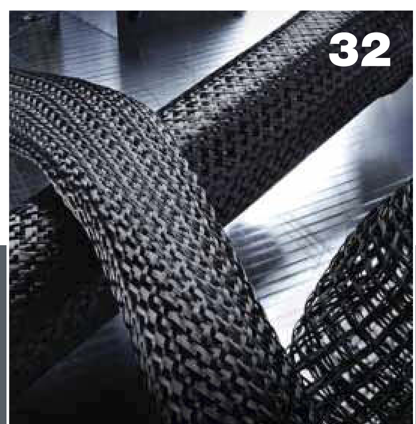

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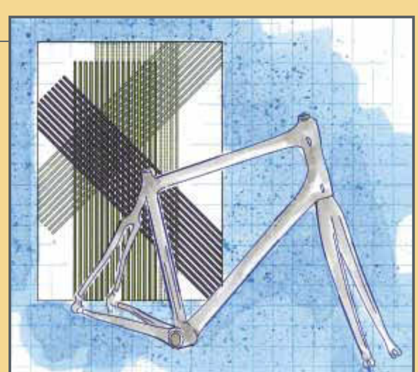

ON THE COVER

Braid produced by a unique *radial* braiding technology, developed by August Herzog Maschinenfabrik GmbH & Co. KG (Oldenburg, Germany), enables the fabrication of bike frame tubes with varying cross-sections and seamless transitions between locally optimized fiber patterns on the *impec* racing bike frame (see p. 32) developed by Bicycle Manufacturing Company (BMC, Grenchen, Switzerland).

Source: BMC

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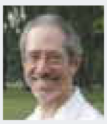

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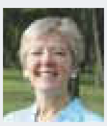

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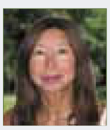

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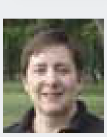

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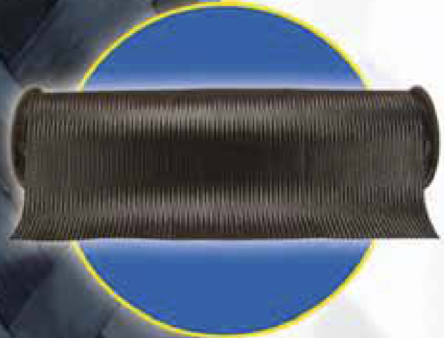

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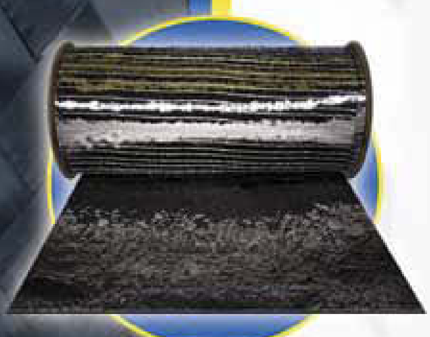

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FROM THE EDITOR

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The wait for $5/lb carbon fiber is over. That is, you can stop waiting because it's not coming. That's the word from CompositesWorld's Carbon Fiber 2012 conference, which was held Dec. 4-6 in La Jolla, Calif.

For more than 20 years, one of the Holy Grails of the carbon fiber composites market has been the automotive industry. Lighter, stronger and more fatigue- and corrosion-resistant than steel and aluminum, carbon composites would be a perfect fit for primary structures in cars and trucks if it weren't so expensive and could be fabricated at or near auto industry production rates. Since the dawn of composites time, the auto industry has said, "If only carbon fiber were $5/lb, and if only cycle times were two minutes or less."

Where and how the demand for $5/lb started is unknown. Speaking at CF 2012, Geoff Wood, CEO of Profile Composites, said he had his first brush with the $5/lb demand in a meeting with Big Three auto executives back in *1989*. Whatever its genesis, "$5/lb" has become a mantra mostly by virtue of repetition — and a sort of straw man for some automotive engineers and executives, who, deep down, don't want to switch to carbon fiber and use the $5/lb threshold as a way to keep the composites industry at bay. Never mind that the demand for $5/lb carbon fiber has persisted *despite inflation*. If we date the first demand for $5/lb carbon fiber to 1989, inflation alone would have boosted that number to about $10/lb today.

> Expect a gradual adoption of composites in automotive as carmakers sort out the cost/benefit of carbon fiber to the car buyer.

Certainly, hope persists. Consultant Ross Kozarsky, in his Market Trends column this issue (p. 7), predicts we'll yet see $5/lb carbon from a lignin-based precursor in 2017. But at the conference, many carbon fiber manufacturers made clear that they believe $5/lb carbon fiber is not only not within reach but never will be. Despite efforts to find a cheaper, feasible alternative, they say polyacrylonitrile (PAN) is still the precursor of choice. And although the efficiency of the carbon fiber manufacturing process has increased incrementally, that won't bring a big drop in the price of fiber anytime soon.

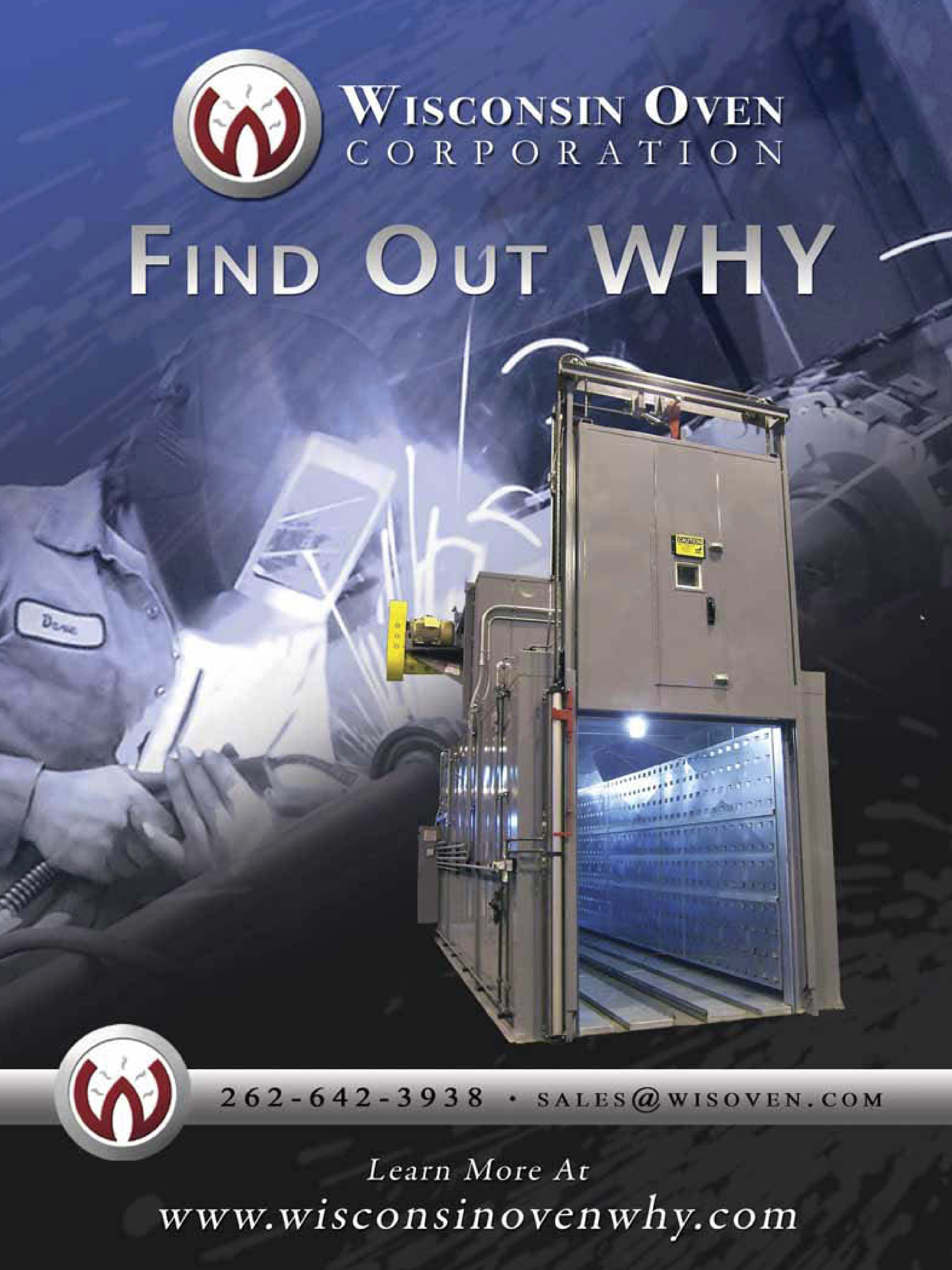
What *is* dropping is mold cycle time. We've come a long way since autoclaved prepreg was the only way to go. Teijin says it is fine-tuning a 60-*second* process for the molding of carbon fiber/thermoplastic parts for automotive applications. Dieffenbacher and KraussMaffei have jointly developed a three-minute part-to-part process to mold carbon fiber/thermoset parts — in use right now by Audi. Quickstep reported at CF 2012 on its efforts to develop Resin Spray Transmission for the high-speed manufacture of automotive parts. And Globe Machine continues work with Plasan Carbon Composites on a high-speed molding process.

What all of this means in the long run remains to be seen. In any case, the argument in favor of carbon fiber's use in almost every other application has always been focused on something *beyond* unit cost. Even if an inexpensive precursor were developed, carbon fiber will win the day not because it's cost-competitive pound-for-pound with aluminum or steel but because it is cost-*efficient* throughout the vehicle's lifecycle by vastly increasing fuel-efficiency, prolonging product life and preserving resale value.

That's how carbon fiber earned such a large presence on the Boeing 787, the Airbus A350 XWB, and other composites-intensive aircraft coming onto the market. In automotive, however, the variables are different: Aircraft are designed to last 30 years, while cars are designed to last about 10; aircraft volumes are typically not greater than 100 a year, while a single car model's volume is measured in the hundreds of thousands. Thus, you can expect to see a gradual adoption of composites in automotive as carmakers sort out in production vehicles the cost/benefit of carbon fiber to the car buyer.

See the March issue of *HPC* for a complete report on the Carbon Fiber conference and the fiber's prospects in automotive, aerospace, wind energy, pressure vessels and more.

Jeff Sloan



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MARKET TRENDS

OPTIMIZING MATERIALS SELECTION IN AUTOMOTIVE AND AEROSPACE STRUCTURES

Ross Kozarsky is a senior analyst and the leader of the Lux Research (Boston, Mass.) Advanced Materials team. He provides strategic advice on, and ongoing intelligence about, emerging coating, composite and catalyst materials that serve as enabling technologies for new markets and applications in industries ranging from oil and gas to electronics. He has advised large multinationals, investment firms and government agencies on strategic innovation decisions in domains such as transportation, lightweighting, energy security and nanotechnology. Kozarsky also has presented at conferences in Asia, Europe and North America on topics that include carbon fiber composites. Previously, he worked as a chemical engineer at Solexant (San Jose, Calif.). He holds a Ph.M in advanced chemical engineering from the University of Cambridge and a BSE in chemical engineering from Princeton University.

AHSS, Al, Mg, Ti and CFRP all have benefits and drawbacks

	BIGGEST BENEFITS			BIGGEST OBSTACLES		
AHSS	Cost	Availability	Manufacturing compatibility	Welding	Ductility	Providing Class A finish
Al	Cost	Availability	Light weight	Forming	Corrosion	Low melting point and high CTE
Mg	Light weight	Damping	High-temperature performance	Availability	Ductility	Corrosion
Ti	Tensile strength	Environmental resistance	Compatibility with composites	Cost	Difficulties in machining	High scrap rates
CFRP	Light weight	Part consolidation	Corrosion resistance	Cost	Throughput	3-D performance

AHSS = advanced, high-strength steel
Al = aluminum
CFRP = carbon fiber-reinforced polymer
Mg = magnesium
Ti = titanium

Source: Lux Research

Comparison matrix: Benefits & drawbacks of competing materials

The car of the future will be a multimaterial construction in which composites and advanced metals will be combined to achieve the best performance/cost balance.

In my role as an analyst who helps clients find new business opportunities in emerging technologies, I have scouted a wide range of advanced materials that span the "innovation funnel," from the invention and prototyping stages all the way through production. For the automotive and aerospace markets, both of which are dynamically expanding, my firm has targeted several technologies: carbon fiber composites, nanocrystalline metals, such as magnesium, and — in my opinion, the dark horse — additive manufacturing.

First recognized and used in 1879 by Thomas Edison as the filament in light bulbs, carbon fiber is progressing along the development path. Since the advent of polyacrylonitrile (PAN) precursor in the 1960s, the application of high-strength carbon fibers has grown markedly, from sporting goods to aircraft structures to automotive chassis and body panels. At present, the cost of fiber prevents widespread adoption.

Absent an alternative precursor or faster, less-expensive thermal treatment technologies, fiber cost will gradually increase, due to rising operating expenses. But I believe that lower-cost fiber is possible in the near-term based on ongoing work by Oak Ridge National Laboratory (ORNL, Oak Ridge, Tenn.) in collaboration with SGL-The Carbon Co. (Wiesbaden, Germany) on textile-grade PAN precursors. In the long term, ORNL's work with Ford Motor Co. (Dearborn, Mich.) and Dow Automotive (Auburn Hills, Mich.) on polyolefin-based precursors should yield more dramatic cost reductions.

As emerging technologies come online, in precursor, oxidation and carbonization, best-in-class carbon fiber costs will fall to around $11/kg ($5/lb) by 2017. With more competitive pricing, the total carbon fiber-reinforced polymer (CFRP) market will reach $36 billion by 2020, with aerospace at $14.4 billion and the automotive sector growing to $2.7 billion. Despite difficulties, lignin precursor-based carbon fiber will continue to receive attention, and I believe that CFRPs that employ thermoplastic resins will grow and be more widely applied.

That said, those who deal in advanced metals are not watching idly as carbon fiber composites move to increase their share in aerospace and automotive — the metals industry also is innovating. Fig. 1, which illustrates a matrix of advanced metals and CFRP, demonstrates both the ben- ➲

efits and the obstacles to adoption of competing materials. Going deeper, a decision-tree, material-trade analysis of aerospace material selection for aircraft components shows that, for example, high-strength steel has an assured position in landing gear today, but titanium and carbon likely will grow in those applications. Aluminum will remain a strong contender in ribs, stringers and bulkheads, but carbon fiber and titanium are poised to take larger shares in that area. In the automotive sector, semistructural components, such as seats and instrument panel beams in the vehicle interior, represent a four-horse race, with steel, aluminum, magnesium and carbon fiber vying for dominance in future cars. I see carbon fiber taking some of aluminum's share in powertrain parts that don't need high thermal stability.

In reality, the car of the future will be a multimaterial construction in which composites and advanced metals will be combined to achieve the best performance/cost balance.

A material to watch, in aerospace and automotive, is nanocrystalline magnesium produced in sheets by nanoMAG (Livonia, Mich., a Thixomat company). The company uses a proprietary thixomolding thermal/mechanical process that converts billets to sheet form and is currently targeting high-value applications in defense, armor, aerospace and sporting goods, with the help of grants from the U.S. Army and others. This material could represent a kick to the gut for other structural materials, depending on its development and adoption.

Finally, additive manufacturing must be viewed as both a competitive and a complementary solution in many applications. This fascinating technology, which includes stereolithography (SLA), selective laser sintering (SLS), fused deposition modeling (FDM), 3-D printing and similar processes, can produce virtually any shape or feature, without much postform processing. The materials used in the processes include metals and polymers that have embedded functional fillers and/or chopped fibers. However, the processes do have cost, yield and scalability limits compared to incumbent subtractive manufacturing and require a strategic business model for commercial success that includes a focus on small, complex, high-value parts, such as components for gas turbine engines and orthopedic implants (see "Learn More," below). Savvy developers will sell optimized raw material powders at high margins to enable part manufacturing. Manufacturers who need complex, high-temperature plastic or metal parts should consider engaging with one of the leaders in this growing sector. ■

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Read this article online at http://short.compositesworld.com/PBTUYbtd.

Read more about additive manufacturing technologies and materials in the following:

"The rise of rapid manufacturing," *HPC* July 2009 (p. 32) or visit http://short.compositesworld.com/s1Zf43Fh.

"Focus on Design: The promise of rapid manufacturing," *HPC* January 2008 (p. 54) or visit http://short.compositesworld.com/Dz51Y0r6.

TESTING TECH

COMPOSITES TESTING: THE CONTINUING STANDARDS DILEMMA

Dr. Donald F. Adams is the president of Wyoming Test Fixtures Inc. (Salt Lake City, Utah). He holds a BS and an MS in mechanical engineering and a Ph.D in theoretical and applied mechanics. Following a total of 12 years with Northrop Aircraft Corp., the Aeronutronic Div. of Ford Motor Co., and the Rand Corp., he joined the University of Wyoming, directing its Composite Materials Research Group for 27 years before retiring from that post in 1999. Dr. Adams continues to write, teach and serve with numerous industry groups, including the test methods committees of ASTM and the *Composite Materials Handbook 17*.

In May 2007, this column was devoted to the standardization of test methods and the need for same. A detailed discussion of the evolution of standards was presented, and it is, perhaps, well worth rereading today. That column was followed in the next issue (July 2007) by a discussion of attempts to achieve globalization and harmonization (see "Learn More," p. 11). More than five years have passed since these articles were written. It's time for a progress report.

Globalization — the spread of composites technology, including composites testing, independent of geographical and political boundaries — has exploded during the past five years. The commercial aircraft industry has led the way, driven particularly by The Boeing Co. (Chicago, Ill.) and Airbus (Toulouse, France). These major commercial airframe manufacturers have involved many subcontractors around the world in developing the new materials and processes they need. Thus, they are spreading these advanced technologies around the world. This has given many individuals, companies, countries and special-interest groups worldwide a strong opportunity to exert their individual opinions and biases on the current technology. That is, we now have more concepts than ever about the best way to proceed. This definitely includes test methods. Although many of these concepts will fall into disuse as they are eventually shown to be deficient or ineffective, some will become new standards or additions to existing standards.

In summary, globalization has led to much new research activity on an international scale in a relatively short time period, and as such, it has been a very favorable development.

Long before globalization, however, various groups around the world had developed their *own* standard methods for testing composites. These were discussed in my May 2007 column. As the composites industry has become a more global enterprise, these groups were no longer isolated and came into increasing contact with one another. This led to recognition of the need for harmonization. That is, the groups sought to answer this question: *When two (or more) different test methods follow different procedures to obtain data on the same material property, do the different methods produce statistically equivalent results, such that the methods can be used interchangeably*?

> Many testing laboratories are forced to have two (or more) test fixtures available to perform the same test.

About 10 years ago, it was recognized that the answer to this question was "*not necessarily*." The need for harmonization of test methods was acknowledged, and some preliminary work was conducted during the next few years. This included gathering experimental data from the literature and generating new data to permit direct comparisons of selected test methods. This was a time-consuming, difficult and expensive activity. Unfortunately, the initial enthusiasm for this approach and the pursuit of harmonization has faltered, with little sign, at present, that the movement will regain its vitality. Instead, the oft-used approach, currently, is to select a specific standard test method for the particular design application at hand and strictly follow it. And because there often are multiple test methods available to measure a particular property, many different standards are currently being followed and many methods are used, with little or no attempt at harmonization.

In the global aerospace industry, most of the testing standards in use at present are derivatives of U.S. aerospace industry procedures formalized over the years by ASTM International (West Conshohocken, Pa.). That is, most of the aerospace-oriented standards (e.g., DIN, EN, prEN, ISO) have been taken from the ASTM standards, typically with only minor changes.

Unfortunately, these minor changes are the source of many current major problems. A test fixture developed for one standard will not necessarily satisfy the requirements of another standard. And ASTM itself caused many of these problems when its committees developed these test methods by insisting on using "soft conversions" of dimensions from the U.S. Customary (English) units when they calculate the S.I. (metric) unit values for their "dual unit" standards. That is, rather than using direct (exact) conversions of the U.S. Customary units to S.I. units (hard conversions), they have mandated the practice of arbitrarily rounding conversions to convenient (hence, the name "soft") even numbers. For example, a 0.25-inch diameter loading or support cylinder on a flexure fixture becomes a 6-mm diameter cylinder in the metric version of the standard. It has been well demonstrated, both analytically and experimentally, that this small difference in size has no measurable effect on the experimental results obtained. Nevertheless, the strict follower of the metric standard will not use an available test fixture that has 0.25-inch diameter cylinders.

Another example is the Open-Hole Compression Test Method (ASTM

D6484), adopted directly from a Boeing internal document. The Boeing specimen was 12 inches long. When the ASTM standard was written, the "soft" metric conversion was 300 mm. But this is 4.8-mm shorter than the original Boeing specimen and, therefore, the English version of the ASTM D6484 test fixture is not suitable for use. This is because the Boeing test provides 0.2 inch/5.1 mm of clearance between the two halves of the fixture to allow for elastic compression of the specimen before failure at the hole. There will be insufficient clearance (only 0.3 mm) if the shorter S.I. units specimen is used in the U.S. Customary units fixture. The fixture will bottom out before specimen failure is achieved. Dozens of similar examples could be listed.

The ASTM soft conversions issue aside, other standards organizations also introduced minor changes that introduce similar complications. The result is that many testing laboratories are forced to have two (or more) test fixtures available to perform the same test, depending on the standard they are obligated to follow for a particular customer.

It's possible that all of this could be justified *if the differences mattered*. But they don't. For example, let us follow-up with the Open-Hole Compression test method. At essentially the same time that Boeing developed its test configuration (in the mid-1980s), Northrop Corp. (West Falls Church, Va.) developed its own test method. Although Northrop's method also required a 0.25-inch diameter hole, its specimen is only 1-inch wide rather than 1.5-inches wide and, more importantly, only 3-inches long. It was later clearly shown that the Northrop test method produced the same test results as the Boeing method, even though the specimen was 9-inches/229-mm shorter. It becomes obvious that the small (4.8 mm) difference between the U.S. Customary units specimen length and the S.I. units length for the Boeing specimen itself is of little technical importance.

ASTM could single-handedly make a major contribution to solving these problems by simply converting all of their standards to S.I. units only and abandoning all English units. ASTM could even keep the existing soft conversions. However, the U.S. aerospace industry is strongly opposed to converting to S.I. units, and because it has a strong influence on ASTM, the latter is unlikely to make the change.

This opens the possibility that, in this age of growing globalization, the remainder of the world will leave the U.S. and its U.S. Customary units behind, isolated from the global mainstream. Perhaps, in fact, this is already happening. ■

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Read this article online at http://short.compositesworld.com/COb24rlR.

Read Dr. Adams' previous columns on the subject of composites testing standards:

"Why standardization?" in *HPC* May 2007 (p. 11) or visit http://short.compositesworld.com/9pOAXI1r.

"Test method globalization and harmonization" in *HPC* July 2007 (p. 9) or visit http://short.compositesworld.com/vs8StqBt.

NEWS

Boeing ramps up 787 production to five per month

Build rate expected to reach 10 per month in late 2013

The Boeing Co. (Everett, Wash.) reported on Nov. 12 that it had rolled out the first 787 *Dreamliner* built at the new rate of five airplanes per month. The airplane is the 83rd 787 to come off the line. Boeing earlier this year increased the rate from 2.5 to 3.5 airplanes per month and is on track to achieve a planned 10 per month by late 2013. The program production rate accounts for airplanes built at Boeing South Carolina (North Charleston, S.C.) and Everett, including the Temporary Surge Line that was activated in Everett earlier this year.


Source: Boeing

Boeing reports that about 500 employee involvement teams across the 787 program are actively seeking ways and means to meet quality, safety and production-rate goals. Among the new tools Boeing has deployed to improve productivity in the Final Assembly areas are Orbital Drilling machines by Novator (Stockholm, Sweden). The machines are used to drill holes for the fasteners that are used to attach the wings to the center fuselage section of the airplane.

The drilling technique is unique in that the cutter rotates in a circular motion to carve out the hole, rather than a conventional drill that cuts straight into the material (for more about the technique, see http://short.compositesworld.com/rpWQR5bG). The benefits of the machines include improved precision and time savings for mechanics. A third benefit is improved safety because the machines require lower thrust and torque.

"This accomplishment, doubling our production rate in one year, is the result of the combined efforts of thousands of men and women across Boeing and at our partners," says Larry Loftis, VP and general manager of the 787 program. "The entire 787 team is focused on meeting our commitments. They've gotten even smarter in how they build this airplane and applied real ingenuity in making our processes and tools more efficient."

At *HPC* press time, 35 787s had been delivered to eight airlines, and the program had more than 800 unfilled orders with 58 customers worldwide.

Airbus A350 XWB program begins static airframe validation

Airbus (Toulouse, France) reported on Nov. 23 that its A350 XWB static test airframe had been moved into the facility where it will undergo testing to validate the structural design of the composites-intensive, midsized, twin-aisle passenger jet.

In mid-November the airframe rolled out of the A350 XWB final assembly line at Blagnac Airport in Toulouse and was transferred to the L34 static test hall situated across the airport in the Lagardère industrial zone — also home to the A380 final assembly line. This cleared the way for the A350 XWB airframe to be integrated into a test rig for a testing campaign that will submit the airframe to nearly a year of evaluations, including limit load and ultimate load validations, along with residual strength and margin research.

The L34 static test hall covers an area of 10,000m^2 (107,639 ft^2) and is supported by 200 workers during peak testing activity. It houses a massive test rig that incorporates 2,500 metric tonnes (5.5 million lb) of steel framing and 240 jacks/loading lines that are used to induce structural loads. The testing is recorded by 12,000 sensors. The static test airframe was the first to be built on the A350 XWB's new Roger Béteille final assembly line in Toulouse, and it was the focus during Airbus' inauguration ceremony for this production facility in October. The airframe is sized to represent the A350-900 version of Airbus' newest jetliner family, which is the intermediate aircraft of the three fuselage-length versions: the A350-800, A350-900 and A350-1000.

Florida State HPMI to scale up buckypaper production

Research at Florida State University's High-Performance Materials Institute (HPMI, Tallahassee, Fla.) has focused for some time on development of buckypaper — flat sheet material made of compressed carbon nanotubes (CNTs). HPMI reported in November that the previously experimental material now shows promise for a variety of real-world applications.

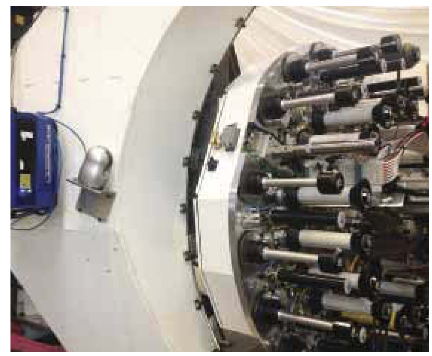
Although HPMI now can produce buckypaper only in small quantities at a high price, Frank Allen, HPMI operations director, says researchers are looking to scale up production with a prototype batch process that would produce buckypaper strips at a rate of 5 ft/min (1.52m/min). HPMI says the electrically conductive material could replace metal lightning-strike mesh on aircraft, and its extraordinary strength-to-weight ratio could make aerostructures stronger and lighter. HPMI reports that it cuts and machines the buckypaper-based composite with an OMAX (Kent, Wash.) 55100 waterjet cutting machine.

BIZ BRIEF

The Carbon Fibre Industry Worldwide 2011-2020: An Evaluation of Current Markets and Future Supply and Demand, a 400-page report by Tony Roberts, principal at AJR Consultant (Lake Elsinore, Calif.), provides detailed statistical data, analysis of likely trends and an in-depth survey of carbon fiber manufacturers worldwide, including new players in China and the Middle East. Survey data include details about plant capacities, production outputs, expansion plans, product ranges and full financial results. Among the highlights: CFRP sales will grow from $16.11 billion in 2011 to $28.2 billion in 2015 and more than double to $48.7 billion in 2020. For more details or to order the report, visit www.carbonfiber-report.com.

AFP/laser projection integration a first

Machinery manufacturer Electroimpact (Mukilteo, Wash.) has announced the development of an automated fiber placement (AFP) machine cell that fully integrates the LASERGUIDE laser projection system from Assembly Guidance Systems Inc. (Chelmsford, Mass.). "One interface now allows operators to monitor and control both the AFP machine and the laser projection system, seamlessly," explains Electroimpact engineer Todd Rudberg.



Source: Assembly Guidance

Integration addresses the remaining bottlenecks in automated production of composites — tasks that demand human intervention, including the transfer of data from the build sequencer to the projection software. Now, that data transfer step has been eliminated.

Creation of the single system was enabled by Assembly Guidance's software development kit (SDK). "SDK provides ... tools that allow composites manufacturing systems to control Assembly Guidance laser projectors with their software," notes Scott Blake, Assembly Guidance president. Reportedly, projection errors are reduced by a factor of five. "By having the laser system integrated," Rudberg says, "the locations of the AFP machine, mandrel, and laser system are all precisely known relative to a common coordinate system, which results in considerably reduced discrepancy in projections and actual ply boundaries." Accordingly, the laser system can be used to locate a part or machine within 0.015 inch/0.38 mm, without any physical contact between the part and the machine. Further, an automated touch probe can be used without risk of part damage due to uncertainty about its location.

BASF, SGL seek carbon fiber/polyamide match for T-RTM, RIM

BASF (Ludwigshafen, Germany) and the SGL Group (Wiesbaden, Germany) will jointly develop a composite material based on a reactive polyamide and carbon fibers in pursuit of faster, more cost-effective production of carbon fiber-reinforced thermoplastics. The material system, intended for use in the relatively new thermoplastic resin transfer molding (T-RTM) process and in reaction injection molding (RIM) processes, is expected to permit considerably shorter processing cycles than are possible in conventional thermoset RTM. The key challenge for BASF and SGL is adjusting the material system to these faster processing techniques. That research effort is said to hold the key that will permit entry of lightweight, high-strength carbon composite structural components into automotive mass production.

"To achieve good wetting of the fiber and short cycle times in T-RTM or reactive injection molding, we start from low-viscosity highly reactive caprolactam formulations," explains Dr. Martin Jung, head of structural materials research for BASF Research. The research effort will seek a means to attain optimal bonding at the matrix/fiber interface. The new polyamide will require development of a "custom-formulated sizing" for the fiber, says Dr. Hubert Jäger, SGL's head of technology and innovation, that will optimize fiber-resin adhesion and, thus, the composite's strength and stiffness.

CORRECTION

In the November 2012 issue of *HPC*, a graph posted on p. 35 as part of our Work in Progress feature titled "Structural health monitoring: Angling for the air," was incorrectly identified. *HPC* editors mistakenly named Advanced Fiber Materials Technologies Co. Ltd. as its source. The article's author, however, acquired the graphic from the company profiled in the article — Luna Technologies (Roanoke, Va.) — and informed *HPC* about its genesis since publication. Apologies to Luna Technologies. *HPC* regrets the error.

Business jets, regional jets in the news

Bombardier Aerospace (Montréal, Québec, Canada) announced on Nov. 19 that the first composites-intensive wing shipment for its *Learjet* 85 business jet had arrived at the Wichita, Kan., assembly line. Crews already were involved in the process of readying the wings for attachment to the fuselage of the first Flight Test Vehicle (FTV1). Bombardier also reported that the fuselage for FTV2 had successfully completed its integrity inspection. Installation of the nose, bulkheads, floor, windshield and door surrounds were scheduled to begin in late November. When it is complete, the main fuselage will be shipped with the aft fuselage to the final assembly line.


Source: Bombardier

Wings for the complete FTV2 static test article were expected to arrive from Querétaro, Mexico, by the end of November as preparations for static ground testing continued.

"Seeing the wings arrive for our first *Learjet* 85 test aircraft is a wonderful moment … that could not have happened without the hard work and dedication of every single person involved in this project," says Ralph Acs, Learjet VP and general manager. "This development program is gaining ever more momentum as we tirelessly work towards first flight and the first customer delivery."

The *Learjet* 85 is designed to fly 3,000 nm/5,556 km at speeds of up to 470 kts (871 kmh). In practice, that means it can fly direct from Montréal to Caracas, Venezuela, or from Montréal to Los Angeles, Calif.

Bombardier announced on Nov. 7 in an investor call that its larger *CSeries* commercial aircraft program is making progress, with the build for both the Complete Airframe Static Test (CAST) and the first flight-test aircraft moving forward, says president and CEO Pierre Beaudoin. A number of key milestones had already been met, but Bombardier also had encountered supply-chain delays which resulted in a delay. First flight, therefore, was rescheduled for the end of June 2013. Entry into service of the *CS100* aircraft is now expected to occur approximately one year after first flight. According to published sources, including *Aviation Week & Space Technology* magazine (Nov. 19, 2012, by Jens Flottau and Bradley Perrett), the delay is due to issues at Bombardier's Chinese partner Shenyang Aircraft, part of AVIC Aviation Technologies (Shenyang, China). Work is reportedly being pulled back from China to other Bombardier facilities, including the one in Belfast, Northern Ireland.

On another single-aisle jet program, GKN Aerospace (Isle of Wight, U.K.) and Shanghai Aircraft Manufacturing Co. (SAMC, Shanghai, China) announced on Nov. 15 that they have revised their memorandum of understanding and signed further agreements that cover manufacturing, development and intellectual property rights for structures on Commercial Aircraft Co. of China Ltd.'s (COMAC) *COMAC 919*. The plane is a next-generation, twin-turbofan, narrow-body aircraft with 150 seats.

In collaboration with SAMC, a wholly owned subsidiary of COMAC, GKN Aerospace is to manufacture and assemble the composite horizontal tail plane (HTP) for the *C919*. The carbon-fiber composite HTP consists of two major torque-box assemblies joined together at a center rib and includes the elevator assemblies. Working with SAMC, GKN Aerospace will carry out the HTP development activities and, on completion of this phase, move into a manufacturing joint venture that will be called Shanghai GKN-SAMC Aerospace Composite Structure Manufacturing Co. Ltd.

Marcus Bryson, CEO of GKN Aerospace and Land Systems, says, "The ongoing success of this collaboration with SAMC represents both an important expansion of GKN's long-established working relationship with China and a vital technological step forward in our work on the design and manufacture of advanced composite components and structures." GKN employs 5,000 people and has 12 manufacturing locations in China.

In other U.S./China aviation news, Cessna Aircraft Co. (Wichita, Kan.) has entered into a joint venture with China Aviation Industry General Aircraft Co. Ltd. (CAIGA, Zhuhai, China) to conduct final assembly of the Cessna *Citation XLS+* business jet in China for the Chinese market. Cessna's relationship with CAIGA is expected to help the former tap into what it predicts will be a decade of significant growth in the aviation market. At *HPC* press time, formation of the joint venture company was still subject to various government approvals and customary conditions.

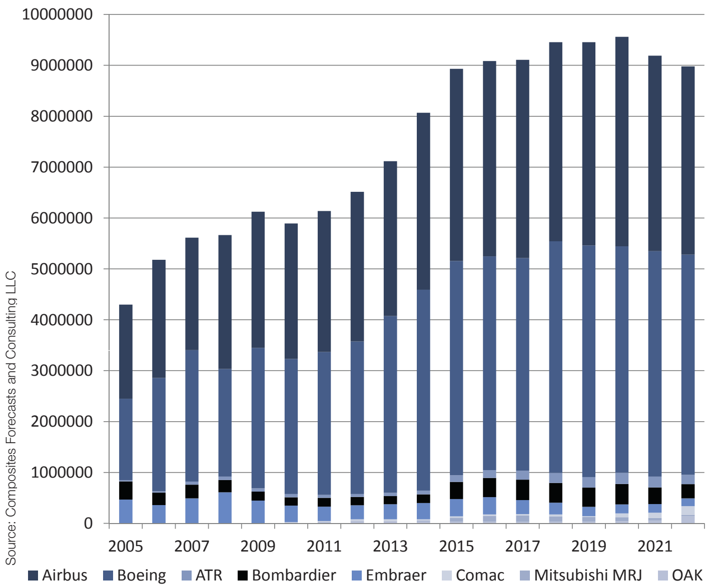
Cessna's Wichita, Kan., operations will provide components and parts manufacturing and subassemblies for the joint venture aircraft. The fairings and radome on the *Citation XLS+* are composite components. CAIGA operations in Zhuhai will include final assembly, painting, testing, interior installation, customization, flight-testing and delivery of *Citation XLS+* jets to in-country customers. This joint venture contract stems from the strategic framework agreement that Cessna entered into with CAIGA's parent company, Aviation Industry Corporation of China (AVIC), in March 2012.

CW 2012
COMPOSITESWORLD
HIGH-PERFORMANCE COMPOSITES FOR AIRCRAFT INTERIORS

CONFERENCE REVIEW

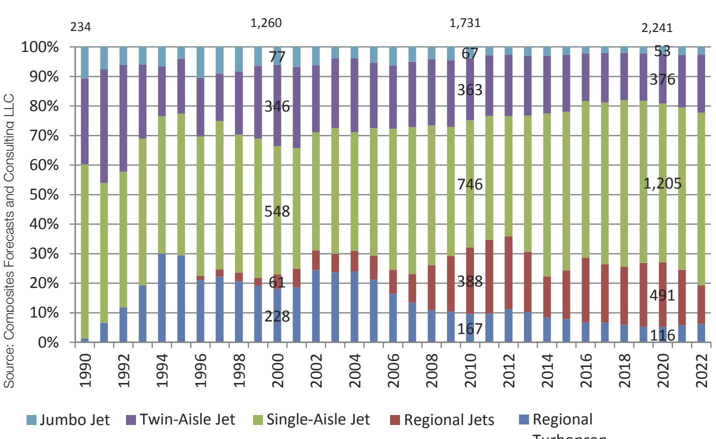
Colocated with the Aircraft Interiors Expo Americas, CompositesWorld's High-Performance Composites for Aircraft Interiors Conference focused on ways to get more composites inside the aircraft.

By Karen Wood



Forecast: New-build Interiors

Presenter Chris Red (Composites Forecasts and Consulting LLC, Mesa, Ariz.) said the new-build market represents about 6 million lb (2,722 metric tonnes) of composite components annually, and approximately 16,250 new aircraft are scheduled for delivery between 2012 and 2022. By the time the Airbus A350 and Bombardier *CSeries* enter production, the OEM market could grow by at least 50 percent compared to 2012.



Forecast: Aftermarket Interiors

Aftermarket potential, driven by replacement cycles and economic conditions, is more difficult to calculate than that of new-build programs. Generally, passenger seating is replaced every one to two years. Paneling, class dividers and other major components are turned over every four years. Complete cabin refurbishments take place every six to eight years.

Held Sept. 25-26 in Seattle's Washington State Convention Center, CompositesWorld's High-Performance Composites for Aircraft Interiors conference included frank discussion of the potential for composites to build its share in this competitive and complicated arena. Cochaired by David Leach, composites market manager, Henkel Aerospace (Bay Point, Calif.), and Dan Slaton, associate technical fellow, Boeing Commercial Airplanes, Flammability and Airworthiness (Seattle, Wash.), the event was kicked off by composites market analyst Chris Red (Composites Forecasts and Consulting LLC, Mesa, Ariz.), who presented an outlook for composite materials and manufacturing in commercial transport interiors.

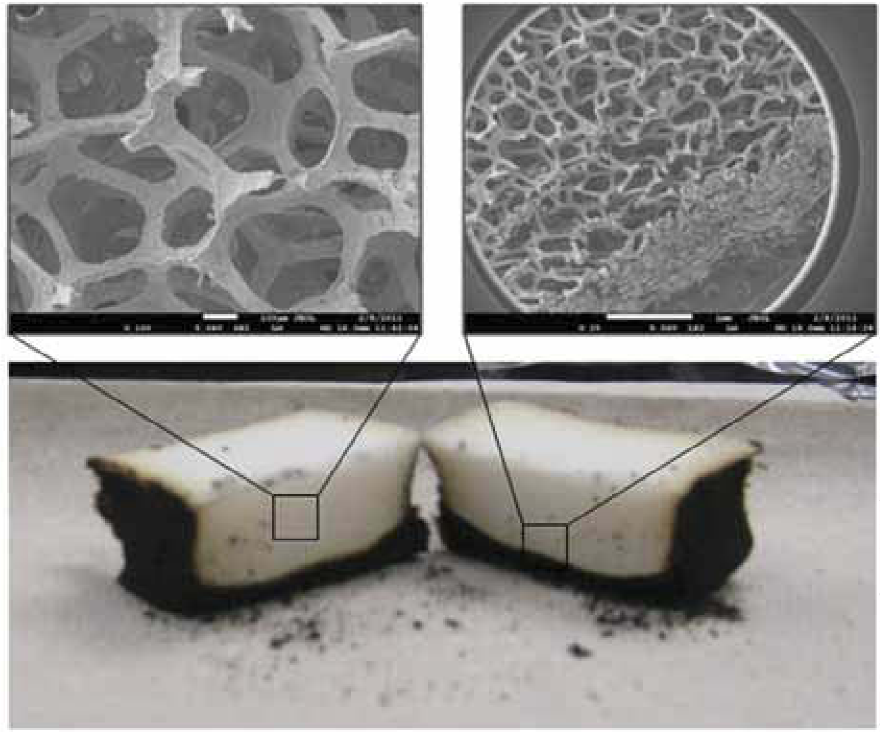
Interiors market: The inside story

Red pointed out that for composite materials and manufacturing processes, aircraft interiors actually represent a *larger* market (by volume) than airframe structures. Interior components account for as much as 40 percent of the commercial airliner's empty operating weight. He assured attendees that there is room for composites to penetrate further.

Red broke the interiors market into two distinctly different segments: the OEM-driven *new-build market* and the much more volatile — and two to three times larger — *aftermarket*. The new-build market, says Red, currently represents about 6 million lb (2,722 metric tonnes) of composite components annually. "By the time the [Airbus] A350 and [Bombardier] C*Series* … and other new single-aisle aircraft enter production," he reported, "the OEM market is expected to grow at least 50 percent compared to this year."

The aftermarket potential, driven by replacement cycles and economic conditions, is more difficult to calculate, he said. Generally, passenger seating is replaced every one to two years. Paneling, class dividers and other major components are turned over every four years. Complete cabin refurbishments take place every six to eight years. "Given the tough fiscal environment, the tendency has been to push these time frames as long as possible," said Red of the period since the 2008 economic downturn. "However, in the past five fiscal quarters," he observed, "latent demand has caused a dramatic upswing in activity."

"Seats represent one of the biggest near-term opportunities," Red contended, adding that new and re-



Source: Polymer NanoComposites Lab/Texas A&M University

Focus on fire protection

A new nanocoating from Texas A&M University's Polymer NanoComposites Lab brings fire-retardant nanoclay filler to the part surface in an ultrathin coating. In tests, 1 percent anionic montmorillonite clay (MMT) and 0.1 percent cationic chitosan were deposited on open-cell polyurethane foam. After 10 seconds of exposure to direct flame, only the coatings' outermost surface was charred. No flame was observed after 22 seconds of exposure, and white flexible foam was revealed under the protective char layer when the exposed foam was cut open.

placement seating has the potential to consume 4 million to 5 million lb (1,814 to 2,268 metric tonnes) of composites within the next five years. "Switching to composite seats can save in the neighborhood of 400 to 450 kg [882 to 992 lb] on a single-aisle aircraft." According to Red, there is a potential new-build and replacement market of more than 2 *million* coach seats per year.

Potential areas for composites growth include brackets, trays and clips, cockpit flooring and seat rails. "Combined," says Red, "the existing suite of composite applications plus some of these new opportunities indicate that composite materials will make up perhaps as much as 40 percent of the total tonnage of interiors components, going forward."

Phenolic resins — the current systems of choice for interiors — will continue strong in the future, but Red believes thermoplastics will play a big role in displacing metals in new aircraft cabins and might also begin to displace phenolics in some composites applications.

Hot topic: Fire safety

Not surprisingly, flammability was a burning issue. There was much discussion of certification standards and test methods. An abundance of new materials and coatings were announced, designed specifically to meet the stringent flame, smoke and toxicity (FST) requirements for aircraft interiors applications.

Robert Ochs, project engineer, FAA Technical Center (FAATC, Atlantic City, N.J.), updated attendees on the Federal Aviation Admin.'s (FAA) ongoing fire safety research projects. Special mention was made of the agency's proposal to update, reorganize and improve safety requirements for materials flammability, a move that would shift requirements to a more threat-based approach. Ochs stressed that in-flight fires in inaccessible areas are the most dangerous. Large-scale testing at the FAATC indicated that previous test methods permitted the use of materials that, in practice, perform very poorly. "Mitigation of flame spread is the most effective means of preventing catastrophe," he said, noting that updated and more stringent test methods have been mandated for insulation and are in progress for ducts and wire insulation.

Scott Campbell, director of flammability engineering, and Panade Sattayatam, engineering manager, both at C&D Zodiac (Huntington Beach, Calif.), and Michael Jensen, manager, Composites and Adhesives at Boeing, teamed up to present an update on the Flammability Standardization Task Group (FSTG), a subgroup of the FAA's International Aircraft Fire Test Working Group, which was formed to collaborate and propose industry-wide standard methods of compliance. FAA flammability requirements and compliance methods were being interpreted differently by regional FAA organizations, other regulatory agencies and industry suppliers and manufacturers, Jensen explained. A primary goal of the effort, then, is to address some of these inconsistencies and provide greater test standardization.

Task group members have studied substrates, adhesives/syntactics, textures, laminate colors and paints in an effort to determine which flammability tests, and combinations thereof, will yield the most accurate and repeatable results. Although new types of cores, prepregs, adhesives, panel inserts and so forth will still require testing, Jensen says these methods can streamline the overall testing process.

Innovation in carbon

A real attention-grabber was Hexcel's (Stamford, Conn.) HexMC, a quasi-isotropic molding compound for structural aerospace applications. Designed to bridge the gap between low-performance, low-cost sheet molding compound (SMC) and high-performance, high-cost autoclaved prepreg, the material begins with an aerospace-grade unidirectional (UD) prepreg precursor (8552 resin system/38 percent RC and AS4 carbon fibers/150 g/m^2) that is slit, chopped and randomly redistributed to make approximately 2-mm/0.079-inch thick, 200 g/m^2 mat, available in 450-mm/17.7-inch wide rolls.

SIDE STORY

New method for foam-filled honeycomb

Source: M.C. Gill

Foam-filling via curtain coating

A unique system for filling honeycomb with foam was presented by M.C. Gill (El Monte, Calif.). Called GillFISTS, it features a liquid coating applied by a curtain-coating apparatus (below) to ensure that it uniformly coats the honeycomb's cell surfaces.

Source: M.C. Gill

Tailorable foam expansion

During a subsequent thermal process (standard to processing), the coating foams and fills the cells. The foam can be pre-expanded for use in applications such as VARTM or dried at a lower temperature and stored for thermal foam-fill processing at a later date.

Said to be extremely damage tolerant, HexMC can be molded into a variety of geometries, reported Bruno Boursier, Hexcel's R&T manager. Attainable shapes include sharp angles, deep draws, box corners, curves and gussets. Tension, compression and flexure moduli are 90-plus percent that of quasi-isotropic UD tapes, but in-plane strength drops to 50 percent.

Hexcel has developed proprietary mold designs and processes that it says will preserve the transverse isotropy of the HexMC material in critical areas of parts and ensure minimum fiber distortion. Currently, a special epoxy formulation is used for parts that need to comply with FST requirements (but not heat-release requirements) of *FAR* 25. A structural thermoset formulation that will meet *FAR* 25 OSU requirements (65/65 heat release) can be produced, but it will not perform as well for OSU as thermoplastics, explained Boursier, who sees OSU as the factor that currently limits HexMC use in interior applications.

Also of interest was a presentation on recycled carbon fiber given by Jim Stike, CEO, Materials Innovation Technologies-RCF (MIT-RCF, Lake City, S.C.).

To date, MIT-RCF says it has reclaimed 1.5 million lb (680.4 metric tonnes) of carbon fiber scrap from landfills, not to mention the material that comes directly from manufacturers. A test barrel for Boeing's 787 program, for example, was chopped up and recycled, and bicycle manufacturer Trek (Waterloo, Wis.) has implemented a recycling program for its carbon bike frames that has, thus far, amassed 140,000 lb (63.5 metric tonnes) of scrap. (For more on carbon fiber recycling, see "Learn More," this page.)

Opportunities for thermoplastics

SABIC (Pittsfield, Mass.) product development engineer Mohammad Moniruzzaman discussed high-flow, high-strength, OSU-compliant carbon fiber-filled Ultem compounds. Ultem resins are a family of amorphous thermoplastic polyetherimide (PEI) resins with elevated heat resistance. Reportedly, the company's EX008PXQ compound (40 percent carbon fiber, PEI and proprietary additives) is 50 percent lighter than aluminum, stronger than die-cast aluminum and offers similar specific modulus and specific strength as machined aluminum (see "Learn More").

Tim Greene, global product manager at Greene, Tweed & Co. (Kulpsville, Pa.), discussed carbon fiber-reinforced thermoplastics for metal replacement in challenging aircraft interior components. There's a "lack of cost-effective, complex-shaped composite solutions," said Greene. The company has developed discontinuous fiber composites intended to bridge the gap between continuous fiber composites, which offer superior performance but limit part complexity, and injection-molded composites, which can reproduce complex detail but are semistructural. In the process, aerospace-grade carbon fiber-reinforced UD prepreg tape (thermoset or thermoplastic matrix) is processed into random "chips." Finished parts are matched-die compression molded. The resulting part reproduces complex 3-D geometry with high fiber content. Unlike with injection molding, the fiber length (0.5 to 2 inches/12.7 mm to 50.8 mm) is preserved.

The company's Xycomp DLF offers discontinuous long fiber and a thermoplastic matrix. Greene stressed that the material is intended not to displace thermoset composites, but rather to replace metals in complex multipiece assemblies. "We're looking at all the bits and pieces of metal that remain on the aircraft," he said. Xycomp Carbon/PEEK DLF, which offers between 35 and 50 percent weight savings compared to metal, has been certified for and is currently flying on Boeing 787s.

Source: Gurit

Interiors-bound cyanate ester

Gurit (Isle of Wight, U.K.) reported that its PN900, a phenol-formaldehyde-free, low-pressure cure, low-shrink cyanate ester resin system, offers good surface quality in applications that do not require high impact strength, such as this complex air duct.

Focus on applications

Redesigning aircraft seating to reduce weight and optimize capacity has become a priority. Bob Yancey, senior director, Global Aerospace and Marine, Altair Engineering Inc. (Troy, Mich.), highlighted his company's efforts on this front. His team uses topology optimization software to define the nondesignable spaces, such as attachment points, and the designable spaces in between. Then the team considers applied loads and boundary conditions and determines the optimal structure. One result is a better understanding of where the main load paths are, which also enables better control of fiber orientation.

A high-concept seat design was presented by Christine Ludeke, principal, ludekedesign (Zurich, Switzerland). Based on the idea of "active seating," the seat is constructed using a trademarked *aeras knit* ergonomic cover on a carbon fiber back shell. The recline is built into the fabric, eliminating the need for a mechanical recline mechanism. The seat concept is still in development.

Patrick Phillips, director of business development, Norduyn (Montréal, Québec, Canada), showed off the company's new lightweight Quantum galley cart by easily lifting it up onto the speaker podium. The cart has a carbon fiber single-body shell, produced via vacuum-assisted resin infusion. A primary manufacturing challenge was to produce the straight sides without bowing, which was overcome via fiber manipulation during processing.

The testing was extreme, explained Phillips. The cart withstood 900 lb/408 kg of pull on the front door, 5,000 cycles of impact on the side panels and door, scratch tests and an impact test that applied 90 units of impact force to its door. Although aluminum doors typically bend under this test, the composite door, which flexes, can be closed and used again, reported Phillips. Reportedly, the cart also offers improved thermal efficiency. ■

Source: *HPC*/Photo: Karen Wood

"Think like an airline"

That was Bill Archer's encouragement for attendees. The president and CEO of Landmark Aerospace (Kennesaw, Ga.) stressed the need to understand the very complicated aircraft interiors arena from the customer's point of view. (For more, read the expanded article noted in "Learn More.")

CW LEARN MORE @ www.compositesworld.com

Read an *expanded* version of this article at http://short.compositesworld.com/JmYJeaFB.

Read more about carbon fiber recycling in "Carbon fiber reclamation: Going commercial," *HPC* March 2010 (p. 30) or visit http://short.compositesworld.com/Ah8s0EcZ.

A SABIC Ultem resin-impregnated compound enabled a recent aircraft interior application of carbon composites, discussed in "Carbon fiber food tray arm: Better and cheaper," *HPC* November 2011 (p. 11) or visit http://short.compositesworld.com/pRMxlj9Q.

PRESSURIZED WATER-BASED MOLD TEMPERATURE CONTROL COMES TO COMPOSITES

Water-based mold temperature control units (TCUs) have been used in the thermoplastic injection molding industry for decades. They have repeatedly proven to be reliable tools for quickly and accurately ramping mold temperatures up and down to meet fast cycle time requirements.

In the composites industry, however, they have been slow to gain ground. Many manufacturers prefer to use electric cartridge heaters or oil-based mold temperature control systems. Electric cartridge heaters have appeal because they are easy to install and operate, but they don't offer cooling capability. Critics also say they have been known to heat inconsistently. Oil-based systems are favored by molders of composites because of their familiarity, but they are slow to build temperature and, in the process, consume a great deal of energy.

Putting claims to the test

Active in the composites industry over the past couple of years, mold temperature control manufacturer SINGLE (Hochdorf, Germany and Charlotte, N.C.) has had success placing water-based mold TCUs with a few automotive composites molders — Mercedes, VW, BMW, Lamborghini and others — but SINGLE's business development manager – composites, Kip Petrykowski, contends that the rest of the composites industry still has much to learn about fast, efficient mold temperature control. To help educate its prospective customers, SINGLE recently conducted studies to demonstrate for molders of composites the capabilities of water-based vs. oil-based and cartridge heater systems. In the process, the company amassed a significant collection of performance data. Petrykowski reports that his company's head-to-head comparisons of water-, oil- and electric cartridge-based mold TCUs have shed considerable light on the capabilities of each technology.

Water vs. oil

The first trial compared the performance of two SINGLE TCUs, an H.02 pressurized water system and a D.02 oil-based system. Both units had been used previously in commercial production. The mold, supplied by Weber Manufacturing Technologies Inc. (Midland, Ontario, Canada), was a single-sided, externally plumbed test tool. Petrykowski notes that the test was conducted with control units the company happened to have in stock. For that reason, the oil unit had twice the heating capacity, 2.8 times the cooling capacity and 1.6 times the maximum rated flow of the pressurized-water unit. Also, the inside diameters of the oil unit's heating and cooling inlets were 1.8 times larger than those of the water unit, giving the oil unit a significant advantage in terms of potential flow rates through the mold.

The results of the tests (Tables 1 & 2) indicate that the flow rate through the tool was greater with the oil unit, something Petrykowski says would be expected, with a flow of 100 liters/hr (2.4 gal/hr) compared to 60 liters/hr (15.9 gal/hr) for the water unit. The temperature differentials for incoming and outgoing fluid in the oil unit averaged 3.75°C. The water unit averaged 2°C. Both numbers are within the range of typical values for tools flowing at optimum rates. Based on this data, SINGLE reports it is unlikely that either system's heat transfer efficiency would benefit from additional flow. Not charted in the study was the fact that the oil unit averaged a 2.75°C temperature differential across the tool face, while the water unit averaged less than 1°C.

However, even with twice the heating capacity (24 kW vs. 12 kW), 2.8 times the cooling capacity (116 kW vs. 41 kW) and 1.6 times the flow rate (100 liters/min vs. 60 liters/min), the oil unit was unable to heat or cool the mold faster than the water unit. The oil unit also consumed 69 percent more electricity. The limitation of greatest concern for the oil unit, says Petrykowski, is the large temperature difference between the TCU and the mold surface. The temperature of the mold surface should, ideally, closely match the temperature control set point to minimize uncertainty about mold temperature parameters.

Water vs. electric cartridge heater

SINGLE also compared a pressurized water TCU with an electric cartridge unit. The mold here was a two-sided 18 kg/39.7 lb test mold. During the test, mold temperature readings for both units were taken at one-minute intervals, using a surface pyrometer placed at the center of each mold surface. The temperature of the water-based units' outgoing and returning fluid as it circulated through the mold and the energy it consumed were read directly from the controllers on the unit.

The mold temperatures during the electric cartridge test were controlled by comparison of input received from a thermocouple placed in the mold to a temperature set point on the unit's controller. The test mold, says Petrykowski, was not optimized for water flow and, therefore, allowed a flow of only 9 liters/min. Further, the water-based TCU was the smallest SINGLE unit available and was rated at only 6 kW — *one-fifth* the rated capacity of the electric cartridge unit. The material used to mold the part was a fiber-reinforced polyetheretherketone (PEEK).

Tables 3 & 4 show the results from the pressurized water vs. electric cartridge tests. The readings, notes Petrykowski, indicate that the water-heated mold cy-

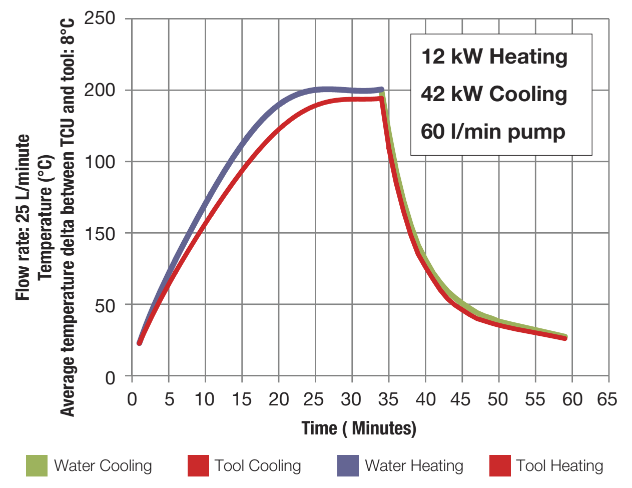


TABLE 1. Pressurized Water Temperature Control Unit vs. Tool Heating/Cooling Profiles

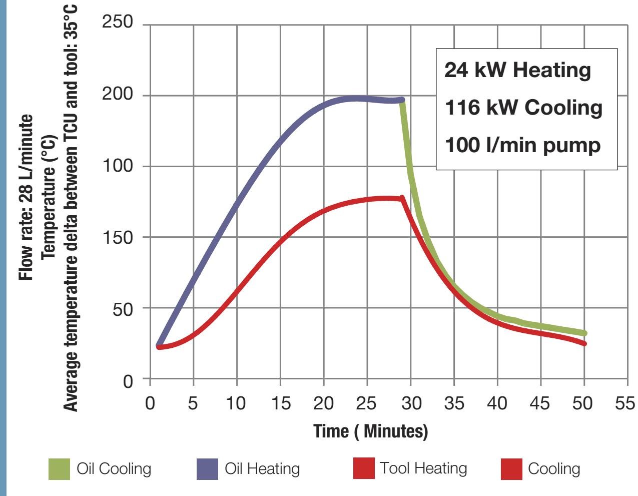


Table 2. Oil Temperature Control Unit vs. Tool Heating/Cooling Profiles

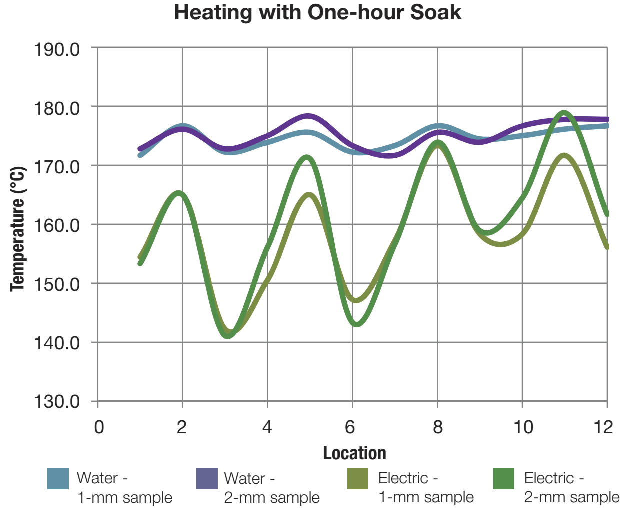


Table 3. Temperature vs. Location — Water and Electric Heating with One-hour Soak

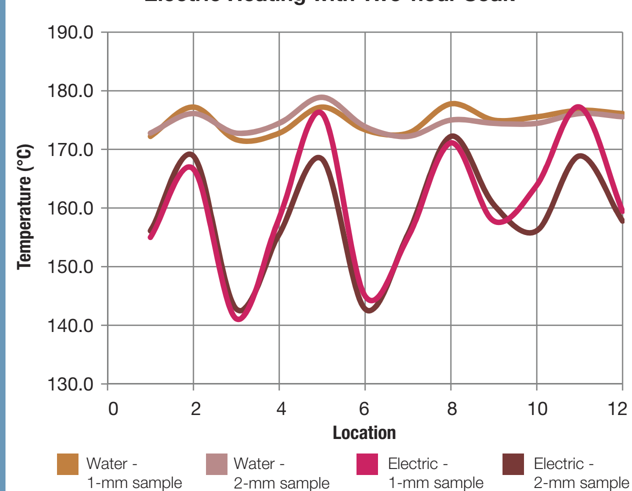


Table 4. Temperature vs. Location — Water and Electric Heating with Two-hour Soak

cles were more consistent. The average temperatures measured at the same location on the mold surfaces during the two-hour test period were 1.94°C for the pressurized water TCU and 6.7°C for the electric cartridge system.

Another important distinction, Petrykowski notes, was the difference in temperature over the length of a part. The average temperature differential across one part at the same moment was 21.0°C during the electric cartridge trial; the average differential for the pressurized water trial was only 2.7°C.

A temperature differential as large as that recorded over the length of one part in the mold that was heated by the electric cartridge could result in crystallinity variations within the part, Petrykowski contends. This, in turn, could result in shrinkage differences throughout the part, producing molded-in stress that could manifest in part warpage, creep and physical property differences within the same part.

To determine if the parts produced with each TCU attained acceptable levels of crystallinity, they were analyzed via differential scanning calorimetry (DSC) to determine the percentage of crystallinity. The DSC results demonstrated that the parts produced in the water-heated mold had consistent and acceptable crystallinity along their lengths. For the parts produced in the electric cartridge-heated mold, however, different crystallinity percentages were measured along the test parts' lengths.

These new data, says SINGLE, clearly demonstrate that pressurized-water TCUs can not only meet the needs of composites manufacturers but also can do so efficiently and economically. This capability could prove beneficial as the advanced composites manufacturing community continues to evolve toward more fast-cycle, rapid-cure, out-of-autoclave (OOA) fabrication processes. ■

A400M WING ASSEMBLY:
CHALLENGE OF INTEGRATING COMPOSITES

BY JEFF SLOAN

The *Atlas* military transport's decade of development has lighted the path for Airbus wing development on the A350 and future programs.

Many of the articles published in *HPC* focus on the manufacture of a single composite component or structure. Often, these components become part of a larger product — an aircraft, spacecraft, racecar or some other complex structure in a high-performance application. But it's rare that *HPC* is offered more than a glimpse of the machinery, processes and techniques used to assemble and integrate those components and many others into those larger structures.

And so it was that in October 2012, *HPC* editors were extended that rare invitation and paid a visit to the Airbus Military A400M *Atlas* military airlifter wing assembly facility in Filton, just north of Bristol in South Gloucestershire, U.K.

It's at this facility that Airbus completes the complex task of integrating wing spars, wingskins and an assortment of other large carbon fiber composite structures into the A400M's massive wing before equipping the structure with an array of complex systems, covering "fuel, electrics, pneumatics and hydraulics." In addition, the plant installs all fixed and moveable structures, including trailing-edge devices (e.g., ailerons and flaps), leading edges and wingtips. This assembly effort represents one of the largest such operations in the world, producing a wing that weighs only 6500 kg/14,330 lb, but can contain and carry aloft as much as 25,000 kg/55,116 lb of fuel.

Among the assembly puzzles Filton engineers had to solve was how to manage the carbon fiber composites that are so critical to the wings' structural and weight-saving success. "For us," says Paul Evans, A400M lean consultant and *HPC's* tour guide, "getting to grips with the carbon fiber was our biggest challenge. We've used carbon fiber in aircraft structures for many years, but this is the first time we've used it so extensively in such a large structure."

Heavy lifters with lifters in place

On Airbus Military's A400M Final Assembly Line (FAL) in Seville, Spain, aircraft numbers MSN8, MSN9 and MSN7 are shown with finished wings attached. HPC was invited to tour the Filton, U.K. plant in which those wings are assembled.

Wing assembly workstations

An overhead view of the A400M wing assembly facility. Assembly begins at one of six jigs (right) in which wings are oriented vertically for integration of composite leading and trailing edge spars, aluminum ribs and composite wingskins (see photo below). The wings are subsequently moved to Pre-Equip 1 (foreground left), where they are oriented horizontally and installation of fasteners, wiring, fuel pipes and other equipment begins. After Pre-Equip 1, wings move to Pre-Equip 2 (background left) and Final Equip (background right) where assembly is completed and wings are tested before shipment to Spain.

A400M background

The A400M *Atlas* is the world's newest and most advanced military airlifter, designed to ferry troops, equipment, vehicles, supplies, fuel and other materials in support of military operations. Scheduled for delivery in second quarter 2013, the *Atlas* is 45.1m/148 ft long, has a 42.4m/139-ft wingspan, measures 14.7m/48.25 ft tall and is powered by four Europrop TP400-D6 turboprop engines, each fitted with eight composite propeller blades. It has a maximum payload of 37,000 kg/81,600 lb, a range of 3,298 km/2,049 miles at maximum payload, a cruising speed of 780 kph/485 mph and a service ceiling of 11,300m/37,073 ft. As of October 2012, Airbus Military (Madrid, Spain) had fielded 174 orders for this new heavylifter.

Beginning with spars and ribs

An Airbus worker inspects a wing, oriented vertically in its fixture for integration of spars, ribs and skins. Assembly starts with the leading edge spar (with orange covers in this photo), to which are attached the aluminum wing ribs (green and white). Each wing is drilled to accommodate the 12,000 fasteners it takes to assemble the spars, ribs and wingskins.

Source: Airbus

Prepping the one-piece wingskin

An A400M composite wingskin, manufactured by Airbus in Stade, Germany, and Illescas, Spain, is prepared by Airbus workers for attachment to the spar/rib assembly in the vertical jig.

More than 30 percent of the A400M's aerostructure comprises composites, and the material is a vital part of Airbus' efforts to reduce aircraft weight, increase fuel efficiency and extend service range. The largest single composite parts on the plane are the one-piece wingskins, each of which is 19m/62 ft long and 12 to 14 mm (0.47 to 0.55 inch) thick. When conceived and implemented, it represented one of the composites industry's largest design, engineering and assembly challenges. Evans notes, in fact, that Airbus' experience with carbon fiber composites on the A400M laid the groundwork for the company to do the same — more easily — on its A350 XWB. "It set up Airbus well to design and manufacture the more advanced A350," says Evans.

The fact is that almost every assembly process Airbus has developed relative to composites on the A400M is a first for the company and, in some cases, a first in composites. The Filton team relied on lessons learned from Airbus composite experience at plants in Germany, Spain and France to develop innovative and efficient technical solutions. The spars and wingskins, says Evans, represented for Airbus the first use of carbon fiber composites in a wingbox application.

Stage 1

The A400M assembly facility is organized in three stages and in the shape of an inverted "U," with Stage 1 at the left hand leg, Stage 2 along the arch and Stage 3 at the right hand leg. Stage 1 involves primary wing box structural assembly. Stage 2, comprising Pre-Equipping 1 and 2, includes addition of fasteners and minor structural work, wiring and other components in systems preparation, as well as testing. Stage 3 involves the addition of electrical harnesses, more wiring and piping, and full functional testing before shipment to Airbus' A400M Final Assembly Line (FAL) in Seville, Spain.

The most intensive composites work occurs at Stage 1. It's here that Airbus receives the composite front and rear spars, manufactured by GKN Aerospace at its nearby Bristol, U.K. facility. Also integrated at Stage 1 are the composite upper and lower wingskins. These are manufactured via automated fiber and tape placement by Airbus at its plant in Stade, Germany. The wing in Stage 1 assembly the day of the *HPC* visit was for A400M aircraft number 13.

The first step at Stage 1 is spar assembly. Spars are delivered in two sections and joined with customized carbon fiber joint plates made by GKN Aerospace (Bristol, U.K.). The front spar is oriented flat in one of six holding fixtures, with the wing ribs and skins attached and assembled in a vertical orientation, with the spar serving as the base.

After the spar is joined, 24 aluminum ribs are attached at molded-in attachment points along the spar. (Evans says Airbus assessed use of carbon fiber composites in rib manufacture, but given the roughly 600 orders expected for the plane, the tooling for composites was deemed too expensive.)

After all of the ribs are attached, the wingskins are moved into place over the ribs and Airbus begins the most demanding work involved in the wing's assembly: the drilling of 12,000 holes in a wing set. This is accomplished with what Airbus


Source: Airbus

Quality from the inside out

A worker inspects the inside of an assembled wing. Fuel access holes in the wingskin (top of photo) allow workers to access the inside of the wing to perform several tasks, including that of providing torque for bolts used to attach the wingskin to the spars and ribs.

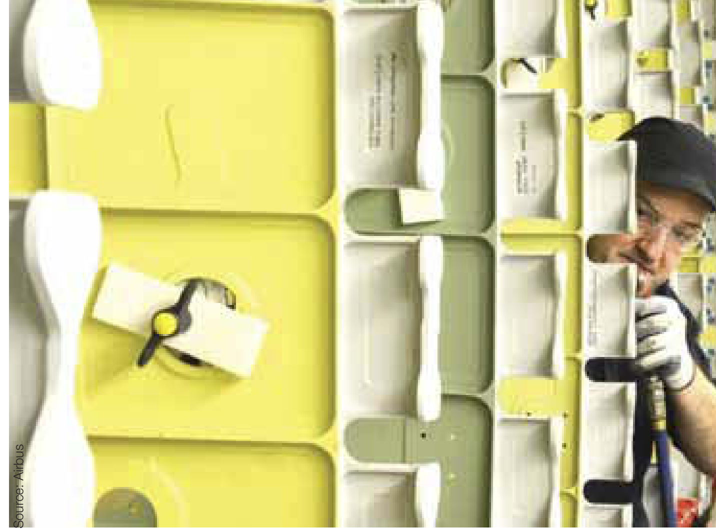
calls CAWDE (composites automated wing-drilling equipment) of which the company uses two in the Stage 1 assembly process. Years in development, each CAWDE unit comprises a set of tools designed and engineered specifically for this application. On the machinery side is a massive, 20-ft/6m tall by 10-ft/3m wide by 10-ft/3m deep, rail-mounted, 6-axis drilling system, designed and manufactured by Electroimpact Inc. (Mukilteo, Wash.). It's made to move around each fixture in which a wing is held, drilling 90 to 95 percent of the 6,000 holes required for each wing. It uses a diamond-tipped cutting tool provided by Precorp (Spanish Fork, Utah), partially owned by Sandvien, Sweden-based machine tool supplier Sandvik Coromant. The tool is custom-designed to drill through a stack of carbon fiber and aluminum, providing pilot, drill, ream and countersink operations in one unit, says Evans. After all holes are drilled, the wingskin is removed, inspected and deburred if necessary. "We have eight days to drill 12,000 holes," reports Evans.

After deburring, the wingskin is repositioned over the ribs and spars and the process of actually fastening the skins begins. Bolts used to attach the wingskins must be accessed from outside and inside the wing. To do this, technicians crawl into the wings via pre-cut fuel tank access holes in the skins. From the inside, they provide the guidance and torque required, respectively, to position and tighten the bolt as technicians insert them from the outside.

Because the wings must contain fuel, each bolt is coated with a sealant to prevent leakage, "We just can't have any fuel leaks," says Evans. "For that reason we have very tight tolerances."

Stage 2

After drilling, bolting and sealing are complete, the wing weighs about 3,500 kg/ 7,716 lb. At this point, the wing is removed from its fixture via vacuum lift-



Source: Airbus

12,000 reasons to be careful

About 95 percent of the holes drilled in each A400M wing are generated by the automated Electroimpact drilling system, but the balance is hand-drilled. Drilling currently takes a little more than eight days. Skins are drilled in place, removed, deburred and then attached with bolts that include a sealant to prevent fuel leakage.

ing equipment, transported via crane to the first of two Stage 2 workstations, called Pre-Equip 1, and oriented flat on a new work fixture that gives operators and installers easy access to the wing's leading and trailing edges.

At this stage, Airbus conducts a series of metrology checks with laser trackers and photo-imagery to verify that the wing meets a variety of critical dimensional specifications. Workers also do some drilling of the leading edge before sending the entire structure on to the second Stage 2 workstation, Pre-Equip 2.

Pre-Equip 2 sees the installation of the initial equipment needed to complete assembly of the wing. This includes harness brackets (which are positioned with the aid of laser-projection equipment and adhesively applied) and weight-supporting brackets for the leading and trailing edges. Once they are installed, Airbus conducts a tank pressure test, first with air, then with hydrogen/nitrogen, to verify the integrity of the fuel-storage capability of the wing.

Stage 3

After the wing passes the pressure test, it's on to Stage 3, the Final Equip line, which handles the final stage of wing assembly before it's sent on to the A400M FAL. Most of the heavy-duty hardware is installed on this line, followed by wing actuation and testing.

Included here is installation of electrical wiring, air bleeds, fire protection equipment, fixed leading edges, ailerons, spoilers and flaps. Notable here is the installation of carbon fiber composite fuel pipes throughout the wing. The pipes are fabricated and supplied by Adel Wiggins Inc. (Los Angeles, Calif). It's at this stage that Airbus also installs one more carbon fiber component of note: A driveshaft for flap actuation, provided by Goodrich Corp.'s Crompton Technology Group (CTG, Banbury, Oxfordshire, U.K.). The shafts, about 1m/3.3 ft long and 40 mm/1.57-inches in diameter, are filament wound carbon fiber and feature stainless steel end fittings. CTG reports that its shafts go through a minimum four- to six-lifecycle qualification process and are designed for a minimum operating life of 20 years.

After all components are installed and attached, the wing attains its full weight of ~6,500 kg/~14,330 lb and goes through a full function test of all components to verity that the wing is operating as it should. It's then ready to be sent to the FAL in Spain.

Since the A400M was first conceived 10 years ago, and the decision was taken to use carbon fiber composites as extensively as Airbus did in the wings, other aircraft have come to market that use composites in similar ways — Boeing's 787, the Airbus A350, the Bombardier C*Series*, and more. In many ways, however, the A400M *Atlas* started the trend, set the standard and, in the military market, remains the largest aircraft to use composites so aggressively. Evans stressed repeatedly to *HPC* that composites lessons learned on the A400M *Atlas* wing assembly line have been applied throughout the Airbus organization, and these lessons will benefit Airbus design and manufacturing practice for years to come. "This was a scale of composites use in a structure Airbus had not tried before," says Evans. "It took a lot of effort and learning to get this far, but it certainly has been worth it." ■

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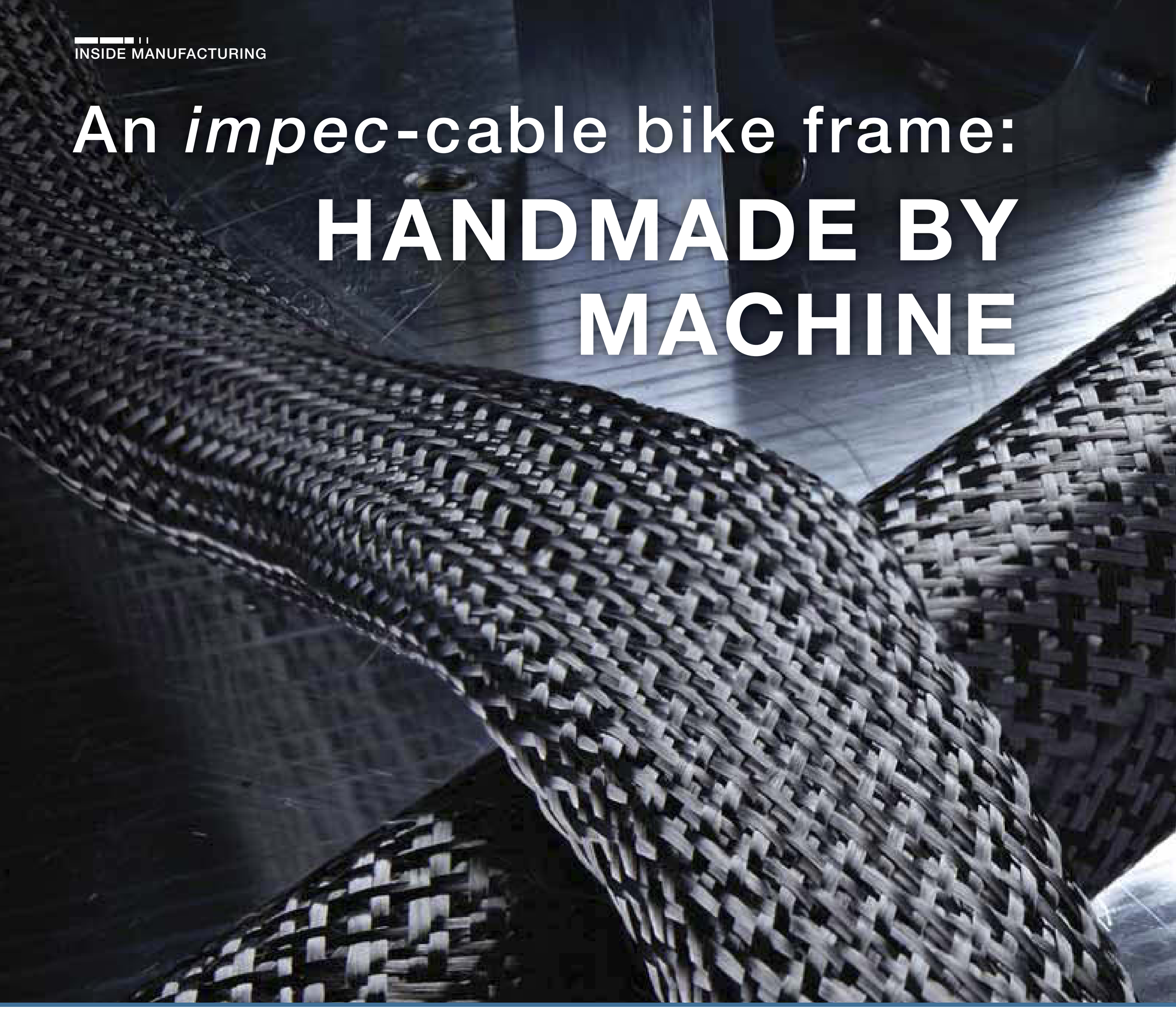


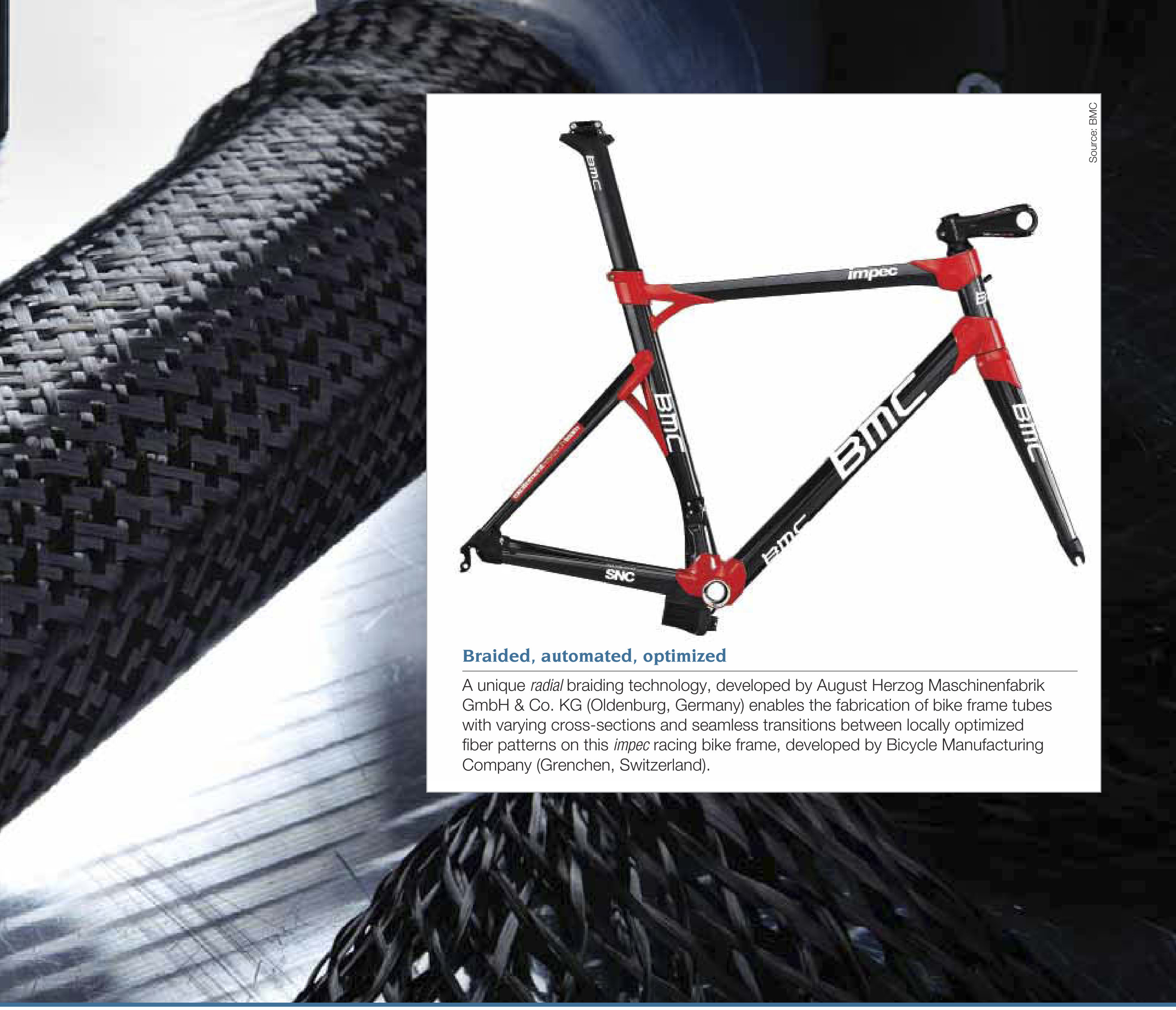
An *impec*-cable bike frame: HANDMADE BY MACHINE

Long on technology firsts, this optimized and automated manufacturing process produces nothing short of the "perfect" bike frame.

BY GINGER GARDINER

Based in Grenchen, Switzerland, home to world-class watchmakers Rolex and Breitling, Bicycle Manufacturing Co. (BMC) has likewise become an icon of Swiss engineering, precision and style. BMC's racing team, led by Cadel Evans — the 2009 world champion and 2011 Tour de France winner on a BMC bike — is a *Who's Who* of the sport, including Thor Hushovd, George Hincapie, Philippe Gilbert, Tejay van Garderen and Taylor Phinney. "We simply want to build the fastest and best bikes in the world," says BMC owner Andy Rihs. "And, to ensure we are living up to this goal, we work with the best riders in the world."

Now BMC leads cycling with its production of a 100 percent carbon fiber frame with a uniquely high level of automation and process control: the *impec*. Short for "impeccable," the frame is the result of Rihs' conviction that the industry practice of building frames in Asia using hand-layed prepreg permits neither full exploitation of carbon fiber's benefits nor sufficient process control and precision. BMC spent more than €40 million ($51.8 million USD) and four years developing the materials, robotic processes and entirely new factory that was necessary to back the claim made on one of its factory billboards, *"We built a Swiss factory to produce the perfect carbon bike."*



Source: BMC

Braided, automated, optimized

A unique *radial* braiding technology, developed by August Herzog Maschinenfabrik GmbH & Co. KG (Oldenburg, Germany) enables the fabrication of bike frame tubes with varying cross-sections and seamless transitions between locally optimized fiber patterns on this *impec* racing bike frame, developed by Bicycle Manufacturing Company (Grenchen, Switzerland).

Beginning with engineering

BMC already had a track record of engineering innovation. Its Advanced Pivot System (APS) is billed as the "ideal" rear-wheel mountain bike suspension (see illustration, p. 35), able to deliver the "perfect" combination of efficiency, power and comfort.

Another engineering hallmark is BMC's Tuned Compliance Concept (TCC), which uses a precise combination of different carbon fibers and orientations, along with stepped frame tube profiles, to provide increased flexibility in vertical components (frame, fork and seatpost) yet maintain high lateral and torsional rigidity. This improves handling and increases comfort and power transmission, slowing the onset of rider fatigue.

The perfect racing bike frame, however, would transform *all* of its rider's pedal-turning energy directly into propulsion with *no* negative impact from its own weight. In pursuit of that goal, BMC's *impec* engineers redesigned each frame tube to optimally perform its unique function in the frame, absorbing and distributing its individual stresses across its entire length, by tailoring both the shape of the tube and the architecture of the composite materials. It turns out that the perfect frame tube is hardly ever round. And, says plant manager Martin Kaenzig, "We also knew we wanted seamless tubes."

Tuning the tubes

The solution was BMC's Load Specific Weave (LSW) process. This three-stage, robot-controlled production line combines braiding, resin transfer molding (RTM) and trimming into a continuous process. Automated, computer-controlled braiding enables quick and accurate fiber placement and orientation. Moreover, it can negotiate changes in the cross section of the tube and provide seamless transitions along the tube between fiber patterns that are optimized for local stiffness and those that are optimized for overall torsional rigidity (see right side of lower diagram on p. 35 and check out "Learn More," on p. 37).

Step 1

The Load Specific Weave (LSW) process begins as a robotic arm removes the mandrel from the workpiece shuttle and feeds it into this Herzog radial braiding machine. Once the braid is done, robots put the overbraided mandrel back in the shuttle.

Step 2

In the RTM workcell, A robotic arm transfers and precisely locates the braided carbon sleeve into the left tool cavity of this female matched metal mold. A special two-component resin is injected and the composite tube is cured.

Step 3

In the Trim cell, a 6-axis robot first removes the fiberglass mandrel from the leftward end of a tube.

Step 4

Here, a computer-controlled diamond saw automatically moves into position and trims the tube to precise dimensions.

Step 5

The keys to the Shell Node Concept (SNC) are its injection molded short carbon fiber-reinforced connector half shells. The carbon fiber compound is fed into a state-of-the-art injection molding machine, where the interior and exterior of the node half are precisely monitored and controlled. Here, half shells seated in mold halves show the internal ribbing, while two half-shells, in the background, show the connector's exterior.

Source (all step photos): BMC

Step 6

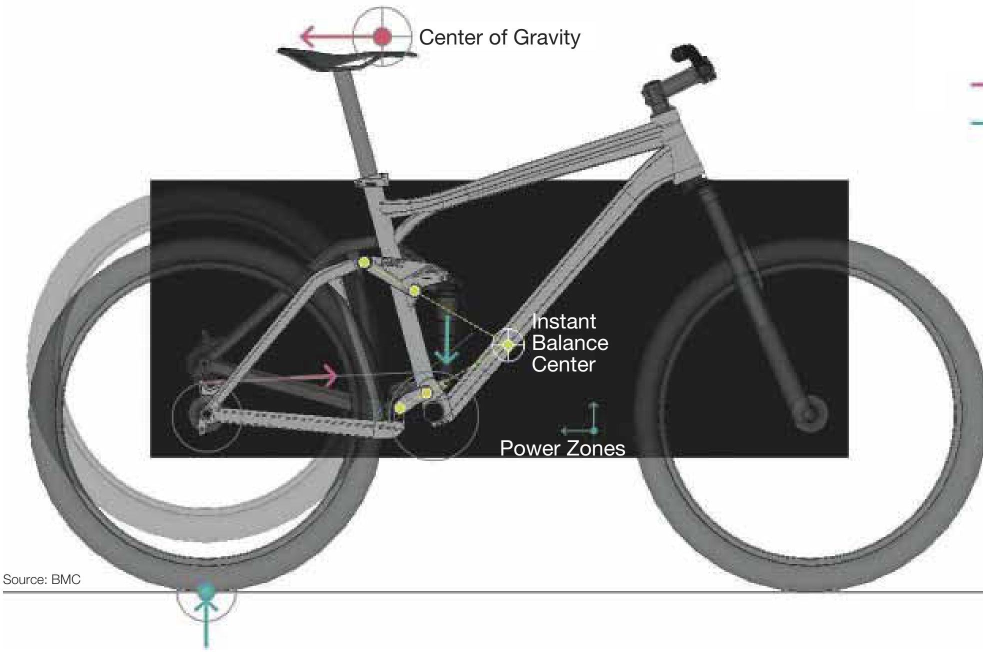
In preparation for frame assembly, a robot applies the precisely metered amount of two-component adhesive appropriate to each node shell half. The robot is computer-controlled and monitored via digital camera.

Step 7

The tubes and connectors are then mated within bonding fixtures, clamped, allowed to cure ambiently and then postcured at elevated temperature in an oven.

Step 8

The finished frame and its corresponding front fork is measured via coordinate measuring machine and then static load tested to ensure that dimensional and strength requirements have been met.



Always innovating

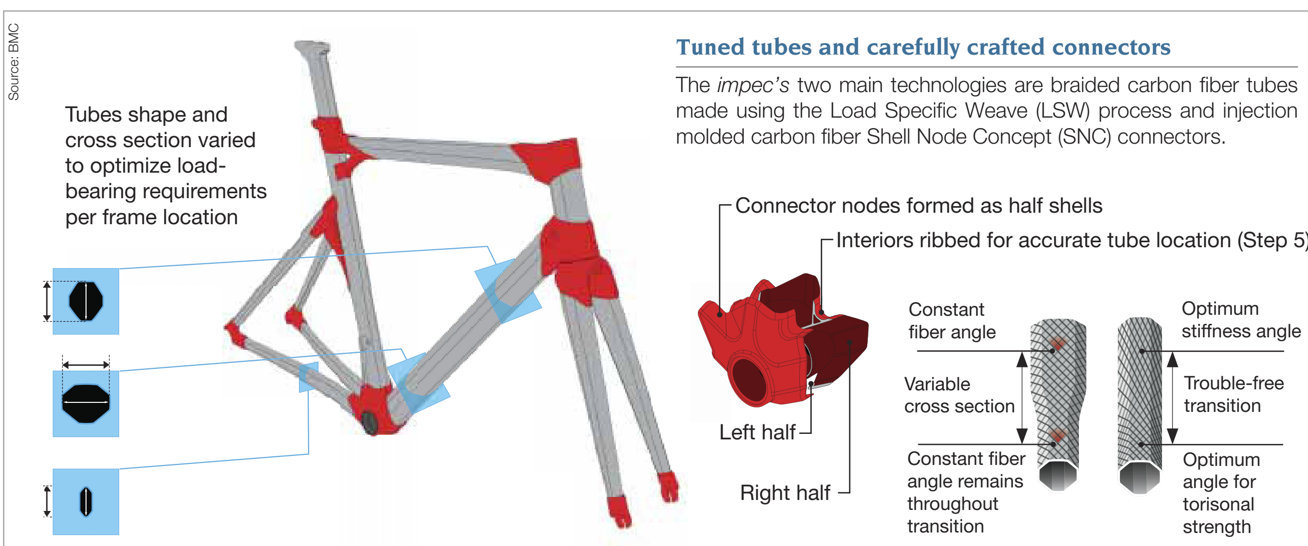
For its Advanced Pivot System, BMC analyzed the inertial loads that compress the suspension unit's shock-absorbing system and used the data to precisely locate the system's pivot points, such that it enables the chain tension to compensate for the acceleration effect. Thus, more of the rider's energy is converted into propulsion with less energy loss while maintaining optimal rider comfort and tire traction.

Tube production begins with a mandrel, referred to by BMC as the "soul." Previously aluminum, it is now a glass-fiber composite. "The soul," says Kaenzig, "is the skeletal center of the mandrel. It does not have any geometry features." The tube's geometry is, instead, shaped into a silicone overlay that BMC calls the "core." As will be made clear, the two-stage construction permits easy mandrel extraction. And because the resin won't adhere to silicone, the core provides its own mold release, saving a process step.

The soul/core is fitted into a workpiece carrier that will enable mandrel transport, by means of specialized industrial robots, through computer-controlled and individually sealed braiding, molding, trimming, painting and assembly work cells, which are separated by automated guillotine doors. Each carrier contains a digital tag with its identification number and programs that activate and control each machine as it moves through the process stages. The computerized system also commands the handling robots and records relevant data for each workpiece. Thus, each tube is made-to-measure per specification, with accuracy verified within 0.1 mm (4 mils).

As processing begins, a robotic arm removes the workpiece carrier from the production line's shuttle and feeds it into a radial braiding machine made by August Herzog Maschinenfabrik GmbH & Co. KG (Oldenburg, Germany). The data matrix for the part is read from the workpiece digital tag, and the braider draws carbon fiber tow supplied by Toho Tenax Europe GmbH (Wuppertal, Germany) from more than 100 bobbins as it begins weaving it along sinusoidal paths to produce a seamless braided tube or sleeve on the mandrel. The mandrel shape and rate of advance in the radial braider determines the density and arrangement of the carbon tows. When the braid is complete, robots cut the sleeve free, withdraw the workpiece carrier from the braider and replace it in the shuttle, which then proceeds to the RTM cell.

BMC claims theirs is the first fully automated composites RTM station in the world. A robotic arm transfers and locates the braided sleeve into a corresponding female matched metal mold, which is made from hot-formed steel. A special two-component nano-toughened ➲



Tuned tubes and carefully crafted connectors

The *impec's* two main technologies are braided carbon fiber tubes made using the Load Specific Weave (LSW) process and injection molded carbon fiber Shell Node Concept (SNC) connectors.

epoxy resin is injected — injection time averages about four minutes — and the workpiece cures inmold in ~30 minutes at 80°C/176°F. Then the cured tube is demolded and placed back in the shuttle.

In the third production stage, also the final step in the LSW process, the tube is moved into the trim cell and cut to length. A 6-axis robotic arm transfers the workpiece from the shuttle to a holding fixture, where the soul is removed from the core. Then, the flexible silicone core can be retracted from the part. Next, the now hollow carbon tube is positioned via robot within a cutting cell that self-seals to contain carbon dust. After a precision diamond saw trims the tube to final size, it is removed from the cell and placed in a bin. A worker collects the binned tubes and performs a series of quality-assurance tests before depositing them at the assembly station.

Making precise connections

Having mastered the process for "perfect" tubes, the next question was how best to connect them. BMC calls its answer, the Shell Node Concept (SNC), "revolutionary" because it forms the frame's nodal points not as one-piece collars, but instead as two bonded half shells. Each half shell's inner and outer geometries, therefore, are more easily designed to optimize frame loading, and the shell's ribbed interior (see Step 5, p. 34) defines how the adjoined tubes fit with absolute precision. The shells are injection molded using a 40 percent carbon fiber/thermoplastic compound (by weight), with fibers ~4 mm/~0.2 inch in length. The combination of the stiff fibers and resilient matrix make the shells rigid and light yet shock absorbent.

Engineers defined the fiber orientation in each shell, using a CAD-based mold flow analysis simulation. The data was used to construct small batches of matched-metal tools. To verify the mold flow analysis results, these tools were subjected to a series of tests, including computed tomography, which accurately gauged the wall thickness and inspected the structure for faults. After necessary changes were made, the final metal tools were ready for injection.

Injection molding of shells is carried out offsite by a partner company that specializes in the process. The injection molding machine is equipped with the mold of the given shell, and an engineer loads in carbon compound pellets supplied by EMS Grivory (a business unit of EMS-Chemie AG, Domat/Ems, Switzerland). The machine melts and injects the compound. The finalized CAD data for the specific metal tool enable engineers to visually monitor the formation of the shell's interior ridges and to control all of the key process parameters (temperature, fill time, flow rate and flow properties). During the molding cycle, these and other data are recorded, enabling further optimization. Molding is completed in minutes, after which the shells are deflashed and inspected.

Back at BMC, the shell halves are hand-placed into an adhesive application fixture (green fixture shown in Step 6 on p. 34) that has been mounted onto a carrier. Then they enter an automated workstation, where a robot equipped with an optical monitoring system recognizes each component and defines the quantity and location of adhesive before applying it to each part. BMC uses epoxy adhesive supplied by Huntsman

Advanced Materials (Basel, Switzerland). Each contact point is again analyzed to ensure that quality requirements have been met. Next, a worker places shell-halves into bonding jigs. When corresponding tubes and machined metal parts are placed in the shells, the interior ridges of the shells ensure that the frame comes together accurately. Pressure is applied with built-in clamping devices (Step 7). The bonded and clamped frame is cured for 12 hours at room temperature. It is then replaced onto the carrier, which moves the assembly into an oven for a two-hour postcure at 80°C/176°F.

Quality control, first to last

BMC underscores the importance of continuous quality control. During tube manufacturing alone, 60 test parameters are recorded and analyzed. Each completed frame and its corresponding fork is also checked (Step 8). "We apply loads that match those a bike frame is exposed to while being ridden by a typical male rider. We then measure the deformation and check this and the stiffness value vs. our requirements," Kaenzig explains, adding that random physical samples are periodically taken from throughout the process and destructively tested to ensure the product meets BMC's zero-error mandate.

Notably, BMC originally painted the shells and tubes *before* assembly, using 6-axis robots. But today, shells and tubes are assembled first, then hand sprayed. "Our geometries were really too complex for the robot," says Kaenzig. Until robots demonstrate sufficient agility and suitable quality-assurance measures can be developed, he says, "it is faster for us to paint by hand and have 100 percent assurance of the quality we need."

Pursuing perfection pays

The *impec* has earned BMC many kudos, including the "iF gold product design award" in 2011 and 12 Gold Bike Awards at the 2011 EuroBike show. But has the time and cost spent developing the impec paid off? According to Kaenzig, it has in several ways, including *differentiation*. "The weaving technology is one of our unique selling points and shows our competence to produce a high-end carbon bike using a completely different process." He adds, "It also helps to show our competitors as well as our customers that we are capable of developing a product from scratch and not just purchasing products from Asia, as so many of the other top companies are doing."

In the context of tooling, equipment and other production costs, the impec is already profitable. But Kaenzig admits that it will take several years of solid sales to recoup four years of development cost. However, Kaenzig points out, "The technology is not limited to high-end bikes, and we are already applying the lessons learned to other products and looking into the next generation of innovation." ■

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CALENDAR

Jan. 7-10, 2013	Composite Arabia 2013 Dubai, United Arab Emirates | www.arabplast.info/compostearabia.html
Jan. 28-31, 2013	37th Annual Conference on Composites, Materials and Structures Cape Canaveral, Fla. | http://advancedceramics.org/index.php?src=gendocs&ref=hotelinfo&category=Main
Jan. 29-31, 2013	ACMA COMPOSITES 2013 Orlando, Fla. | www.compositesshow.org
Feb. 4-7, 2013	EWEA 2013 Vienna, Austria | www.ewea.org/index.php?id=2101
Feb. 26-27, 2013	SPE 2013 TOPCON – Thermoset Topical Conference New Orleans, La. | www.spetopcon.com
March 11-12, 2013	SAMPE Europe (SEICO 2013) Paris, France | www.sampe-europe.org
March 12-14, 2013	JEC Europe 2013 Paris, France | www.jeccomposites.com
March 19-21, 2013	Composites Manufacturing 2013 Long Beach, Calif. | http://composites.sme.org/2013
May 5-8, 2013	Windpower 2013 Conference and Exhibition Chicago, Ill. | www.windpowerexpo.org
May 6-9, 2013	SAMPE 2013 Long Beach, Calif. | www.sampe.org/events/2013LongBeachCA.aspx
May 20-25, 2013	13th International Symposium on Nondestructive Characterization of Materials Le Mans, France | www.cnde.com
June 11-12, 2013	7th International CFK-Valley Stade Convention Stade, Germany | www.cfk-convention.com
June 17-20, 2013	Alabama Composites Conference (ACC 2013) Birmingham, Ala. | www.uab.edu/composites
July 28-Aug. 2, 2013	ICCM19 – 19th International Conference on Composite Materials Montreal, Quebec, Canada | www.iccm19.org

See more events at www.compositesworld.com/events

APPLICATIONS

Cutting and laser layup technology supports tier fabricator in Boeing project

Source: Gerber

The Boeing Co.'s (Chicago. Ill.) Enhanced Medium Altitude Reconnaissance and Surveillance System (EMARSS) aircraft (artist's rendering at right) is designed to gather intelligence for the U.S. Army. It will provide a persistent capability to detect, locate, classify and identify targets, such as enemy positions, with a high degree of accuracy, 24/7. To streamline the project and reduce risk during the certification process, the aircraft will be built around the already Federal Aviation Admin.-certified Hawker Beechcraft (Wichita, Kan.) *King Air* 350ER turboprop. An initial prototype flew on Oct. 22, 2012.

Unitech Composites & Structures (Hayden, Idaho), part of the AGC Aerospace & Defense – Composites & Aerostructures Group (Midwest City, Okla.), manufactures the aircraft's lightweight composite nose skin panels and multiple exterior fairings that enclose and provide transmissivity for radar equipment. Unitech was able to meet the project's tight tolerances with the help of a GERBERcutter GTxL computer-controlled cutting system, which it used to cut and kit the **Cytec Engineered Materials Inc.** (Tempe, Ariz.) prepregs, and a Virtek LaserEdge laser templating system, both supplied by **Gerber Technology** (Tolland, Conn.). "This new program called for 26 parts each for five aircraft, so in addition to precision we needed repeatability of the process," says Al Haase, president and CEO of AGC. "By eliminating the use of physical templates, layup productivity was improved by as much as 50 percent."

Source: Boeing

Two Virtek LaserEdge projection units were installed on the ceiling to provide adequate coverage for the many sizes and angles of the parts. Gerber sent a trainer to Unitech to teach the engineers how to use the equipment, and they, in turn, trained other shop floor employees, says Josiah Drewien, engineering manager for Unitech Composites.

"Before we implemented this technology, employees cut every prepreg ply by hand with scissors using templates, which took considerable time and led to a great deal of waste." With Gerber's nesting software, the waste reportedly has dropped to 10 percent, saving money and time, adds Drewien. Additionally, the Virtek LaserEdge projection system enables Unitech to lay up more *complex* parts.

"For some complex parts, with complicated geometries requiring dozens of partial plies located with greater precision, using a template would be impractical or impossible," says Drewien. The enhanced technical capabilities provided by the Gerber and Virtek systems not only meet the growing needs of the customer, but also help the company remain price competitive, says Haase. ■

Kinetic sculpture made possible with carbon fiber composites

An unusual wind-activated kinetic sculpture, designed by two of Australia's preeminent public artists, Jennifer Turpin and Michaelie Crawford, was realized with the help of **Gurit** (Newport, Isle of Wight, U.K.) and molder Innovation Composites (South Nowra, New South Wales, Australia). The composite creation, dubbed H*alo*, is a giant tapered yellow ring, measuring 12m/39 ft in diameter. The ring is attached to a 6m/19.5-ft long silver arm, which, in turn, is mounted atop a 13m/42.2-ft tall silver pole. With an eccentric balance point, the ring tilts and turns in response to changes in wind speed, direction and gusts. The unpredictable movement provides a visually intriguing contrast to the stationary pole, especially when illuminated at night. Notably, the weight of the ring and arm is balanced on a ceramic bearing the size of a small glass marble.

Source: Gurit

The sculpture project was managed by structural engineers Partridge Event Engineering (St. Leonards, New South Wales, Australia). Gurit's structural engineering team was called in to help turn the unique design into a tangible piece of public art for Central Park in Sydney, Australia. The artists' design called for the ring to taper dramatically from its root to its far edge and to be as light as possible to maximize movement in the wind, yet appear to sit flat at rest. After the initial structural design concept was developed, Gurit engineers used advanced finite element analysis (FEA) to run a series of design optimizations with various fiber architectures. The FEA determined that to meet the weight and stiffness criteria and minimize deflection, a carbon fiber/epoxy composite was the only feasible material.

The plug and mold for the ring were made by **mouldCAM** (Tingalpa, Queensland, Australia), using Gurit T-Paste 70-2 machinable tooling paste. Then, the ring was hand laminated by Innovation Composites, using Gurit double-bias carbon/E-glass cloth and unidirectional carbon tape, wet out with Gurit's Ampreg 22 epoxy resin. The ring's supporting arm was designed and fabricated with a crescent-shaped cross-section (to better react to the wind) using Gurit SE 84 LV prepreg to lay up the arm and to maintain very tight tolerances where the part had to fit into metal end-brackets for attachment to the pole. The sculpture was installed in November 2012. ■

NEW PRODUCTS

Automated material delivery system

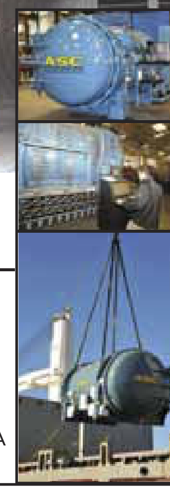
Fluid-Bag Ltd. (Jakobstad, Finland) has developed the PowerBagPress, a flexible container designed to discharge highly viscous and semisolid materials from the company's 900 and 1,000 liter (237 and 264 gal) Fluid-Bag MULTI and FLEXI flexible reactive chemical containers. The company's new press enables suppliers who use the tubular containers to safely ship their products (e.g., adhesives and other resin products), and it allows the customers who use those products to avoid the common problem of leaving a good deal of product in the container as waste. During discharge the flexible container, fitted into the customer's press, is squeezed flat and rolled up, much like a tube of toothpaste. Fluid-Bag claims that material residue in the containers can be reduced to as little as 0.5 percent. The PowerBagPress was specifically developed to reach a material flow of more than 35 kg/min (77 lb/min), but in its first implementation with a solid adhesive resin it reportedly achieved a rate of 50 kg/min (110 lb/min). The press allows for two-component mixing and is designed for use in the manufacture of large components, such as aerospace structures, wind turbine blades and other sandwich constructions. **www.fluid-bag.com**

High tensile modulus glass fiber

Glass fiber manufacturer **AGY** (Aiken, S.C.) has developed a new glass fiber with a tensile modulus of 99 GPa/14,359 ksi — a level AGY says is unprecedented in commercial glass fiber products. Trademarked as S-3 UHM Glass, the ultrahigh modulus material was developed using AGY's advanced Modular Direct Melt (MDM) production technology. Its mechanical properties, however, are the result not only of the improved fiber manufacturing technology, but also, says AGY, an in-depth understanding of the constituent chemistries that enabled the company to realize a tensile modulus 40 percent higher than that of traditional E-glass fibers. The new material reportedly makes it possible for composites designers and manufacturers to use glass fiber reinforcement in applications previously open only to other types of fiber. S-3 UHM is available in a range of formats, including yarns, rovings and chopped fibers. **www.agy.com**

Data aggregation software for carbon composites

A new software platform from **NLign Analytics** (Cincinnati, Ohio) is designed exclusively for manufacturers of carbon-fiber composites and the maintenance, repair and overhaul (MRO) organizations that see them in service. The NLign platform aggregates inspection, maintenance and manufacturing data and then displays it in a 3-D environment, an approach said to reveal hidden relationships in the data that can be exploited to reduce the time, cost and effort necessary to make and maintain carbon composite structures. NLign reportedly transforms raw data into actionable information that simplifies the manufacturing and repair process. Data are mapped to a 3-D computer model of the part, making it easier to find and access information. The system can automatically collect aircraft inspection data from nondestructive inspection (NDI) equipment, inspector annotations, digital images, SAP systems, paper forms and other process data. Early adopters of NLign — including the U.S. Navy, U.S. Air Force and private-sector companies in the Airbus and Boeing supply chains — have reportedly cut costs and reduced scrap rates by improving their first-pass yields (that is, increasing the number of parts that pass inspection the first time). Over time, trends in multiple structures can be identified more quickly, saving time and money by helping to prevent problems before they occur. NLign also has applications for aircraft in the field. By snapping a digital photo, precise damage location information can be captured and relayed back to MRO teams. According to the U.S. Navy, repair tasks that used to take one to two days can now be completed, using NLign, in as little as an hour. According to the company, the system has the potential to save the U.S. Navy more than $1 million in labor costs annually on one aircraft fleet that is now managed with NLign. **www.nlign.com**



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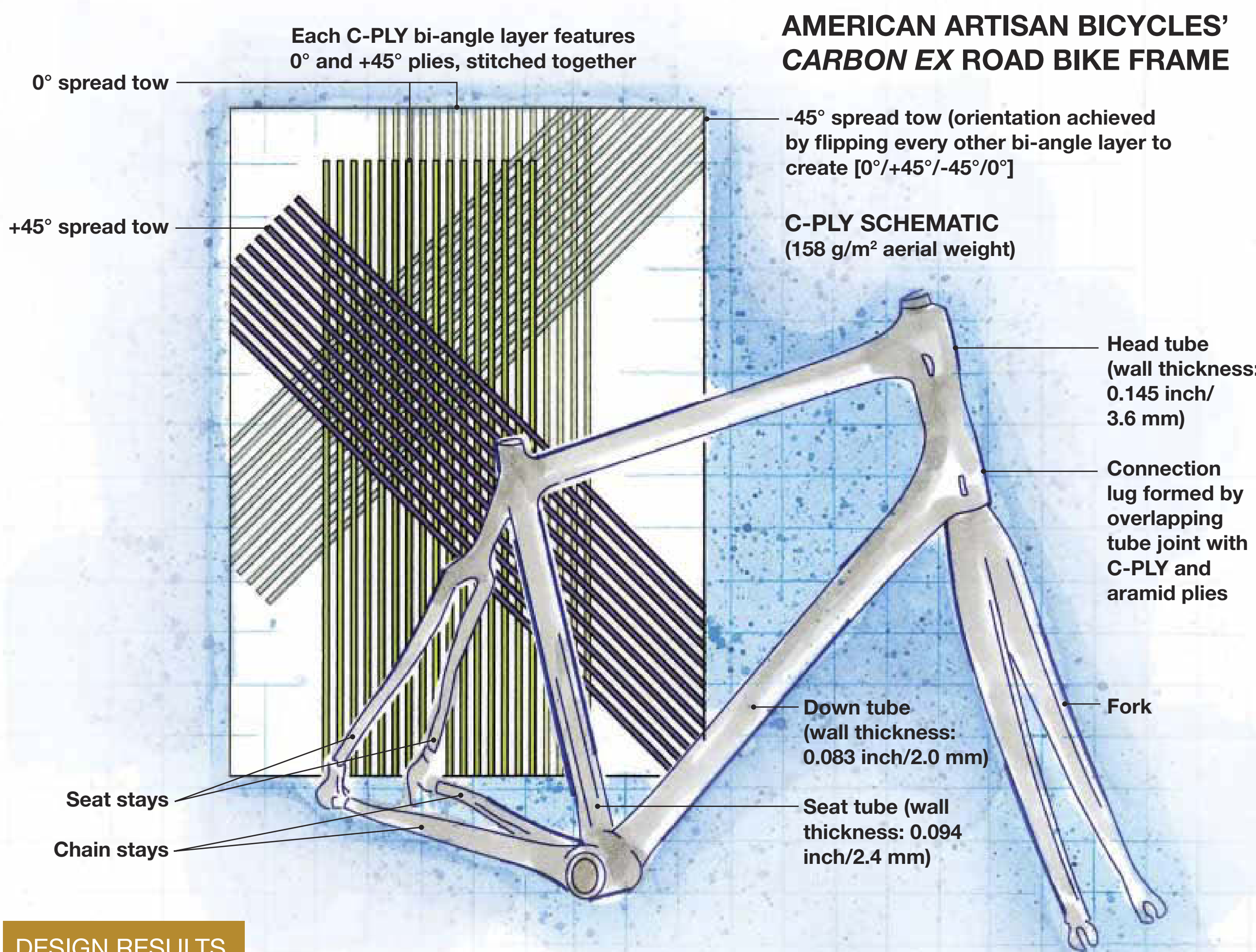
BI-ANGLE FABRICS FIND FIRST

Bicycle manufacturer sees dramatic productivity gains using unbalanced

For decades the composites industry has emulated the homogeneous properties of metals, designing quasi-isotropic structural laminates with stacked unidirectional tapes — "black aluminum." The classic 0°/90°/+45°/-45° layup has predominated not only because resulting laminates exhibit similar stiffness in all directions, but also because it minimizes bending/twist coupling *and* gives metal-centric engineers more confidence. But this symmetrical and, until recently, sacrosanct configuration, could be giving way to a unique alternative.

"I had this idea for a very long time that there was a way to relax these design rules and achieve optimized results with asymmetrical layups," recalls the alternative's inventor, Dr. Stephen Tsai, professor emeritus at Stanford University (Palo Alto, Calif.). In fact, Tsai and the late Edward M. Wu first addressed the issue in 1971, when they introduced the Tsai-Wu Failure Criterion (see "Learn More" p. 48). In the paper's introduction, they contended that a more reasonable approach was to stack alternating *unbalanced* (anisotropic) layers (e.g., 0° and a shallow angle). Forty years later, this "bi-angle" concept (pat. pend.) has found its first commercial application in a new pro-



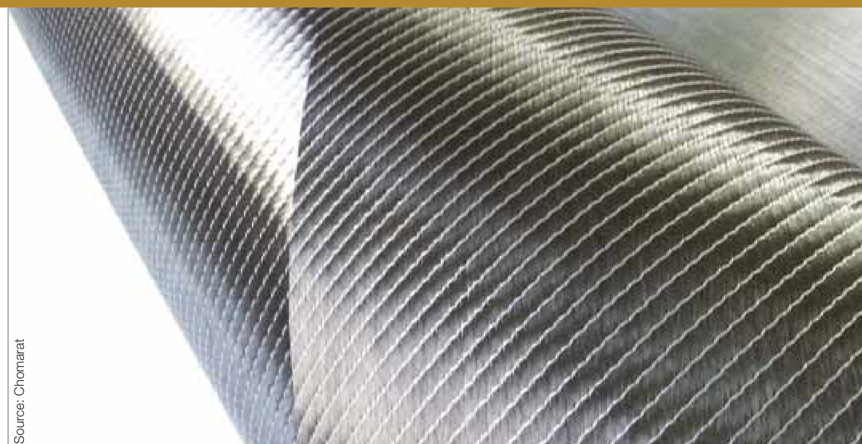
DESIGN RESULTS

- Unbalanced, shallow-angle laminates of new, very thin biaxial fabrics replaces "black aluminum" and simplifies layup.
- "Potato-chip warping" is prevented by stacking 16 or more layers of the thin unbalanced layers.
- Small bicycle firm has achieved aerospace quality, with a ten-fold decrease in labor costs, out of the autoclave.

BY SARA BLACK
ILLUSTRATION / KARL REQUE

Unbalanced fabric finds favor in new bike frame

C-PLY material, manufactured by Chomarat (Le Cheylard, France), features two plies of carbon fiber, at 0° and a shallow angle (shown here at 45°), stitched together. C-PLY reportedly enables Sonoma, Calif.-based American Artisan Bicycles to achieve part quality and performance usually seen only in much more expensive autoclaved parts.



duction bicycle frame from American Artisan Bicycles (Sonoma, Calif.).

Bye-bye, black aluminum

Why *bi-angle* material? The answer lies in the mathematical prediction of laminate failure, traditionally a difficult subject due to the multiple plies in various directions, differences in material properties from ply to ply and even outside influences, such as temperature or moisture. In a nutshell, if a quasi-isotropic laminate is subjected to increasing load in the direction of the 0° fibers, matrix cracking eventually occurs in the off-axis or transverse plies. This phenomenon, known as *first-ply* failure, decreases matrix stiffness. Eventually, as loads increase, ultimate, or *last-ply*, failure occurs. The load levels at the two failure points and the difference between them depend on the layup and the fiber/resin combination, among other factors.

"You put load on a quasi-isotropic laminate and the off-axis plies fail early and microcrack, due to shear," says Bob Skillen, founder and chief engineer at VX Aerospace (Morganton, N.C.), who has tested the material in aerospace parts. "You're essentially accepting microcracking in your design," he contends, but he points out that "there's no reason to do that."

Because early methods for predicting progressive failure were unsophisticated, says one industry analysis expert, most designers compensated with conservative first-ply-failure solutions. But adding "insurance" plies — *over*designing — sacrifices the design advantages of composites (see "Learn More"). Tsai, therefore, pushed *non*-quasi-isotropic designs over the years and even developed spreadsheet-based failure analysis software, called MIC-MAC (for micro-macromechanical analysis), which quickly calculates optimized layups at any angle and predicts how they will behave, and fail, under load. Fig. 1, p. 48, shows that when the cross-ply angle is reduced in relation to the 0° direction, the resulting laminate withstands significantly greater stress before first-ply failure and last-ply failure and generally performs better in many load applications, thanks to the reduction in interlaminar forces. The figure also shows that the stresses that cause first-ply failure and last-ply failure *equalize* at a cross-ply angle of about 20°. Concern that very low-angle cross plies might result in "potato-chip warping" of the laminate is alleviated, says Tsai, *if* enough layers are stacked together. "The difference between symmetrical and asymmetrical laminates disappears when 16 or more bi-angle layers are stacked," he explains. "Continuous stacking makes the location of plies, and reversing the order of stacking relative to the mid-plane, irrelevant." In other words, the large number of repeated layers effectively homogenizes the laminate.

The unexpected result is mechanical performance that matches that of autoclaved uni prepreg tapes, via easier vacuum-bag processing. Moreover, the resulting laminate is lighter and thinner than a quasi-isotropic counterpart because "more, thinner plies make a stronger and tougher part than fewer, thicker plies," Skillen explains.

Out-of-autoclave aerospace part

An H-46 *Chinook* helicopter tunnel cover prototype, made with vacuum-infused C-PLY by VX Aerospace (Morganton, N.C.).

Such a layup also has a >30 percent higher first natural frequency, a factor that often dominates laminate design, Tsai adds. With a higher first natural frequency, the operating range of the part in terms of vibration performance is greater.

From theory to practice

Tsai knew, however, that hand cutting of shallow angles using uni tapes was impractical. The key was to make available a fabric with 0° and a shallow angle *already plied together*, which would en- ➲

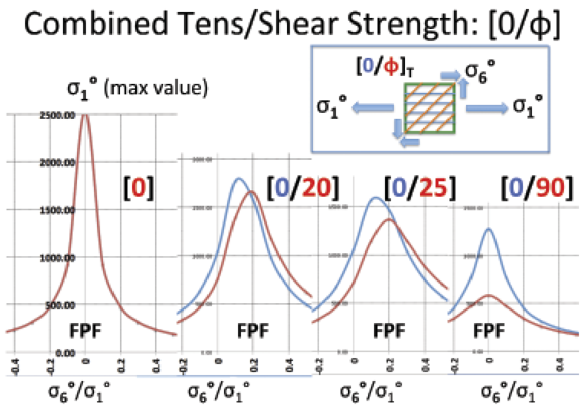


Fig. 1 Source: Chomarat

This diagram, output from MIC-MAC software, shows that shallower cross-ply angles better withstand first-ply failure.

able fast fabrication and adapt the bi-angle concept to automated processing. Tsai found a partner in Michel Cognet, group managing director of Chomarat (Le Cheylard, France). The textile specialist now manufactures noncrimp bi-angle fabrics called C-PLY, which can be converted to prepregs by Aldila (Poway, Calif.).

Brian Laufenberg, president of Chomarat North America (Anderson, S.C.), says conventional multiaxial machinery can assemble cross plies to about 45°, but Chomarat's equipment can combine 0° fibers with off-axis plies as acute as 20°. The company's efficient tow-spreading process can produce fabrics at areal weights as low as 75 g/m^2, and ongoing development is likely to reduce weight further. Chomarat thus can provide a complete range of thin, low-areal-weight, spread-tow, multiaxial noncrimp C-PLY fabrics.

C-PLY laminates were first trialed in 2010 by Dr. Alan Nettles, a visiting scholar at Stanford. His extensive coupon testing under static and impact loading scenarios showed that infused bi-angle laminates are virtually equal in performance to unidirectional prepreg.

A material change

After discussions with Tsai, Dr. John Eggers, who holds a certificate in composite design from Stanford and is the founder and CEO of the nonprofit cooperative American Artisan Bicycles, converted his company's Carbon EX road bike frame from prepreg layup to infused C-PLY. His team had previously designed the frame using engineering software program Adobe Inventor, supplied by Adobe Systems Inc. (San Jose, Calif.), MIC-MAC from Stanford's Composites Design Group and bicycle frame-specific BikeCAD Pro from The Bicycle Forest Inc. (Kitchener-Waterloo, Ontario, Canada). Intermediate-modulus, 300 g/m^2 uni carbon fiber prepreg was originally selected for the top tube, head tube, down tube and seat tube, and woven small-tow fabric combined with a titanium mesh was selected for the rear triangle (or seat/chain stays). The *lugs* (tube connections) were made by overwrapping joints with woven carbon and aramid fabrics; the latter was used to improve "shock absorption," says Eggers.

"Using 0° and ±45° directions is the 'standard' layup orientation in carbon bike frames worldwide. Of course we tried different angles, including ±25 and ±77, as well as all three at the same time," Eggers recalls. "We found that tube breaking strength was the highest using the ±45 orientation. But, it was a real headache for us, and very time-consuming, to produce balanced and symmetrical layups by cutting 45° angles manually from uni prepreg tapes. It was difficult to get right." He adds that managing prepreg shipments, freezer storage and out-time increased the difficulty and led to wasted materials.

With help from Tsai and Stanford's Composites Design Group, the Carbon EX frame was reset for the new material. The previous layup involved four unidirectional prepreg tape plies (0°/+45°/-45°/0°) inside two-piece tube molds. Follow-up analysis by Eggers and the Stanford team showed that four C-PLY layers — each a 0° ply of uni 12K stitched to a +45° ply of 12K (both high-strength carbon at an areal weight of 79 g/m^2) — is sufficient for the top and down tubes. Eight carbon plies result in a wall thickness of 0.083 inch/2 mm. To create the +45° and -45° orientations, every other C-PLY layer is flipped. To prevent mold slippage, plies are secured with tackifier, reports Eggers. For the seat tube, 10 C-PLY layers are used (20 total plies) for a wall thickness of 0.094 inch/2.4 mm. For the head tube, which must withstand frontal impact, 16 C-PLY layers (32 plies) form a tube wall of 0.145-inch/3.6-mm thickness.

The layups are infused with West System (Bay City, Mich.) epoxy in a heat-assisted light resin transfer molding (LRTM) process. Demolded tubes are mitered, placed in an assembly jig and tacked together with high-density structural epoxy filler. Then the lugs are hand wrapped, using wet out C-PLY and woven aramid. Cured frame assemblies are primed and painted.

Eggers reports that there is no significant wall thickness difference between the original uni prepreg tubes and the infused C-PLY tubes: "The C-PLY's extreme thinness and light areal weight results in very light yet very strong tubes."

Material processing, claims Eggers, is "dramatically faster." Hand layup of prepreg took 40 hours per frame. Now, a frame can be produced with C-PLY in only *four* hours. "There are no problems with dry spots or voids," he adds. Frame testing confirms better mechanicals and riders report a "better ride." The new material "is a bonus," he sums up. "This has really helped our company's mission of producing bikes in the U.S. at a competitive price ... with autoclave quality."

Today, 23 Carbon EX frame sizes, classed in five stiffness regimes, provide a near-custom fit for a wide range of riders. Chomarat's Laufenberg, however, expects wider application: "An unbalanced 0°/25° layup, for example, can take advantage of shear coupling to reduce bending and twisting in wing-type structures or wind blades." Aerospace industry curiosity is high. Skillen at VX Aerospace is reporting good results from using C-PLY in some rotorcraft test articles and C-PLY is under consideration by other airframers, notably Spirit Aerosystems Inc. (Wichita, Kan.). ■

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Read this article online at http://short.compositesworld.com/8937KYrm.

Read about efforts to reduce the need for conservative design in "Virtual testing of composites: Beyond make & break," *HPC* November 2012 (p. 36) or visit http://short.compositesworld.com/51EcWxPY.

Tsai and Wu published their failure criterion findings in "A General Theory of Strength for Anisotropic Materials," *Journal of Composite Materials*, 1971, Vol. 5, pp. 58-80.


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