CW COMPOSITESWORLD

HIGH-PERFORMANCE Composites

NOVEMBER 2013 / Vol. 21 / No. 6

- NDI integration: Faster, better *and* cheaper
- CMCs best metal superalloys in the hot zone
- Wing spars: Airbus A350 & A400M compared
- Compression molding lightens aircraft interior

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FEATURES

26 A350 & A400M Spars: A Study in Contrasts

In three short years, GKN Aerospace has taken its composite wing spar manufacturing strategies to new heights by dramatically reducing part weight, process complexity and production-cycle duration.

By Bob Griffiths

32 Nondestructive Inspection: Better, Faster and Cheaper

Faced with new time and cost pressures, NDI system suppliers are integrating inspection with manufacturing to reduce its share in part cost and cycle time.

By Michael LeGault

38 Ceramic-Matrix Composites Heat Up

Lightweight, hard and stable at high temperatures, CMCs are emerging from two decades of study and development into commercial applications.

By Karen Wood

COLUMNS

5 From the Editor

HPC editor-in-chief Jeff Sloan notes the role of emerging materials as composites continue to displace aircraft metals.

7 Composites: Perspectives & Provocations

Consultant Dale Brosius sees the Toray buyout of Zoltek as a potential auto-industry game changer.

9 By the Numbers

Gardner Business Media's director of market intelligence Steve Kline, Jr. updates the Composites Business Index.

11 Testing Tech

Dr. Donald F. Adams suggests larger support and loading cylinders for the Short Beam Shear test method.

DEPARTMENTS

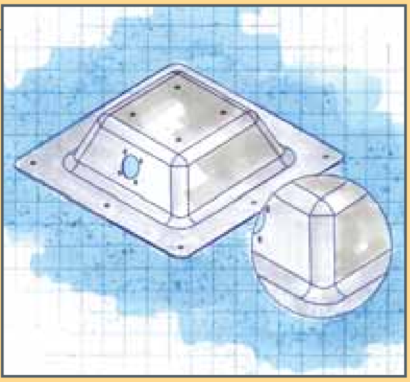
NOVEMBER
volume: twenty-one
number: six
2013

FOCUS ON DESIGN

54 Compression Molding Mass Out of Aircraft Interiors

Compression molding is fast and efficient, but continuous-fiber design requires optimization to avoid wrinkles and shrinkage.

By Jeff Sloan



ON THE COVER

At GKN Aerospace (Filton, U.K.), the wing spars for the Airbus A350 XWB are built up in one step by automated fiber placement (AFP) on a rotating mandrel, yielding *two* net-shaped parts — port and starboard spars — simultaneously. GKN takes advantage of the AFP machine's ability to cut and restart each tow independently to build up spars separately, with a small gap between them.

Source: GKN Aerospace

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Publisher	**Richard G. Kline Jr.** / rkline2@gardnerweb.com
Graphic Designer	**Susan Kraus** / skraus@gardnerweb.com
Marketing Manager	**Kimberly A. Hoodin** / kim@compositesworld.com

Midwestern U.S. & International Sales Office
Associate Publisher **Ryan Delahanty** / rdelahanty@compositesworld.com

Eastern U.S. Sales Office
District Manager **Barbara Businger** / barb@compositesworld.com

Mountain, Southwest & Western U.S. Sales Office
District Manager **Rick Brandt** / rbrandt@gardnerweb.com

European Sales Office
European Manager **Eddie Kania** / ekania@btopenworld.com

GARDNER
Business Media, Inc.

6915 Valley Avenue
Cincinnati OH 45244-3029
P 513-527-8800 / Fax 513-527-8801
gardnerweb.com

PO Box 992,
Morrison, CO 80465
P 719-242-3330 / Fax 513-527-8801
compositesworld.com

Richard G. Kline, CBC	President
Melissa Kline Skavlem	COO
Richard G. Kline, Jr.	Group Publisher
Tom Beard	Senior V.P., Content
Steve Kline, Jr.	Director of Market Intelligence
Ernest C. Brubaker	Treasurer
William Caldwell	Advertising Manager
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Jason Fisher	Director of Information Services
Kate Hand	Senior Managing Editor
Jeff Norgord	Creative Director
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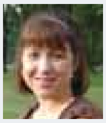
EDITORIAL OFFICES

CompositesWorld / PO Box 992 / Morrison, CO 80465
p: 719.242.3330 / f: 513.527.8801 / www.compositesworld.com

Jeff Sloan / Editor-in-Chief
jeff@compositesworld.com / 719.242.3330

Mike Musselman / Managing Editor
mike@compositesworld.com

Sara Black / Senior Technical Editor
sara@compositesworld.com



Ginger Gardiner / Senior Editor
ggardiner@compositesworld.com

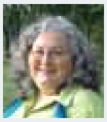
Lilli Sherman / Senior Editor
lsherman@compositesworld.com

CONTRIBUTING WRITERS

Dale Brosius
dale@compositesworld.com

Donna Dawson
donna@compositesworld.com

Michael R. LeGault
mlegault@compositesworld.com



Peggy Malnati
peggy@compositesworld.com

Karen Wood
karen@compositesworld.com

HI
FIVES !

Pronounced [feev]

FIVES is proud to announce the acquisition of MAG Americas and its international brands Cincinnati, Giddings & Lewis and Liné Machines.

FIVES is an industrial engineering group with over 200 years of history. FIVES manufactures machines, processing equipment, production lines and turnkey plants for the biggest global companies of the aluminium, steel, glass, cement, automotive, logistics, energy and sugar industries.

The acquisition of the world-renowned brands Cincinnati, Giddings & Lewis and Liné Machines confirms the growth strategy of FIVES in the sector of high-performance industrial equipment.

Ever since their creation in 1859 for Giddings & Lewis and 1884 for Cincinnati, these brands have been icons of the American machine tool industry.

1000 professionals in 5 countries will join the 6500 employees of FIVES, bringing their expertise in high-precision machine tools and high performance composite processing machines.

In addition to these skills, this acquisition will also contribute its 400 million dollars turnover to the Group, bringing FIVES total annual turnover to close to 2 billion euros by the end of the year.

The personnel of MAG Americas are joining the industrial success story of FIVES, famous since 1812 for works such as the Alexandre III bridge or the lifts of the Eiffel tower in Paris.

With this acquisition, FIVES confirms its role as leader among the industrial greats of the world of tomorrow.

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FROM THE EDITOR

jeff@compositesworld.com

Since before GE Aviation introduced the carbon fiber composite-intensive GEnx engine for the Boeing 787 Dreamliner, manufacturers of the jet engines used on commercial aircraft have toyed with the idea of integrating ceramic-matrix composites (CMCs) into the hot zones of jet engines to reduce weight.

CMCs were held back for some time by lengthy cycle times, high cost and feasibility issues, but in the past year the landscape shifted considerably for two reasons: First, in May, engine maker Rolls-Royce acquired CMC manufacturer Hyper-Therm HTC, signaling its intent to put the material to use in its engines. Then, in June, GE Aviation announced it would build a new plant in Asheville, N.C. for the manufacture of CMC jet engine parts. Both actions signaled serious and substantial commitment of capital to development and commercial application of a material whose time, apparently, has come.

> The decison to adopt a new material makes the organization an eager innovator, willing to be more aggressive and think outside the proverbial box.

The story behind this shift is explored in depth this month starting on p. 38. Author Karen Wood reveals just how seriously CMCs are being assessed, and where and how they'll be used in next-generation jet engines.

You'll also notice, in the article, that a third player in the commercial jet engine market, Pratt & Whitney, reports that it has decided, at least for now, against use of CMCs due to concerns about the "maturity" of the material. When you read this, you might wonder, as I did, about how to make sense of these decisions.

Rolls-Royce, GE Aviation and Pratt & Whitney are multi-billion dollar companies. Each has manufactured quality jet engines for decades. Each employs engineers and material scientists who must have approximately equivalent knowledge and abilities. Each makes business decisions based on careful cost/benefit analysis and prospects for long-term success. So, how is it that Pratt & Whitney deems CMCs a nonstarter, while GE Aviation and Rolls-Royce see the material as a major ingredient of their future engine designs?

It may be that Pratt & Whitney's corporate culture is more risk averse, and perhaps that is the sum total what separates two yes votes from a no vote, here. But I see an additional factor at work: Early adopters become early adapters.

Clearly, GE Aviation and Rolls-Royce see in CMCs real potential for lightweighting their engines. But that does not make them any less interested than Pratt & Whitney in avoiding risk. GE and Rolls-Royce have risked plenty, buying a company and opening a new plant, respectively. But I argue that once a company makes such a decision, the same desire to avoid risk makes these early adopters into energetic and creative adapters. Rolls-Royce and GE Aviation understand clearly that applying CMCs to engines is not a slam dunk. If it were easy it would have been done already.

With each investment, then, comes a powerful incentive to make that investment *pay off*. The decision to adopt a new material makes the organization an eager innovator, willing to be more aggressive and think outside the proverbial box — from the lab table to the shop floor — to make the risk worth the taking. When a company invests heavily in a new technology, employees take notice. They see that their employer is venturing into new territory, and they want to make that venture successful. And they want to be a part of that success.

For those who adopt early, and those who don't, the risk is similar — missing the future. But early adapters make trails that, if successfully blazed, others can only follow..

Jeff Sloan

COMPOSITES: PERSPECTIVES & PROVOCATIONS

TORAY + ZOLTEK = POTENTIAL GAME CHANGER?

Dale Brosius is head of his own consulting company and the president of Dayton, Ohio-based Quickstep Composites LLC, the U.S. subsidiary of Australia-based Quickstep Technologies (Bankstown Airport, New South Wales), which develops out-of-autoclave curing processes for advanced composites. His career includes a number of positions at Dow Chemical, Fiberite and Cytec, and for three years he served as the general chair of SPE's annual Automotive Composites Conference and Exhibition (ACCE). Brosius has a BS in chemical engineering from Texas A&M University and an MBA. Since 2000, he has been a contributing writer for Composites Technology and High-Performance Composites.

On Sept. 27, Toray Industries (Tokyo, Japan) announced the company had agreed to acquire all the outstanding shares of Zoltek Inc. (St. Louis, Mo.) for approximately $584 million (USD), subject to shareholder and regulatory approval. At first glance, the transaction is a merger of opposites, considering the differences in company culture, language, management style and product lines. Although it is easy to find reasons why such a marriage is destined to fail, there also are good reasons to think the move could truly *transform* the carbon fiber industry.

Toray's reputation in the carbon fiber market is unparalleled. Financially strong and fundamentally conservative, this Japanese chemicals and fibers company has been considered the market and technical leader in carbon fibers for at least the past two decades. Toray is the product-quality benchmark against which all other suppliers are measured, and often commands a premium price as a result. Toray's product line in high-performance PAN-based fibers is exceptionally broad, ranging from standard-modulus materials used in sporting goods, to ultrahigh-modulus fibers prevalent in satellite structures. Toray is the principal supplier of fibers and prepregs for the primary structures of the Boeing 787 *Dreamliner* and other Boeing aircraft. As the world's largest supplier of small-tow fiber, the company has carefully planned capacity expansions to maintain its market position.

By contrast, Zoltek established a reputation over the same two decades as the company intent on upsetting the *status quo*, creating a market position perhaps best described as "everything but aerospace" and, in many ways, the antithesis of Toray. In the mid-1990s, Zoltek's stock was a high flyer, predicated on the promise of large volumes of low cost fiber ($5/lb, or $11/kg) for mass-production applications in the automotive, oil and gas and, later, wind energy markets. Rapid capacity expansions in Europe and North America stressed the company financially, given the recurrent volatility in global carbon fiber demand and pricing. Zoltek's 50K large tow provided a challenge to many processors who were used to handling typical 12K or 24K fibers. And achieving a sustainable economic advantage proved elusive, as did $5/lb fiber. Although the wind energy market finally provided a stable base of demand, the hoped-for uptake in the automotive and oil and gas arenas did not materialize.

Pressed by key shareholders early in 2013, Zoltek began exploring strategic alternatives, including a sale of the company. It's easy to envision any number of reasonable acquirers, given various announcements by large chemical and fiber companies during the past several years. So it came as a bit of a surprise to see Toray play the aggressor, because the two companies, on the surface, seem like polar opposites in the carbon fiber marketplace. But, looking a little deeper, an intriguing synergy emerges.

Like numerous others, I have noted a long trend toward confluence in the industrial and aerospace markets as it pertains to carbon fiber and the conversion of this versatile material into strong, lightweight parts. This has led to a lot of cross-fertilization of manufacturing methods and material forms across many industries.

Looking back, Toray has steadily increased its presence in the automotive arena for more than a decade. It has supplied prepregs for GM's *Corvette* platform since 2001, as well as filament-wound driveshafts to Mazda, Nissan and Mitsubishi. In the past five years, Toray has established an automotive development center in Japan, taken a 20 percent stake in parts maker ACE Advanced Composite Engineering GmbH (Immenstaad, Germany), established Euro Advanced Carbon Fiber Composites GmbH (Esslingen, Germany) in a joint venture with automaker Daimler AG (Stuttgart, Germany), purchased a niche producer of carbon fiber automotive parts in Japan and, in July 2013, purchased a 20 percent stake in Plasan Carbon Composites (Wixom, Mich.), the supplier of finished carbon fiber parts for the *Corvette*.

The missing piece for Toray was low-cost carbon fiber that would make the economics work in the quest to replace steel and aluminum in cars. Zoltek provides that missing ingredient and has significant capacity in low-cost precursor and carbonization lines. Just as significant, the Toray name legitimizes large tow as the future of the carbon fiber industry.

Although the stated objective is that Zoltek will operate as a standalone subsidiary, it stands to reason that Toray will invest plentiful resources from its core fibers business to upgrade Zoltek's facilities and product quality, drive cost down, and accelerate market acceptance of Zoltek products, not only in the automotive arena, but in other markets — including aerospace.

If Toray's strategy is successful, two decades from now, we'll point back to this as the watershed event for the industry. It will be exciting to watch. ■

BY THE NUMBERS

COMPOSITES BUSINESS INDEX 49.0: CONTRACTION SLOWS AGAIN

Steve Kline is the director of market intelligence for Gardner Business Media Inc. (Cincinnati, Ohio), the parent company and publisher of *High-Performance Composites*. Kline holds a BS in civil engineering from Vanderbilt University and an MBA from the University of Cincinnati.

In August, a Composites Business Index of 48.2 showed that composites business activity had contracted for a third consecutive month, but at a slower rate, indicating a possible break with its downward trend. Two subindices made positive contributions: Employment grew for the sixth straight month, and suppler deliveries continued their long-term lengthening trend. Production and exports continued to contract, but did so at slower rates. Exports, in particular, had contracted at a steadily slower rate since December 2012. New orders contracted for the fourth consecutive month. The only subindex to negatively impact the CBI was backlogs. In August, it contracted for the 15th month and had done so faster each month since February.

Material prices increased in August at their slowest rate since November 2012. Prices received increased slightly after decreasing three of the previous four months. Future business expectations fell a bit after leveling for six months.

One month does not a trend make, but August activity based on plant size appeared to shift. Fabricators with 250+ employees contracted for the first time since November 2012. Those with fewer than 19 employees continued to contract, but at a much slower rate. The small facility index, however, moved up to 43.9 from 38.9 in July. Those with 50-249 employees continued strong.

Four regions expanded in August. The fastest rate was in West South Central, which had grown five of the previous seven months. Meanwhile, New England, the South Atlantic and the Middle Atlantic all moved from contraction to expansion. But the West North Central, which had strong growth the previous five months, fell off sharply.

Future capital spending plans were just above the historical average.

Gardner's September CBI, 49.0, showed that business activity contracted at a slower rate for the second consecutive month. But September still marked a fourth consecutive month of contraction.

Four of the six subindices made positive contributions to the overall CBI in September. The largest jump came in the backlogs, which moved to 43.5 from 39.7. However, backlogs have contracted since May 2012. Production also jumped significantly to growth from contraction. Production has grown seven of the nine months this year. New orders reached its highest level since May. Also positive was supplier deliveries, which lengthened slightly. Employment grew for the seventh consecutive month but at a slightly slower rate. This had a slightly negative impact on the overall index. The worst performer was exports, which dropped to 46.0 from 48.3. Exports have contracted for 17 months.

Material prices increased at a faster rate in September, but the rate of increase was the second slowest since November 2012. Prices received by composite fabricators jumped to 52.1 from 50.3. This was the second month in a row that prices received increased at a faster rate. Future business expectations fell slightly but were still above the lower levels recorded in the second half of 2012.

After contracting in August, fabricators with more than 250 employees grew in September. Facilities with 100 to 249 employees continued strong, growing their fastest rate since July 2012. Fabricators with fewer than 100 employees contracted in September. Facilities with 50 to 99 employees contracted for the second time in 2013. Fabricators with 20 to 49 employees saw their best business conditions since March, this year.

Two regions, the West South Central and the Middle Atlantic, grew for the second month in a row. New England and the South Atlantic moved from growth to contraction. The East North Central, Pacific, and West North Central contracted, again, but at a slower rate.

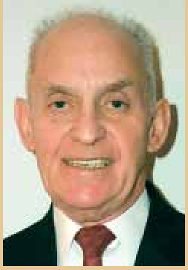
Future capital spending plans were at their lowest level since March 2013. However, planned expenditures were 11 percent higher than in September 2012. ■

THE COMPOSITES BUSINESS INDEX FOR SEPTEMBER 2013

Subindices	September	August	Change	Direction	Rate	Trend
New Orders	48.6	47.4	1.2	Contracting	Slower	1
Production	51.7	49.0	2.7	Growing	From Contracting	1
Backlogs	43.5	39.7	3.8	Contracting	Slower	16
Employment	51.4	51.9	-0.5	Growing	Slower	7
Exports	46.0	48.3	-2.3	Contracting	Slower	17
Supplier Deliveries	52.8	52.6	0.2	Lengthening	More	22
Material Prices	60.6	58.4	2.2	Increasing	More	22
Prices Received	52.1	50.3	1.8	Increasing	More	2
Future Business Expectations	64.3	65.4	-1.1	Improving	Less	22
Composites Business Index	49.0	48.2	0.8	Contracting	Slower	4

TESTING TECH

THE SHORT BEAM SHEAR TEST METHOD FOR COMPOSITE MATERIALS



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 my previous column, I briefly cited the Short Beam Shear (SBS) test method as a much more attractive interlaminar shear test method than the double-notch shear test method. The primary attraction of the SBS method for many users is the simplicity, the small size of the test specimen and the ease with which the test can be performed. As a result, the SBS method is widely used. Yet it is not without its detractors.

The test method loads a beam specimen in three-point bending, as shown in Fig. 1. The term "short beam" indicates that the support span length, *s*, is a *low multiple* of the specimen thickness, *t*. The goal is to force the beam specimen to fail in a shear mode. This can be achieved because the shear stress is independent of the support length, whereas the flexural (bending) stresses are a linear function of the support length. Thus, the shorter the beam, the greater the shear stress relative to the bending stresses.

The SBS test method was first standardized by ASTM in 1965, as ASTM D 2344, and titled "Apparent Interlaminar Shear Strength of Parallel Fiber Composites by Short-Beam Method." The standard suggested using a support span length-to-specimen thickness ratio, *s/t*, of 5 for glass-fiber-reinforced composites and 4 for all other reinforcing fibers, including carbon, steel, boron, aramid and so forth. The questionable distinction for glass fibers was based primarily on some limited analytical studies that were being conducted at the time. The use of "apparent" in the title was to acknowledge that the shear stresses in the short beam are not only not uniform, but also are accompanied by tensile and compressive axial stresses as well as through-the-thickness tensile and compressive stresses. Simply put, it was well known that the SBS method was not a "pure shear" test, as would have been desirable. Nevertheless, it was considered a shear test.

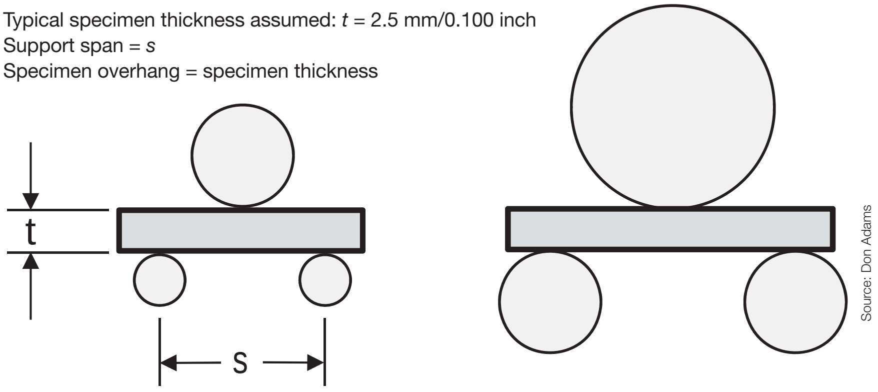
In the 2000 revision of ASTM D 2344, however, the title was altered to "Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates." The word "shear" was deleted from the title *and* from the definition of the strength quantity it measures. In spite of these negative implications, the SBS test continues to be used extensively for the same reason as always — it is easy to perform and can provide a good comparative assessment of material performance, even if it does not necessarily provide accurate quantitative data.

Notably, the revised method eliminated the separate *s/t* ratio for glass fiber composites. The standard now specifies that *s/t* = 4 be used for *all* types of fiber-reinforced polymers. And although the originally defined 0.250-inch diameter loading cylinder and 0.125-inch diameter specimen support cylinders were retained, consistent with ASTM's decision to require "soft" rather than "hard" conversions from U.S. customary units to SI units, the SI "equivalent" diameters became 6 mm and 3 mm rather than the previous 6.35 mm and 3.2 mm.

The soft conversions raise an obvious question: *Is it necessary to use different cylinders if a test is being conducted per the SI version of the standard*? The strict answer, of course, is *yes*. But it has been clearly demonstrated during the past decade (see Adams and Busse,[1] which references a number of other studies) that small changes in cylinder diameter make little difference in the test results.

Further, these studies have demonstrated experimentally and numerically that *larger* cylinder diameters are beneficial because they induce more uni-

Fig. 1 Short Beam Shear specimen test configurations.



Typical specimen thickness assumed: *t* = 2.5 mm/0.100 inch
Support span = *s*
Specimen overhang = specimen thickness

Source: Don Adams

a) Current Test Configuration
s/t = 4
Loading cylinder diameter = 6 mm/0.250 inch
Support cylinder diameters = 3 mm/0.125 inch

b) Proposed Test Configuration
s/t = 6
Loading cylinder diameter = 12 mm/0.500 inch
Support cylinder diameters = 6 mm/0.250 inch

form stresses within the beam specimen. Using small-diameter cylinders introduces high local stress concentrations. Larger cylinders spread the applied load over a wider specimen surface area, resulting in more uniform internal stress states in the specimen. In fact, it would be logical to size the cylinders in proportion to the specimen thickness and, thus, the anticipated failure load. However, this has not yet been proposed and, perhaps, is not practical. A standard loading cylinder diameter as large as 25 mm/1 inch has been suggested.[1] However, considering the small thickness of a typical specimen, a loading cylinder diameter of 12.7 mm/0.50 inch, with a corresponding diameter of 6.35 mm/0.25 inch for the support cylinders, is a more practical option (Fig. 1b).

Note that, for the three-point bending SBS test depicted in Fig. 1, the reaction forces at the supports are *one-half* the force applied on the loading cylinder, justifying the use of smaller support cylinders. In fact, if the test specimen is relatively thin, there isn't sufficient space between the support points to accommodate a large-diameter cylinder. For example, on a typical 2.5-mm/0.10-inch thick specimen with a support span ratio of 6, the distance between supports will be a mere 15 mm/0.60 inch, indicating that the largest support cylinder diameter can be only 15 mm/0.60 inch. Of course, it isn't necessary to use full cylinders because it is only the radius of the surface in contact with the specimen that is significant.

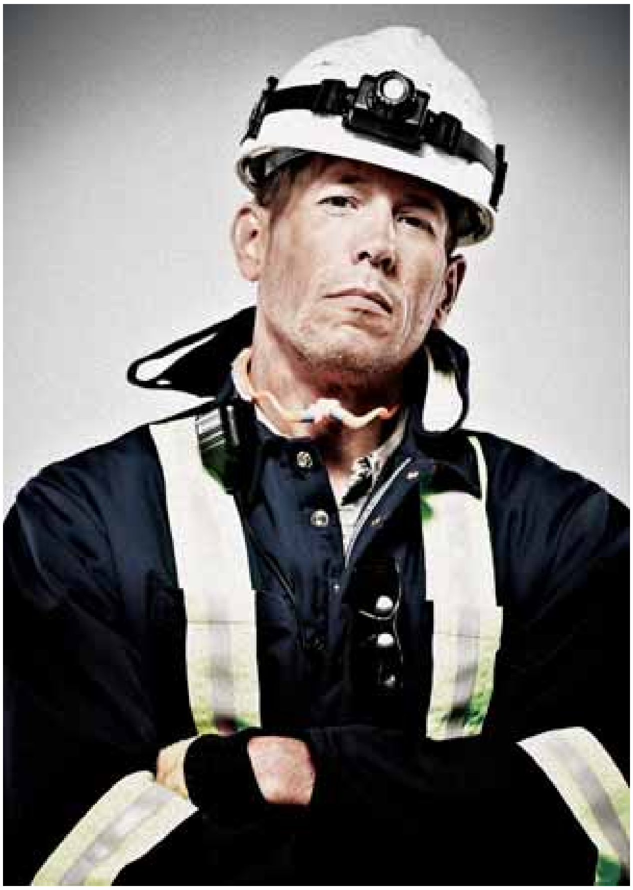
These same studies also have shown that the *s/t* ratio has a strong influence on the obtained "apparent shear strength" and the failure mode. From Fig. 1a, it can be inferred that, as *s/t* decreases from the value of 4, the support cylinders get closer to being directly under the loading cylinder, and there will be more of a through-the-thickness crushing of the specimen, rather than bending, thus altering the failure mode away from shear.

Correspondingly, if *s/t* becomes too great — that is, if the specimen is no longer a short beam — the previously noted flexural (axial tensile or compressive) failures will occur rather than a shear failure. Most likely, there will be compressive failures at or near the specimen surface under the loading point, where the stress concentrations occur. Studies indicate that an *s/t* ratio in the range of 4 (the current ASTM recommendation) to 9 is favorable.[1] Therefore, standardizing a ratio of 6 or 7 would be reasonable. In this *s/t* range, there is typically one large and abrupt load drop at failure, with shear cracks visible at or near the midthickness of the specimen, typically in the region midway between the loading and support points where the shear stress is greatest.

In summary, it is suggested that ASTM D 2344 be revised to specify an *s/t* ratio of 6, a loading cylinder diameter of 12.7 mm/0.50 inch and a support cylinder diameter of 6.35 mm/0.25 inch, as depicted in Fig. 1b. These modifications are minor, will have relatively little influence on direct comparisons of new results with legacy values, and will provide more consistent shear failure modes. ■

Reference

[1] Adams, D.F., and Busse, J.M., "Suggested Modifications of the Short Beam Shear Test Method," *Proceedings of the 49th International SAMPE Symposium* (Long Beach, Calif.), May 2004.




CASINO

NEWS

First flights: Bombardier's CS100, Boeing's 787-9 Dreamliner take to the air

CSeries milestone marks start of flight-test program for new aircraft family


Source: Boeing

Bombardier Aerospace (Montréal, Québec, Canada) celebrated the successful first flight of its C*Series* aircraft on Sept. 16, a major milestone in the company's highly anticipated development program that is expected to provide airline operators with an all-new composites-intensive aircraft family specifically designed for the 100- to 149-seat commercial passenger jet market segment. The maiden flight marks the start of the C*Series* flight test program.

The historic flight of C*Series* flight test vehicle one (FTV1), a *CS100* jetliner, departed from Montréal-Mirabel International Airport at 9:55 a.m. EDT and returned at 12:25 p.m. EDT. "The performance of the C*Series* aircraft was very impressive! We couldn't have wished for a better maiden flight," says Ellis.

"This is a very proud day for Bombardier and a true validation of the C*Series* aircraft's design and development, and of our extensive ground test program," says Rob Dewar, VP and general manager, C*Series* Program, Bombardier Commercial Aircraft. He continues, "Five years in the making, the C*Series* aircraft's first flight is the culmination of an incredible amount of hard work and dedication from our employees, partners and suppliers around the world."

Four more *CS100* flight test vehicles, currently in various stages of assembly, will join the flight test program.

GKN Aerospace (Redditch, Worcestershire, U.K.), which is under contract to Bombardier Aerospace, Belfast, to develop and supply critical structures on the advanced composite wings, offered its congratulations to Bombardier on the first flight. Bombardier's Belfast unit is responsible for C*Series* wing production; the wings are said to be among the largest and most complex composite aircraft structures ever manufactured and assembled in the U.K.

Specifically, GKN Aerospace developed, designed and now manufactures the all-composite aileron and winglet structures for both the *CS100* and *CS300* aircraft. The company's engineering team has completed a three-year design and development program to create an innovative, one-piece aileron and winglet that minimizes structural weight and complexity while offering critical performance benefits to the airframe. A reportedly state-of-the-art manufacturing and assembly process also increases the speed of manufacture and reduces production costs.

Teijin Ltd.'s (Tokyo, Japan) carbon group, Toho Tenax, supplies carbon fiber for major primary and secondary composite structures on the program, including several carbon fiber types for both dry textiles and prepregs. Virtek Vision International Inc.'s (Waterloo, Ontario, Canada) trademarked LaserEdge projection systems eliminate the need for physical templates by precisely projecting a template onto molds to guide operators through the wing's complex ply layup process.

The next day, The Boeing Co.'s (Seattle, Wash.) 787-9 *Dreamliner* took to the skies for the first time, beginning a comprehensive flight test program that will culminate in certification and delivery, predicted for mid-2014. The newest member of the 787 family completed a 5-hour, 16-minute flight, taking off from Paine Field in Everett, Wash., at 11:02 a.m. local time and landing at 4:18 p.m. at Seattle's Boeing Field. With a fuselage 20 ft/6m longer than the 787-8, the 787-9 will carry 40 more passengers an additional 300 nautical miles (555 km). Boeing is on track to deliver the 787-9 to launch customer Air New Zealand in mid-2014.

"Today's first flight marks a significant milestone for our team, including our partners," says Boeing Commercial Airplanes president and CEO Ray Conner. "We ... look forward to delivery of the first airplane to Air New Zealand next year."


Source: Bombardier

The first 787-9 will be joined in flight test by two additional planes. Those airplanes are in the final stages of assembly in Boeing's Everett factory.

Over the coming months, the fleet will be subjected to a variety of tests and conditions to demonstrate the safety and reliability of the airplane's design.

Twenty-five customers from around the world have ordered 388 787-9s, accounting for 40 percent of all 787 orders received to date.

CompositesWorld's Carbon Fiber 2013 conference ready to roll

CompositesWorld, publisher of *High-Performance Composites* and *Composites Technology* magazines and the *CompositesWorld Weekly* e-newsletter, has added to the agenda for Carbon Fiber 2013, Dec. 9-12, 2013, at the Crowne Plaza Knoxville in Knoxville, Tenn. Held this year near the U.S. government's Oak Ridge National Laboratory (Oak Ridge, Tenn.), the annual event's 2013 sponsors are carbon fiber oxidation equipment manufacturers C.A. Litzler (Cleveland, Ohio) and Harper International (Lancaster, N.Y.), the Knoxville/Oak Ridge Innovation Valley, the Oak Ridge Carbon Fiber Composites Consortium, fiber handling equipment source Izumi International (Greenville, S.C.) and fiber supplier Toho Tenax America Inc. (Rockwood, Tenn.).

Carbon Fiber 2013's newest confirmed speaker is Mathieu Boulanger, business development director for induction-heating equipment source RocTool (Le Bourget du Lac, France, and Charlotte, N.C.), whose topic is "High Speed Compression Molding by Induction."

Boulanger joins the following:

- Brett Chouinard, COO, Altair Engineering (Troy, Mich.): "Analysis and Optimization of Composite Structures – Challenges and Opportunities."
- Probir Guha, VP of R&D, Continental Structural Plastics (Troy, Mich.): "Automotive Light Weighting Opportunities & Challenges."
- Tracy Albers, manager-external interactions, and Chong Chen, senior research scientist, GrafTech International (Biddeford, Maine): "High Temperature Insulation from Lignin Carbon Fibers."
- Chad Duty, Oak Ridge National Laboratory: "3D Printing with Carbon Fiber Reinforcement."
- John Larkin, president, LTI Assoc. (White Bear Lake, Minn.): "Export Controls and the Carbon Fiber Industry."
- Dr. Angelos Miaris, Premium AEROTEC GmbH (Augsburg, Germany): "Producing Thermoplastic Matrix Composites for Aeronautical Applications under Industrial Scale Conditions."
- Hendrik Mainka, Volkswagen Group of America Inc. (Herndon, Va.): "Alternative Precursors for Sustainable and

Cost-effective Automotive Carbon Fibers"

- Gary R. Lownsdale, CTO, Plasan Carbon Composites (Bennington, Vt.): "Next Generation Carbon Fiber Composites: Beyond Medium Volume"
- Neel Sirosh, CTO, Quantum Technologies Inc. (Irvine, Calif.): "Carbon Fiber Powering America's Big Rigs"
- Anthony Vicari, research associate, Lux Research (Boston, Mass.): "Planning for Ripe Fruit: Materials Innovation Lifecycles as a Scouting Tool"
- Mark Campbell, new product development, Hyperco Div., MW Industries (Elk Grove Village, Ill.): "Development of Hyperco Carbon-composite 'Bellows Spring' (CCBS) System for Automotive Suspensions"
- Chris McHugh, technical manager, Sigmatex (UK) Ltd. (Runcorn, U.K.): "Application and Processing of Complex Fabrics for Lightweight Structures"
- Gary D. Roberts, research materials engineer, NASA Glenn Research Center (Cleveland, Ohio): "A Hybrid Composite/Metal Gear Concept for Rotorcraft Drive Systems"
- Gordon Lacy, mechanical engineer, NRC Canada (Ottawa, Ontario, Canada): "Design and Fabrication of the DVA-1 Radio Antenna"
- John M. Carson, executive director, Altus Group Inc. (Lancaster, Pa.): "Lighter, Stronger, Greener: How Carbon Fiber is Modernizing Precast Concrete!"
- Aaron Barr, technology advisor, MAKE Consulting (Chicago, Ill.): "Carbon Fiber Usage in the Wind Energy Industry"

For more information or to register, visit http://short.compositesworld.com/CF2013.

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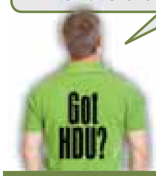

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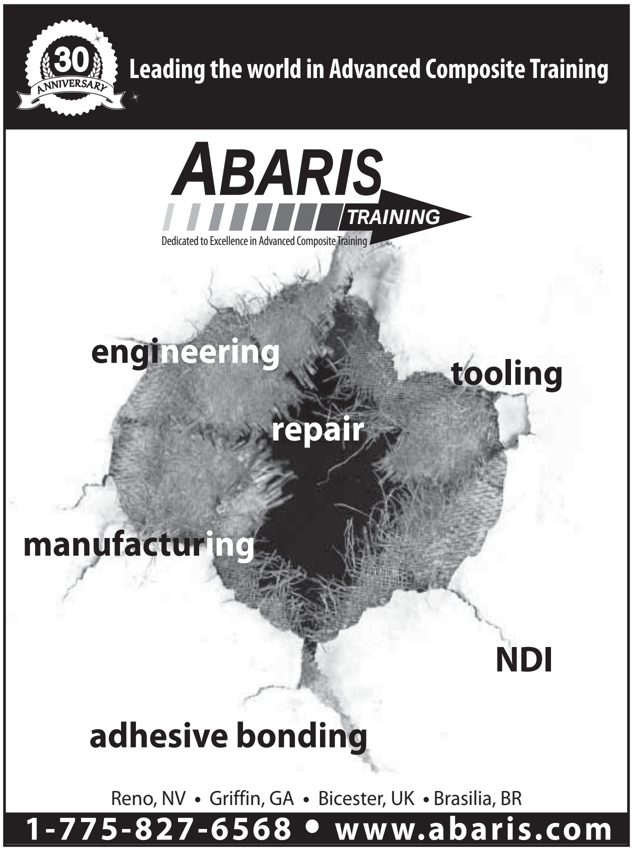
Toray Industries to buy Zoltek Inc.

Toray Industries Inc. (Tokyo, Japan) is set to purchase U.S.-based Zoltek Corp. (St. Louis, Mo.). The announcement first hit the Internet news services on September 26, and Zoltek subsequently confirmed that Toray was poised to purchase the entirety of Zoltek's stakeholder shares at $16.75 per share (total amount, approximately $584 million). The buyout is expected to increase Toray's share of the global carbon fiber market to 30 percent. The breaking news was first reported in the Japanese newspaper *Nikkei Business Daily*. According to a Reuters story, reported by Mridhula Raghavan in Bangalore, India, the deal offers Toray the opportunity to start producing lower-priced industrial/commercial-grade carbon fiber, thus expanding its portfolio beyond its aerospace-grade emphasis.

Zoltek reportedly hired J.P. Morgan Securities (Clayton, Mo.) as a financial adviser earlier this year to help it "explore and evaluate strategic alternatives to maximize shareholder value," reportedly because of a push by an investor group, led by Jeffry Quinn, a former CEO of St. Louis-based performance materials supplier Solutia, for improved results at the company. Quinn's Quinpario Partners group, also based in St. Louis, reportedly sought, at one point, to oust the company's board of directors, saying new leadership was needed.

In August Zoltek had reported a quarterly loss of $900,000, or $0.03 per share, for the three-month period



ending June 30, compared to a profit of $5.6 million, or $0.16 per share, during the same period in 2012.

Zoltek's carbon fiber products, targeted to uses in construction and wind turbine blades, are reportedly priced at about 60 percent of Toray's higher-performance carbon fiber. According to Toray, global demand for PAN-based carbon fiber is expected to expand at an annual growth rate exceeding 15 percent, as carbon fiber contributes not only to energy savings through weight reduction but also in its role in the renewable energy field.

Zoltek's large tow fiber is anticipated to expand PAN-based carbon fiber's applications, based on its reasonable balance of cost and performance. These applications are expected to include not only wind turbine blades and other parts but also, in the future, structural automotive parts.

Read HPC columnist Dale Brosius' commentary on the significance of Toray's entry into the large-tow market, on p. 7.

CORRECTION

In the September issue of *HPC*, the editors missed an error in the text of our Inside Manufacturing story, "Tooling up for larger launch vehicles." An alert reader pointed out that in the last paragraph of the text on p. 66 (sixth line) we misspelled the word *require*. More importantly, from a technical standpoint, we mislabeled, in line 13, the English conversion that follows the SI units for surface profile tolerance, and we missed a stray comma. The text says "±0.508 mm (±0,020 mm)." The conversion in parentheses should read "(±0.020 inch)."

The following is the paragraph with corrections intact:

> The tooling also would require support structures and fixtures to protect honeycomb-cored edges. Further, operators would need access to the interior of the part for core placement and vacuum bag preparation, and would require an inner mold line (IML) surface caul with a vacuum handling system (overhead equipment with suction cups to facilitate moving and positioning). The part — and, therefore, the tool — also would require a surface profile tolerance of ±0.508 mm (±0.020 inch). The structural design and analysis of the tooling was critical because of the myriad requirements combined with its scale: The tool's overall dimensions would be 2.1m by 5.7m by 8.6m (6.8 ft by 18.8 ft by 28.3 ft) with a facesheet surface area of 52.1m^2 (561 ft^2).

HPC regrets the errors.

SPE Automotive Composites & Exhibition attracts more interest this year

At its new and much larger venue, the Suburban Collection Showplace and adjoining Hyatt Place Hotel in Novi, Mich., the Society of Plastics Engineers' (SPE) 13th annual Automotive Composites Conference and Exhibition (ACCE) hosted nearly 900 attendees, offered a strong four-track program of well-attended papers (photo at right) and boasted a crowded exhibit hall (see center photo).

As always, conference presenters shared a wealth of information about innovations in part design, improved materials and more consistent, repeatable and efficient molding processes, citing notable examples of successful composite parts in production automobiles. Many of the innovations came from Europe, where automakers are scrambling to reduce vehicle weight to avoid strict financial penalties for failing to meet vehicle emission targets. Despite one presenter's statement that "the BMW *i3/i8* program is equivalent to the Boeing 787 *Dreamliner* program for automotive composites," some OEM representatives expressed, as they have at past conferences, reservations about full-scale adoption of composites.

Notable papers included one on molding technology from Schuler SMG GmbH & Co. (Waghäusel, Germany) by Patric Winterhalter, who discussed vacuum-assisted high-pressure resin transfer molding (RTM) for carbon fiber car elements. Schuler is working with automaker BMW (Munich, Germany) on molding the carbon fiber composite BMW *i3* Life Module (passenger cell), among other parts. Using this technology, a three-minute cycle is almost within reach, says Winterhalter. A few days after the event, BMW formally began manufacture and assembly of its new all-electric *i3* car in Germany, combining carbon fiber composites and injection molded plastics, as well as innovative production processes.

Mitsubishi Rayon Co. Ltd.'s (Tokyo, Japan) Takeshi Ishikawa described a slit carbon fiber/thermoplastic sheet with "flowability" and high mechanical properties that can be quickly "stamped" or molded at relatively low pressure to create highly complex parts, including ribs. In fact, an entire track was devoted to carbon compos-

(*continued on p.* 22)

(*continued from page* 21)

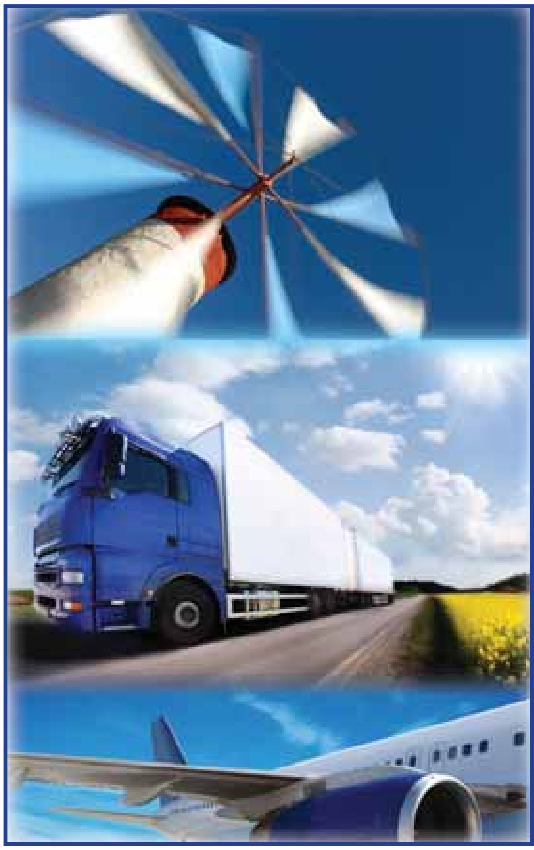
ites, with many speakers predicting that "strong" demand for carbon fiber in autos will accelerate after 2015.

A standout paper presented by Marcie Kurcz, North America business manager for resin maker Polyscope (Geleen, The Netherlands), outlined the design and manufacture of the semiconvertible sunroof frame for Paris, France-based auto OEM Citroen's DS3 *Cabrio* model. Designed by Webasto (Munich, Germany) and molded by Shaper (La Séguinière, France), the frame is molded with a modified glass-reinforced styrene maleic anhydride (SMA) resin from Polyscope. The composite part offers significant cost savings over other materials, part integration (seven parts were combined into one) and a 40 percent weight reduction compared to other considered materials; it is an example of a viable "value proposition" that clearly favored the selection of composites. In another session there was considerable audience interest in a process approach offered by Dale Brosius of Quickstep Composites LLC (Dayton, Ohio) called Resin Spray Transfer (RST). In this fast-cycle method, the structural resin is robotically sprayed directly on the mold surface, a preform is placed over it and the laminate is heated and cured under relatively low pressure in a Quickstep hot-fluid machine. The resin flows in the z-direction to wet out the fiber and produces a Class A finish. According to Brosius, a cycle time of 10 minutes is possible.

Several papers and keynotes discussed new and ongoing industry collaborations aimed at increasing the usage of composites on high-production vehicles. Greg Rucks of the Rocky Mountain Institute (RMI, Snowmass, Colo.) discussed his group's "launch pad," which aims to reduce a vehicle's cost and ensure its life cycle value by means of composites. Electing to focus on a few parts on mainstream models for fleets, such as a door inner that doesn't require a cosmetic finish, RMI is pulling together a supply chain team to create an "innovation hub" expected to produce parts by 2018.

This year, for the first time, the industry discussion panel included two representatives from the aluminum industry: Doug Richman of Kaiser Aluminum (Bingham Farms, Mich.) and Mario Greco of Alcoa (Pittsburgh, Pa., see photo on left side, p. 21). A point repeatedly raised by panel members was that composites technology is certainly possible and attractive, but adoption repeatedly stalls when the industry tries to make a *business* case because material cost is high and processing issues remain unresolved. Additional challenges center around attachments and fastening, said several panel members. As in previous years, panelists agreed that predictive analysis software, training and education are still lacking in many cases, which hampers familiarity with composites. And most asserted that life cycle analysis (LCA) is becoming more important to both the OEMs and consumers; those LCA analyses show that carbon fiber does not fare as well as aluminum, which enjoys a huge and global recycling push.

For more about this event, watch for expanded coverage in the December issue of *HPC's* sister publication, *Composites Technology* magazine. Visit the SPE Automotive Division Web site (http://www.speautomotive.com/aca) to access the presentations.



Composites Europe sheds light on emerging automotive composites

Composites Europe (Sept. 17-19, Stuttgart, Germany) has grown substantially over the past few years, maturing into a full-fledged trade show that attracts many of the composites industry's biggest players. The flavor remains German, but given the large amount of composites R&D done in that country, the location is a favorable one.

Activity on the show floor emphasized the industry's interest in automotive applications. Several car hoods were on display, each designed to demonstrate a different material and process combination. A notable example was a carbon fiber/epoxy hood design developed by the Institut für Kunststoffverarbeitung (Aachen, Germany) and machinery maker Breyer Composites (Singen, Germany) in cooperation with Dearborn, Mich.-based Ford Motor Co. The hood's molding process employs a gap impregnation technique. A preform is loaded into a horizontal press from Breyer. The press is closed, but not fully, and the preform is supported 3 mm/0.12 inch above the mold surface by a series of pins located on each side of the mold. Epoxy is injected into the mold cavity at the bottom of the tool until the resin fills about a third of the space in the mold. The pins then retract and the mold closes completely. The resin is forced up into the rest of the cavity and infuses the entire preform. Heat is provided via circulating hot water. The total cycle time is 15 minutes, and the demolded hood is ready for paint. There is no word on whether Ford will put this part into production.

Taking a different tack, engineering and manufacturing firm Magna Steyr (Oberwaltersdorf, Austria) and partners Rühl Puromer (Friedrichsdorf, Germany), which contributed polyurethane resin knowledge, and Hennecke (Sankt Augustin, Germany), the molding equipment supplier, developed a demo hood based on glass fiber/polyurethane cored with paper honeycomb. Hennecke officials say their goal is not to save weight, but rather to accelerate production and meet European pedestrian-impact requirements. The core and fiber are inserted into the mold and surrounded by a gap of 0.8 to 1 mm (0.032 to 0.039 inch). Polyurethane is injected into the gap, then it is pressed and cured. The process results in a finished part with a Class A surface every five minutes.

Moldmaker Frimo (Lotte, Germany) split the difference, showing its own demo hood that comprises carbon fiber faceskins and a foam core from 3D Core (Herford, Germany) infused with foaming polyurethane in a low-pressure process. Paint is applied in-mold, so the parts emerge finished with a highly textured surface. The process, say Frimo officials, has a five-minute cycle time.

A fully assembled, functional BMW *i*3 electric-powered commuter car was on exhibit and SGL Group (Wiesbaden, Germany) introduced a line of nonwoven carbon fiber fabrics manufactured from scrap generated during *i*3 production. A stitched variation is used in the *i*3 roof.

Continuing the automotive theme, TenCate Advanced Composites (Nijverdal, The Netherlands) and Kringlan Composites AG (Otelfingen, Switzerland) reported that they had signed a memorandum of understanding to develop solutions for manufacturing parts based on thermoplastic composites. Kringlan, with TenCate's help, designed and manufactured a fully carbon fiber-reinforced composite wheel. It includes a single-shot rim and a spoke module that is assembled and bonded separately before integration with the rim. The process is based on press molding and produces a wheel every 10 minutes, offering a 30 to 40 percent weight savings compared to aluminum wheels. Series production is expected in 2014 for a high-end sports car. The fiber is T700 from Toray Industries (Tokyo, Japan). The resin is supplied by SABIC (Sittard, The Netherlands).

A new trade group was announced at the show. Composites Germany, formed by AVK-Industrievereinigung Verstärkte Kunststoffe eV, Carbon Composites eV, CFK-Valley Stade eV and Forum Composite Technology in the VDMA, will focus on public relations, technology innovation and promotion, trade fairs and training. Organization officials also pledged to work with government officials in Berlin, Germany, and Brussels, Belgium, to raise the profile of composites among political leaders.

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Latest volumes of *CMH-17* now published and available

SAE International (Warrendale, Pa.) announced in September that it had completed two new volumes for the *Composite Materials Handbook* (*CMH-17*) series. Metal-matrix composites and structural-sandwich composites are the topics of the two newest titles. SAE and the Composite Materials Handbook 17 organization (Wichita, Kan.) agreed in June to work together on publishing the initial release of the handbook volumes, which will be produced in print, on DVD and in other electronic formats. *CMH-17* is a six-volume engineering reference tool, previously known as *MIL-HDBK-17*, that contains more than 1,000 records of the latest test data for polymer-matrix (Volumes 1, 2, and 3), metal-matrix (Volume 4), ceramic-matrix (Volume 5) and structural-sandwich (Volume 6) composites.

"We are pleased to be working together with CMH-17 through Wichita State University to publish and market this next generation of the *Composite Materials Handbook*," says Kevin Jost, editorial director, SAE International. "The *Handbook* has proven to be a valuable resource for aerospace engineers over the years, and we look forward to making it available to SAE International members and beyond."

Developed over many years by an international consortium of engineering organizations, *CMH-17* provides an overview of composites engineering that evolves to reflect new advances.

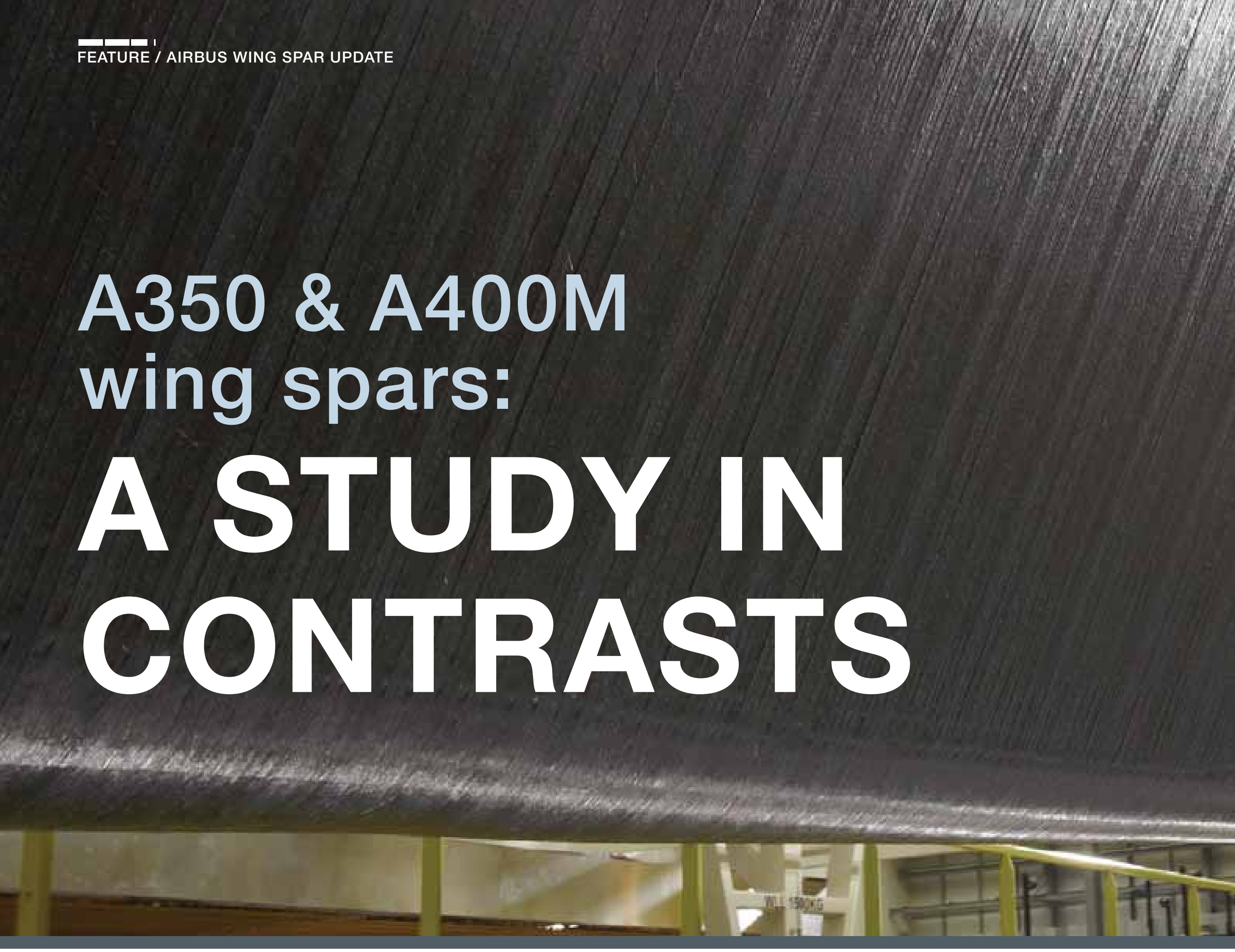
Composite Materials Handbook Volume 4: *Metal Matrix Composites* includes properties on metal-matrix composite material systems for which data are available that meet the specific requirements of the handbook. In addition, it provides selected guidance on other technical topics related to this class of composites, including material selection, material specification, processing, characterization testing, data reduction, design, analysis, quality control and repair of typical metal-matrix composite materials.

The second new volume, *Composite Materials Handbook Volume* 6: *Structural Sandwich Composites*, updates the cancelled *Military Handbook* 23, which was prepared for use in the design of structural sandwich polymer composites, primarily for flight vehicles. The information in the volume includes test methods, material properties, design and analysis techniques, quality control and inspection and repair of sandwich structures in military and commercial vehicles.

CMH-17 provides guidance to those who design and fabricate end items from composite materials, and includes properties of composite materials that meet specific data requirements as well as guidelines for design, analysis, material selection, manufacturing, quality control and repair. SAE International published the first three volumes in July 2012:

- *Volume 1: Polymer Matrix Composites: Guidelines for Characterization of Structural Materials*
- *Volume 2: Polymer Matrix Composites: Materials Properties*
- *Volume 3: Polymer Matrix Composites: Materials Usage, Design, and Analysis*

To purchase *CMH-17* volumes, visit www.cmh17.org/resources.aspx.



A350 & A400M wing spars: A STUDY IN CONTRASTS

In three short years, GKN Aerospace has taken its composite wing spar manufacturing strategies to new heights by dramatically reducing part weight, process complexity and production-cycle duration.

BY BOB GRIFFITHS

The GKN Aerospace (Filton, U.K.) factory in the Western Approach of the U.K. is dedicated to wing spar manufacturing. It produces the front and rear spars for the Airbus A400M military cargo transport and the rear spar for the Airbus A350. *HPC* covered A400M spar manufacturing in 2006, when it was produced at GKN's site on the Isle of Wight, U.K. (see "Learn More," p. 31). Since then, A400M spar production has been transferred to the new dedicated spar facility in Western Approach (see far right photo, p. 27) to take advantage of synergies with the A350 spar operation and benefit from close proximity to the Airbus wing design center in Filton. As the first flight of the A350 drew near this year, *HPC* visited the facility to get an update on GKN's process for the A350 spar.

The A400M and A350 spars: Different by design

Wing spars can be thought of as simple tapered C-shaped channels that make up the front and rear of the wingbox. But this is an oversimplification, because it ignores the hidden complexities of the wing design. First, there is the shape of the wing, dictated by aerodynamic, structural and ground-clearance requirements. Close examination of the A350 spars reveals that the inner spar has a very significant curvature. This is because the A350 inner wing is formed into a curved gull-wing shape. By contrast, the A400M's wing is virtually straight, making the spar a simpler shape to manufacture (see photos, top of p. 28).

The structural issues add further complexity to the spar layup, due to the very high load inputs that occur at various

Automatic fiber placement machine with spar mandrel

The A350 wing spars are built up in one step by automated fiber placement on a rotating mandrel, yielding two net-shaped parts — port and starboard spars — simultaneously.

Source: GKN Aerospace

Source: Airbus/Photo: e'm company/P. Pigeyre

Source: GKN Aerospace

Specializing in wing spars

The GKN Aerospace (Filton, U.K.) factory (photo, far right) in the Western Approach of the U.K. produces the front and rear spars for the Airbus A400M military cargo transport and the rear spar for the Airbus A350 (above).

points along the length of the spar. Attachments points for the engines, main landing gear (on the A350 only, because the A400M has a fuselage-mounted main undercarriage), flaps and other control surfaces require localized increases in laminate thickness at the attachment points. In other attachment areas, sacrificial woven carbon is added under attachment points or, if the attached component is aluminum, a layer of woven glass is added.

The length of the A350 spar is considerably longer, at 34m/111.5 ft, than the A400M spar, which measures only 19m/62.3 ft long. Further, the A400M spar is made in two sections, but the A350 spar is made in three. ◘

Source (both photos): GKN Aerospace

A350 and A400M spars: *Vive la différence!*

The A350 and A400M spars, designed five years apart, reflect some significant differences. The A350 spar (above) is more complex, with an optimized design that reduces weight. Made in three sections rather than the A400M's two, and curved where the A400M spar is straight (photo at left). The A350 spar, however, requires less time and fewer manufacturing steps.

Source: GKN Aerospace

ATL for the A400M spar

The A400M spar is layed up over a flat tool on this TORRESLAYUP automatic tape laying (ATL) machine, supplied by MTorres (Torres de Elorz, Navarra, Spain).

The manufacturing strategies for each spar also differ, for several reasons:

- There were five years between the launch of the two programs; during that period the automation of prepreg layup by automated fiber placement (AFP) made major progress.
- The customer changed the material specification from a conventional toughened epoxy to the latest-generation interlayer toughened epoxy.
- The shape of the A350 spar is much more complex.
- A more optimized design was desired in the A350 spar; weight savings in commercial applications is now a greater priority in a time period in which fuel savings have grown in importance.

ATL vs. AFP

The manufacturing processes for the spars reflect their differences. The A400M spar is made by automatic tape laying (ATL) of carbon fiber over a flat tool (see bottom photo, this page). The ATL is supplied by MTorres (Torres de Elorz, Navarra, Spain). This flat pack of unidirectional material is then hot-drape formed (see photo, p. 30) to the final shape over a male tool. Then, the shaped laminate is transferred to a female Invar tool for final cure. By contrast, the A350 spars are built up in one step by AFP on a rotating mandrel, yielding two parts (port and starboard spars) in their net shapes at the same time (see opening photo, p. 26).

The A400M spar is made from Cytec (Tempe, Ariz., and Wrexham, U.K.) 977-2 carbon fiber prepreg, a material commonly used in military aircraft. The A350 spar is made from Hexcel (Stamford, Conn.) M21E/IMA, a much tougher prepreg system than older materials. The greater toughness is the result of a prepreg manufacturing technique that concentrates the toughening agents *between* the plies, rather than uniformly distributing them throughout the matrix. Notably, this material is the standard prepreg for all structural parts on the A350.

Given the increased complexity of the spars' geometry and the drape-forming difficulties presented by this new generation of prepregs, GKN concluded that AFP was the lowest-risk option. This decision was made all the more easy by the continuing improvement in AFP laydown rates and the ability of AFP to optimize the structure by using a more complex ply layup than can be achieved with ATL.

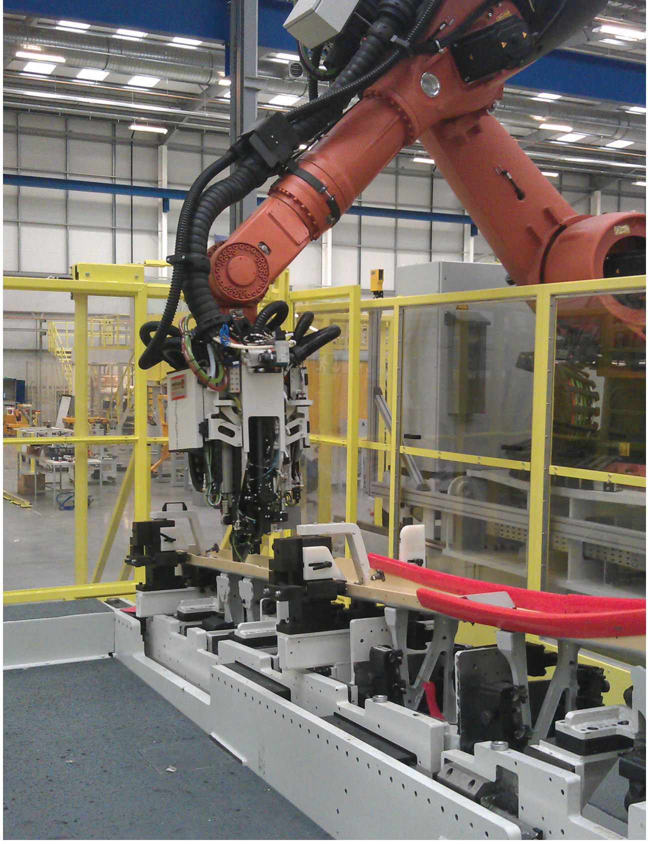
The A350 spar: Layup and molding

Although the most obvious production improvements are seen in the layup and tooling of the A350 spar moldings, much of the novel production engineering has been applied to the machining and assembly processes.

The A350's C-section spar's three segments average 11.5m/37.7 ft in length, with a thickness of 25 mm/0.08 ft at the root end, which tapers to just 5 mm/0.020 inch at the wing tip of the outermost segment. Their size and weight is difficult to convey in words and dimensions. To put it in perspective, the average person could lift one end of the outer spar.

The A350 spar is layed up on CFRP mandrels placed in an AFP machine, also supplied by MTorres. GKN intends to have five of the machines in production; three have been delivered (at €5 million/$6.76 million each), and two more are on order. As noted, two spars are layed up simultaneously. One might have expected material at 90° and 45° to have been placed *continuously* around the mandrel, from one spar onto the adjacent spar. However, GKN takes advantage of the machine's ability to cut and restart each tow independently. Thus, the spars are built up separately, with a small gap between them. This eliminates a cutting step, minimizes material waste, affords greater design freedom, yields a more fully optimized ply layout and reduces the weight of the spar.

The hollow carbon fiber mandrels were designed and manufactured, and the materials were supplied, by Umeco (Heanor, Derbyshire, U.K.) — now part of Cytec Industries and doing business as Cytec Industrial Inc., a division of Cytec Engineered Materials Inc. (Tempe, Ariz.). Stiffness was a major challenge, with a


Source: GKN Aerospace

Automated drilling for fasteners

The A350's middle and outer spar sections — thinner, with lighter fittings than the inner — are drilled for fasteners at a robotic station like this one, where a total of 16,000 holes are drilled per wingset.

Source: GKN Aerospace

Hot-drape forming system

The layed up flat pack of unidirectional material for the A400M spar is formed to final shape over a male tool on this massive hot-drape forming machinery.

requirement of 0.5 mm/0.020 inch or less deflection under a load of 150 kg/331 lb. At the same time, weight targets had to be met; for the inner mandrel, the weight is 4 metric tonnes (8,818 lb). The machine limit was 5 metric tonnes (11,023 lb), due to inertia issues related to the mandrel's rotation speed, which varies depending on whether it is laying a flat area, going around a corner or cutting a ply. To accelerate and decelerate, the machine has to fight the inertia of the mandrel, which is governed by the weight and the shape — the latter being fixed by the design of the wing. Thus the weight and the stiffness requirements drove the mandrel design to CFRP.

A big improvement in processing time has been achieved by reducing the number of consolidation cycles required when laying up the innermost spar. In April 2011, consolidation required *many* cycles. During each cycle, the mandrel and partial layup temperature was elevated using a large (about 13m by 1m/42.7 ft by 3.28 ft) bank of infrared heaters. Then a cylindrical vacuum bag, stored at the end of the mandrel, was pulled over the laminate and vacuum was applied. This was necessary, at the time, to deliver the low void content demanded by Airbus. But today that repetitive procedure has been displaced by a *single, room-temperature* vacuum consolidation after the *entire* laminate is layed up.

The finished laminate is transferred from the mandrel to a female Invar tool for curing, using vacuum lifting equipment. The A350 spar is cured in one of two autoclaves, both 16m by 3.5m (52.5 ft by 11.5 ft), with a standard cycle time of 10 hours, including ramps. This cycle time is used on all spars because the difference between the spars, in terms of mass, is insignificant compared to the *tool's* thermal mass. Two spars are cured at the same time, except for the inner spar, which is done on its own. Two autoclaves meet the needs for the production rate, assuming a 30-minute load and unload at the beginning and end of each cycle.

The molded spars are machined in a double-headed tool provided by Flow International (Kent, Wash.). A waterjet is used to cut the spar profiles, and a conventional machining head (24,000 rpm) is used to reduce thickness in critical areas. For example, there is a ±0.25 mm (±0.010 inch) tolerance on the spar height. To avoid cutting structural fibers, sacrificial woven carbon fiber is added in a separate, manual operation, using laser ply positioning to ensure accuracy. Then the area is machined to tolerance. Sacrificial layers are bonded with colored film adhesive so technicians can see if the structural plies are cut. Woven glass, instead of carbon, is used where aluminum fittings will be attached.

Finally, the spars are subjected to nondestructive inspection (NDI) using an ultrasonic machine of the latest phased-array type, from GE Inspection Technolo-

gies (Lewistown, Pa.). The device reportedly spots defects down to 6 mm^2 (0.009 in^2) in 20 percent of the time taken by conventional NDI technologies. (See also "Nondestructive testing: Better faster and cheaper" in this issue, on p. 32.)

Drilling and assembly

Beyond spar manufacture, GKN also performs a large number of assembly operations. First, a small number of brackets are manually installed in the inside of each spar. This facilitates mounting the spar onto a fixture to transport it around the automated assembly workshop. The spar, with its fixture, is moved on a manually guided vehicle (MGV) to the first station of the assembly process.

Inner spars, which are thicker and have heavy metallic attachments for the undercarriage and flaps, are first taken to a large 5-axis machining center that drills holes through the composite parts and the metallic fittings. From there, the holding fixture and inner spar are transported to a station where fasteners are fitted. The middle and outer spars, which are thinner and have lighter fittings, also are taken to a robotic station where all the holes are drilled. Altogether, on a set of six spars required for one aircraft, a total of 16,000 holes are drilled. (See photo of robot with drilling head on p. 29.) Then the fixture and spar are moved to a second robotic station that applies the fasteners after all the fittings have been located in the fixture.

The three spar sections, still on their holding fixture but with all their attachments fixed, are finally brought together for joining, using the data points on their fixtures. The joints feature flat, butterfly-shaped CFRP plates on the outside and inside of the web, plus angled plates that join the inside of the flanges and radius.

However, the surfaces that will be bolted together do not align perfectly, due to slight variability in spar thickness, which is due, in turn, to variations in prepreg material thickness and slit tape width. The solution is to measure these surfaces using photogrammetric equipment supplied by Steinbichler Optotechnik GmbH (Neubeuern, Germany). An optical device, held in the hand of a robot, collects data that is sent to a machining center, supplied by HG Grimme SysTech GmbH (Wiedergeltingen, Germany), which is located adjacent to the joining fixture. In the machining center, the plates are modified to ensure that any offset in the surfaces to be joined is produced in a mirror image on the surface of the joining plate. The custom plates are then used to join the spar's three sections.

After they are successfully secured, these joints are temporarily undone to make the spar easier to transport to an Airbus facility in Broughton, U.K., where the wing is assembled. ■

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Read more about the A400M spar manufacturing process in "Composite wing spars carry the western world's biggest turboprop engines" in *HPC* July 2006 (p. 60) or visit http://short.compositesworld.com/xWb2fEle.

Nondestructive inspection: BETTER, FASTER AND CHEAPER

Source: iPhoton Solutions

Faced with new time and cost pressures, NDI system suppliers are integrating inspection with manufacturing to reduce its share in part cost and cycle time.

BY MICHAEL LEGAULT

Innovation is often a result of the push and pull of market forces: new products or applications that push forward in one industry can pull in their wake significant technological innovations in a closely related field. Such is the case with nondestructive inspection (NDI) technology. Historically slow and costly, NDI accounts for as much as *25 percent* of the cost of manufacturing high-end aerospace parts. These costs were viewed as an unpleasant necessity and could be absorbed in big-budget, cost-plus military programs. But the advent of the Boeing 787 *Dreamliner* and Airbus A350 programs sparked rapid expansion of the commercial aircraft composites market, where production deadlines and price points are much less forgiving. The aerospace composites manufacturers who serve the commercial aircraft market are seeking more efficient, cost-effective inspection. And in response, NDI systems suppliers are working with customers to commercialize systems that incorporate entirely new approaches or step changes that represent significant improvements in utility, speed and cost.

Robotized NDI for complex geometries

A number of companies are supplying equipment and services for what is the first large-scale, industrial implementation of a new type of NDI, called Surface-Adaptive, Phased-Array Ultrasound, or

Robot automates ultrasonic NDI for greater efficiency

Airbus Nantes (France) and EADS Innovation Works (Ottobrunn, Germany) are currently in the process of qualifying LUCIE, a new noncontact NDI system, which uses the iPLUSIII laser ultrasonic inspection technology, supplied by iPhoton Solutions. Equipped with a 6-axis robot from KUKA (Augsburg, Germany, and Shelby Township, Mich.) mounted on linear rails, the system has the capability to penetrate more than 6m/19.7 ft into the interior of an aircraft fuselage.

Surface-Adaptive ULtrasound (SAUL) for short. SAUL integrates robotics and ultrasound scanning, and uses a unique, surface-adaptive algorithm to conduct faster, more accurate inspections of composite parts that have complex shapes and sharp radii. SAUL enables, for the first time, the inspection of curved parts with a single, flat multi-element matrix probe. Contour Dynamics Inspections Systems (Lévis, Quebec, Canada) is the system designer, integrator and manufacturer. One unit already is installed at EADS Composites Aquitaine (Salaunes, France) and has been used to inspect several shipsets of carbon fiber parts for the Airbus A350. Each shipset comprises several hundred parts with dimensions up to 700 by 200 by 200 mm (27.5 by 7.9 by 11.8 inches), with thicknesses of 1 to 9 mm (0.039 to 0.354 inch), and both convex and concave radii with curvatures that vary from 4 to 7 mm (0.157 to 0.276 inch). Defects of interest are delaminations greater than 6 mm (0.236 inch) in diameter and in-plane porosity greater than 2 percent — both are thresholds for part rejection. The goal is an average inspection time of four minutes or less per part. Although SAUL is now used to inspect relatively small, thin parts, it can be adapted to inspect larger parts, including long fuselage stiffeners and frame sections.

"The aerospace business has changed, and we have many more parts with complex shapes ... than we used to have," says Michel Brassard, a consultant who is under contract to Contour Dynamics to assist with the inspection implementation. "Today, NDI must become more fully integrated with the design and manufacturing process to meet requirements for efficiency and cost control."

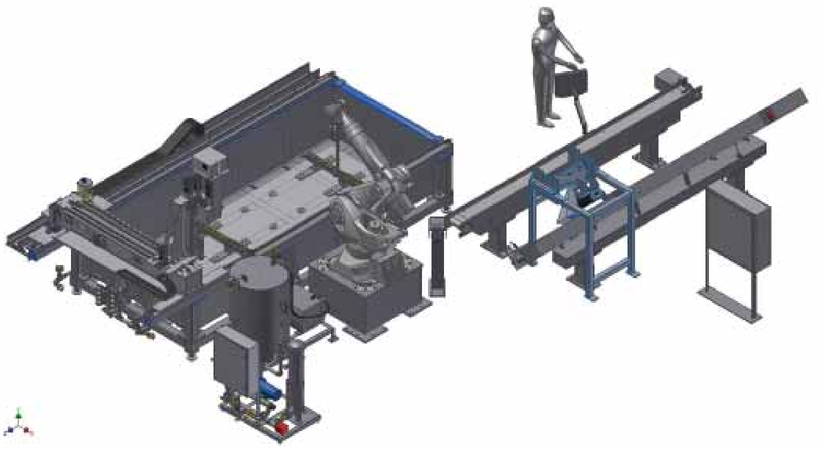
Adopting and adapting technologies

The SAUL technology now in use at the EADS subsidiary incorporates three distinctive functions, each intended to improve the efficiency of inspection and reduce the overall cost by more fully integrating it into the manufacturing process, which includes provision for part recognition, automated part placement and removal, and robotic ultrasonic scanning incorporating surface-adaptive software. SAUL incorporates nine essential pieces of equipment (see diagram, this page):

- Two conveyors for loading and unloading parts, and a part rotator.
- A 5-axis robot supplied by KUKA (Augsburg, Germany, and Shelby Township, Mich.).
- Two cameras for part shape recognition and bar code identification.
- A 5-axis robotic immersion scanner (4.5m by 1.9m by 0.8m/14.8 ft by 6.2 ft by 2.6 ft) built by Contour Dynamics Inspection Systems (Levis, Quebec, Canada, and Wichita, Kan.).
- A 3-D SINUMERIK contour controller supplied by Siemens (Munich, Germany, and Alpharetta, Ga.).
- A 2-D, phased-array, multi-element matrix probe supplied by IMASONIC (Voray sur l'Ognon, France).
- A 64-channel MultiX, ultrasonic phased-array controller with SAUL surface-adaptive software supplied by M2M (Les Ulis, France).

Prior to inspection, the CAD drawing for each part (drawn in CATIA, from Dassault Systèmes, Vélizy-Villacoublay, France), is imported into Mastercam path-generating software (from CNC Software, Tolland, Conn.) to generate a scan plan. The geometric design data for each part is converted into CNC codes, which, via the SINUMERIK controller, direct the 5-axis scanner during inspection. Thus, the scanning plan is much like the tooling paths generated from the CAD drawings that are imported, via a CAM system, into CNC-machining systems. During the implementation, but prior to actual inspections, Contour Dynamics and EADS carried out extensive testing, checking and fine-tuning the scan paths to ensure that the efficiency and quality of the inspection were optimized.

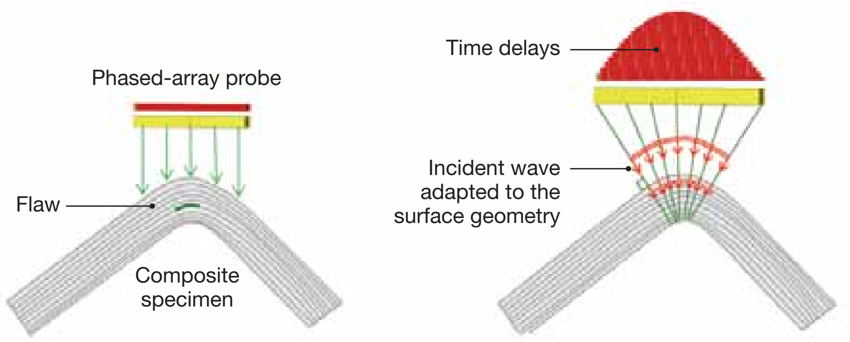
During operation, the robot retrieves a part from the feed conveyor and presents it to the digital cameras, which identify the part by the Datamatrix 2-D bar codes on the part's surface. Each bar code corresponds to a part number that is, in turn, categorized or coded by shape. The part shape determines, via internal programming, specifically where the robot will place it on the inspection table within the immersion tank. There are two inspection tables, or zones, located at each end of the tank. Within each table there are six subzones, each of which accommodates parts in a variety of generic



Source: Contour Dynamics Inspection Systems

Commercial application for commercial airliner

Contour Dynamics has completed the first industrial implementation of its automated Surface-Adaptive Ultrasound (SAUL) system at EADS Composites Aquitaine (Salaunes, France), where it is used to inspect CFRP parts for the Airbus A350. A 5-axis robot retrieves parts from a feed conveyor and places them on one of two inspection tables within a water-filled immersion scanner. An iterative, surface-adaptive algorithm programmed into the phased array controller allows, for the first time, the inspection of curved parts with a single, flat matrix probe.



Source: BERCLI Corp.

Algorithm enables shape-corrected scans

For the surface-adaptive ultrasound inspection technique, the specimen shape is measured from the front-surface echoes, and then an iterative algorithm is applied to adapt the time delays in real time to obtain normalized, shape-corrected scans.

shapes. The robot places the part on suction cups in the correct zone in the tank (±0.2-mm or ±0.010-inch accuracy), then the 5-axis scanner moves into position to commence scanning. Meanwhile, the robot moves to another zone to retrieve the part that the scanner has finished scanning, places it on the output conveyor, picks up a new part and repeats the cycle.

Several technologies were adopted and optimized for use in SAUL. Chief among them is M2M's integration of the surface-adaptive algorithm into its ultrasonic phased-array controller. The patented technique was originally developed by the Commissariat à l'énergie atomique (CEA) in France for systems used to inspect the steel walls of reactors, containment vessels and other components in nuclear power plants.

The alternative to SAUL is to use *curved* arrays to inspect parts with complex shapes, such as hat stiffeners and stringers, that include convex and concave radii. This approach is problematic, however, because it requires extremely precise and consistent positioning of the probe along the entire length of the part to obtain valid measurements. Unfortunately, the slight part-to-part variability associated with composites manufacturing can pose a challenge to the precise positioning of curved arrays when parts are inspected in high volumes. That's why SAUL, by means of its incorporated algorithm, uses a single *flat* matrix probe (located at the end of the 5-axis immersion scanner), comprising an array of 4 by 16 ultrasonic elements.

The M2M controller includes all the electronics needed to generate the electrical pulses to the probe's elements, calculate and apply time delays to the elements to focus, steer and electronically scan the ultrasonic beam, receive the return signals and process and display the data. When SAUL is applied, the elements of the probe are fired in transmission without focusing, and the shape of the specimen is measured from the front-surface echoes. Next, an iterative, algorithm-controlled process is applied that calculates time delays in real time, adapted to the part geometry to transmit an incident wave that is normal to the surface (see diagrams at left). The system records and displays time-of-flight and amplitude data in both B-scans (vertical cross-sections through the specimen) and C-scans (horizontal or top views though the specimen). Raw amplitude vs. time data is translated into 2-D and 3-D images.

The ability of the surface-adaptive algorithm to compensate for changes in surface geometry was demonstrated in a series of tests conducted prior to the implementation of the SAUL inspection system at the EADS facility. In one experiment a conventional curved ultrasonic array was precisely positioned over a carbon fiber composite bike steering column, which contained release film discs in the laminate to simulate delamination defects of less than 0.25, 0.25, 0.5 and 0.75 inch (less than 6.35, 6.35, 12.7 and 19.05 mm) in diameter (see image at lower left). As long as the position of the probe with respect to the curvature of the tube was maintained precisely (i.e., normal to the surface) good results were obtained in the B-scans and C-scans (See images on p. 35). Shifting the probe by 3 mm/0.12 inch in any direction, however, resulted in loss of signal. With the probe in the shifted position, the surface adaptive algorithm was turned on. This restored the signal *and* matched the resolution of the scans obtained when the probe was positioned correctly.

Although no formal tests have been run to compare the efficiencies and inspection costs achieved by SAUL with those obtained by conventional phased-array or other NDI methods, Deborah Hopkins, CEO of M2M's U.S. distributor, BERCLI Corp. (Berkeley, Calif.), says the surface-adaptive technology provides a number of clear benefits. For example, the use of conventional phased-array ultrasonic methods to inspect a single hat stiffener would require a minimum of five arrays — two curved arrays at the radii and three flat arrays for the top and sides. Additionally, the mandate for precise positioning of the probes, and part-to-part variability, usually requires much manual tweaking of fixtures, software and scan plans, which adds more time and cost.

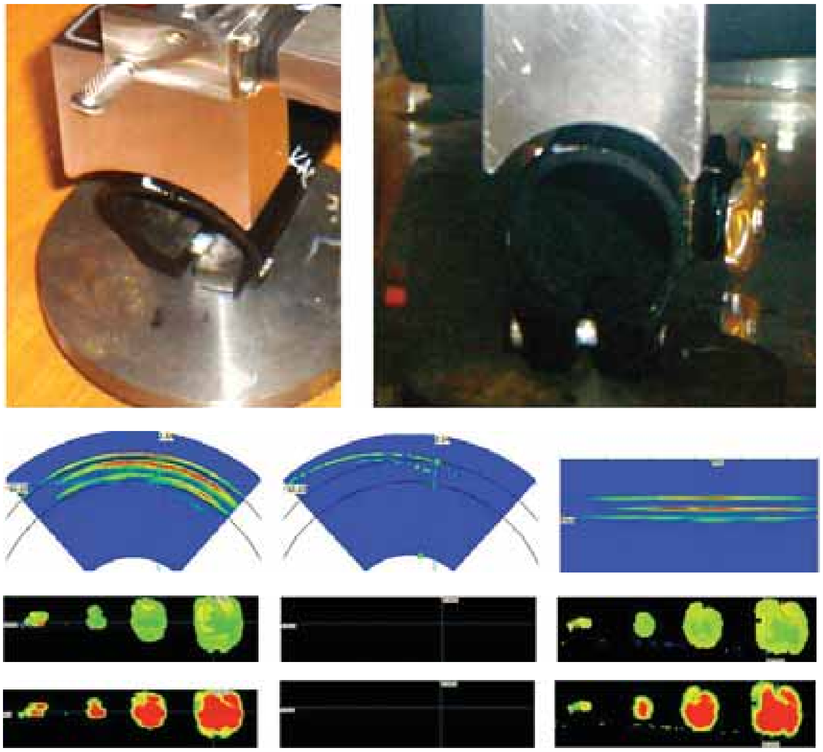
Hopkins claims the integration of the surface-adaptive software into ultrasonic inspection is a boon for the aerospace composites industry. "The technology is not trivial, and the real trick is to do it

Source: BERCLI Corp.

Simulated defects for testing

A carbon-fiber bike steering column tube was molded with release film discs (above) to simulate delaminations of <0.25, 0.25, 0.5 and 0.75 inch in diameter (see photos, p. 34).

on the fly, in real time," she says. "It's a dream come true for designers and manufacturers because now you can truly optimize strength-to-weight on a centimeter to centimeter basis, *and* efficiently inspect the part you've built." Thus far, the program is exceeding its inspection time goal of one part every four minutes, with an actual inspection rate of one part every 2.5 minutes.



Source: BERCLI Corp.

Curved array test results

To demonstrate the surface-adaptive algorithm's ability to compensate for changes in surface geometry, a curved ultrasonic array was precisely positioned over a bike steering column tube (top left and bottom left images), then offset by 3 mm (top right). When the array was moved, the B-scan signal was lost (bottom center), but the surface adaptive algorithm, when applied to the ultrasonic array, restored the signal (bottom right).

Laser ultrasonics gaining commercial acceptance

Like phased-array ultrasonic imaging technology, *laser* ultrasonic inspection systems have been on a development curve that has spanned several decades. In the 1990s, Tecnar Automation Ltée (St-Bruno, Quebec, Canada) became the first licenser of large-scale, commercial, industrial laser ultrasonic technology used for inline wall-thickness measurement of seamless steel tubes. Lockheed Martin is credited with commercializing the first laser ultrasonic NDI test system for composite part inspection. Today, the technology, as it pertains to composites, is closer to new applications in the commercial aerospace market. Companies that sell laser ultrasonic units for composite component inspections include Tecnar, iPhoton Solutions (Fort Worth, Texas) and PaR Systems (West Shoreview, Minn.), which took over the technology developed by Lockheed Martin (Bethesda, Md.) for the F-35 Joint Strike Fighter program.

In a generic configuration, a laser ultrasound device comprises two lasers. One is a *short-pulsed* laser that generates an ultrasound wave in the surface of the composite material; the second is a single-frequency, high-coherence-length beam focused on or near the point of impact of the generation beam on the surface of the material. Any ultrasonic surface displacements that occur are encoded as frequency or phase variations in the reflected or backscattered light and are then converted into pulse-echo signals by an optical interferometer.

The principal advantage of laser ultrasonic inspection is that the generation laser beam does not need to be perpendicular (90°) to the material surface. The angle of incidence can, in fact, be as great as 45°. The inspection point (where the two lasers meet on the part surface) is indexed point by point over the material with an optical scanner to produce 2-D and 3-D ultrasonic images of the material. Because the scanner does not have to maintain a specific or consistent distance from the part surface, the system achieves inspection turnarounds on parts with complex shapes faster than those obtained with conventional, water-based ultrasound NDI systems that require upfront programming of the part shape into the scanner controller. Although laser ultrasonic NDI technology has been used in a variety of military and aerospace programs, including NASA's Space Shuttles, it has yet to be fully qualified for large-scale commercial airline programs.

Supplier iPhoton Solutions manufactures a line of three CO_2 laser ultrasonic NDI systems for composites inspection. The company's iPLUS III model is currently undergoing qualification trials at Technocampus (Pays de la Loire, France) as one of the key components of a noncontact NDI system called LUCIE (see opening photo, p. 32), developed in collaboration with Airbus Nantes (Nantes, France) and EADS Innovation Works (Ottobrunn, Germany).

Tommy Drake, iPhoton CEO, reports that the key differentiator of the company's patented NDI technology is the use of commercial off-the-shelf articulated robots mounted on linear rails to move and position the optical scan head, rather than a large custom gantry robot like those employed in other laser ultrasonic systems. Drake claims the integration of commercial robots reduces the system's footprint, installation foundation requirements, installation time and cost. The iPLUS III system for Technocampus' LUCIE has a 6-axis KUKA robot capable of penetrating more than 6m/19.7 ft into the interior of demonstrator fuselages now undergoing inspection as part of the program. Drake says the inspection rate of the system is about 64 ft^2/hr (about 6 m^2/hr). "A single inspection area

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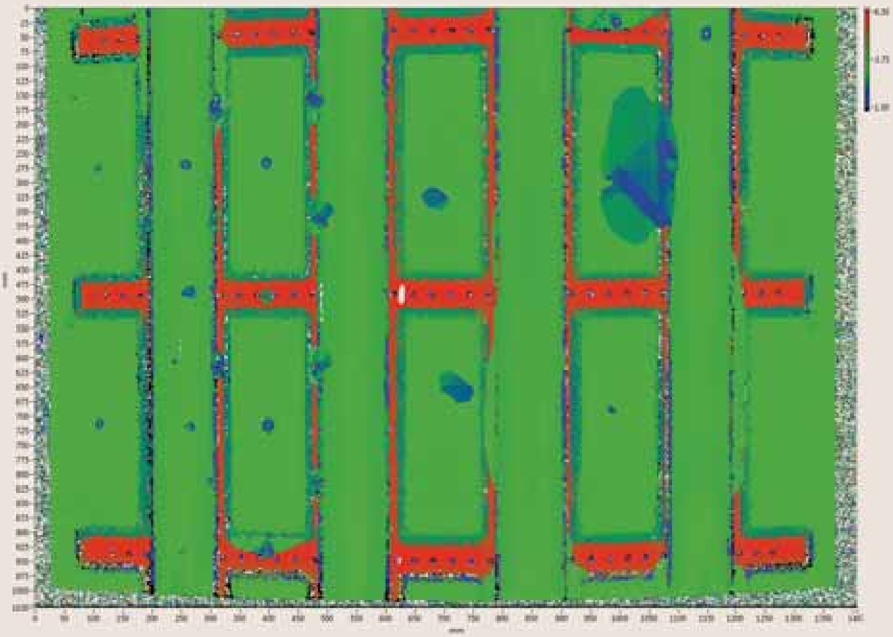
Source: Sandia National Laboratories



Hail impact test simulation

Sandia National Laboratories' (Albuquerque, N.M.) simulated hail impact on full-scale CFRP fuselage sections like this 56 inch by 76 inch (1,422 mm by 1,930 mm) panel. Time-of-flight (TOF) C-scans, conducted with an iPhoton Solutions' (Fort Worth, Texas) iPlusIII laser ultrasonic inspection system yielded images like the one at right: Round blue areas correspond to ply delaminations. Smaller blue areas were created by steel-pin impacts, while the larger blue areas are caused by ice-projectile impacts.

can be fairly large, for example, 5 ft by 5 ft [1.52m by 1.52m], during which the robot remains stationary," he says. "The robot can then be indexed to another inspection area."

Clay McConnell, VP communications at Airbus North America (Herndon, Va.), says the benefits of LUCIE compared to other NDI systems (including those equipped with ultrasonic phased arrays) are the elimination of the coupling media (water) and programming and tooling associated with keeping the scan head in precise position relative to the surface.

McConnell says the validation program is on track, and researchers expect to complete the evaluation of the benefits (laser vs. other ultrasonic systems) in 2014. "We need first to understand the way the laser interacts with each specific carbon fiber laminate used in the manufacturing of Airbus aerospace parts," he says. "After this qualification process, there will, of course, be other activities to improve the performance of the technology — scanning speed, quality of signal, etc."

Recently, iPhoton inspected composite test panels subjected to impact testing for the Federal Aviation Admin.'s (FAA) Airworthiness Assurance NDI Validation Center at Sandia National Laboratories (Albuquerque, N.M.). Tests performed by Sandia's Infrastructure Assurance and Non-Destructive Inspection Dept. will produce data that will be used to evaluate a variety of NDI technologies.

Sandia fabricated two full-scale carbon-fiber fuselage sections, approximately 56 inches by 76 inches (1,422 mm by 1,930 mm). Each featured a 16-ply laminate and included cocured hat-section stringers and shear ties. The panels were fabricated from T800 unidirectional prepreg (Toray Composites America Inc., Tacoma, Wash.) and autoclave cured. The panels are representative of laminates used on transport-category aircraft.

Simulated hail impact testing was conducted on the panels using 2.4-inch/61-mm ice balls and 2-inch/51-mm diameter steel-tip impacts. Using its iPLUS III laser ultrasonic NDI system, iPhoton conducted a C-scan inspection of the first panel, the results of which are shown and explained at the top of this page. As *HPC* went to press, Sandia was completing its testing report. However, iPhoton presi-

SIDE STORY

ABCs of ultrasonic inspection

Conventional (non-laser induced) ultrasound (UT) is generated by an element (transducer) made of a piezoelectric material that converts an electrical pulse into a mechanical vibration, which, in turn, induces ultrasonic waves in a test specimen. Any time there is a change in acoustic impedance — such as occurs with a delamination or void — some of the acoustic energy is reflected. The waves that are reflected back to the transducer are converted into a raw electrical signal, measuring amplitude vs. time (think of a seismogram).

For phased-array systems, the probe is composed of multiple elements, which can independently transmit and receive. Time delays are applied to different elements of the probe to focus, steer and scan the beam across the surface. "In the medical field, you can get most of the transmitted ultrasonic energy into our bodies because we are mostly water, but because there is little change in impedance, signal post-processing is often necessary to obtain high-resolution images," says Deborah Hopkins, BERCLI Corp. (Berkeley, Calif.). "With composites, the issue is strong attenuation caused by inhomogeneity and anisotropy of the material, so you lose energy as a function of distance traveled." Hopkins says most phased-array ultrasonic applications operate in the range of 2 to 15 MHz.

dent Marc Dubois reports the total time for the inspection was about 45 minutes, which included preparation, and the data was considered of the highest quality.

Dubois says that iPLUS systems could appear in production facilities within two years, noting that the time span is due to the fact that the process for new technology approval on commercial aircraft can be more difficult than for military programs. “It takes a lot of time and effort to get a new technology qualified,” Dubois says, but adds, “It’s worth it, because we think our technology can reduce inspection cost by a factor of 10 for complex parts.”

In October 2012, Tecnar entered into an agreement to assist the Beijing Aeronautical Manufacturing Technology Research Institute (BAMTRI, Beijing, China) as it develops a knowledge base in laser-ultrasonic composite inspection.

“Because BAMTRI is a research institute, they are not looking for an industrial system, such as our Laser Ultrasonic Inspection System (LUIS), but rather at smaller laboratory-scale systems we offer, such as the TWM model,” says Marc Choquet, Tecnar’s VP, Laser-NDE. He continues, “We are still in the initial stages of the agreement and exchanging information and looking for funding.” Also in 2012, the company delivered its first industrial-scale laser ultrasonic NDI system, LUIS-2, to the Centre Technologique en Aérospatiale (CTA, Saint-Hubert, Quebec, Canada), which collaborates with aerospace industry on research projects.

Jacques Blain, Tecnar’s VP of systems and technology, reports that the company has taken a different approach in the design of the CTA’s LUIS-2 model. Blain says that when the laser is scanning at angles of incidence greater than 30°, the analysis of the resulting signal for defects, such as porosity, can be problematic. “When scanning a surface, and the laser goes, say, from 0° (perpendicular) to 30°, the absolute level of light intensity may vary easily by an order of magnitude,” he explains. At these higher angles, surface reflectivity and roughness have an effect on signal calibration, which needs to be renormalized as it moves across the surface. Instead of renormalizing signals, the LUIS-2 system is equipped with a small probe mounted on the robotic arm, and a scanning trajectory derived from CAD data is programmed into the robot. This keeps the laser beam in a near-normal configuration as it scans the part, *even on curved surfaces*. “It greatly simplifies the analysis of the signal,” Blain says, noting that many aeromanufacturers are uncomfortable with all the renormalization calculations performed during conventional laser ultrasonic scans.

The accelerated use of composites in aerospace, and the requirement that manufacturers inspect all parts before delivery, guarantees NDI a place in the aerostructures supply chain. But the speed and cost of manufacture are headed in opposite directions, which means that NDI systems must ultimately provide greater accuracy *and* efficiency. These have not been NDI hallmarks in the past, but suppliers are clear about the need and are developing systems that promise to reach those goals. ■

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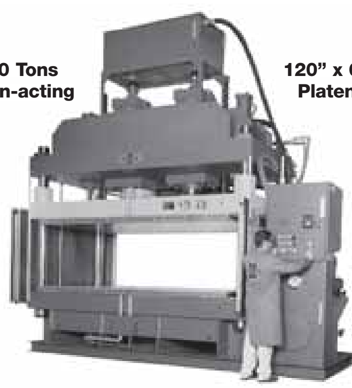


CERAMIC-MATRIX COMPOSITES HEAT UP

Lightweight, hard and stable at high temperatures, CMCs are emerging from two decades of study and development into commercial applications.

By Karen Wood

Into the hot zone … and beyond

Source: The Boeing Co.

In January 2013, a successful 73-hour jet engine test was conducted on a Rolls-Royce Trent 1000 jet aircraft engine, with a Huntington Beach, Calif.-based Boeing Research & Technology (BR&T)-built ceramic-matrix composite (CMC) acoustic exhaust nozzle installed, at NASA's Stennis Space Center (Miss.). CMCs are proving advantageous not only in engine hot sections but also in other applications previously dominated by superalloy metals.

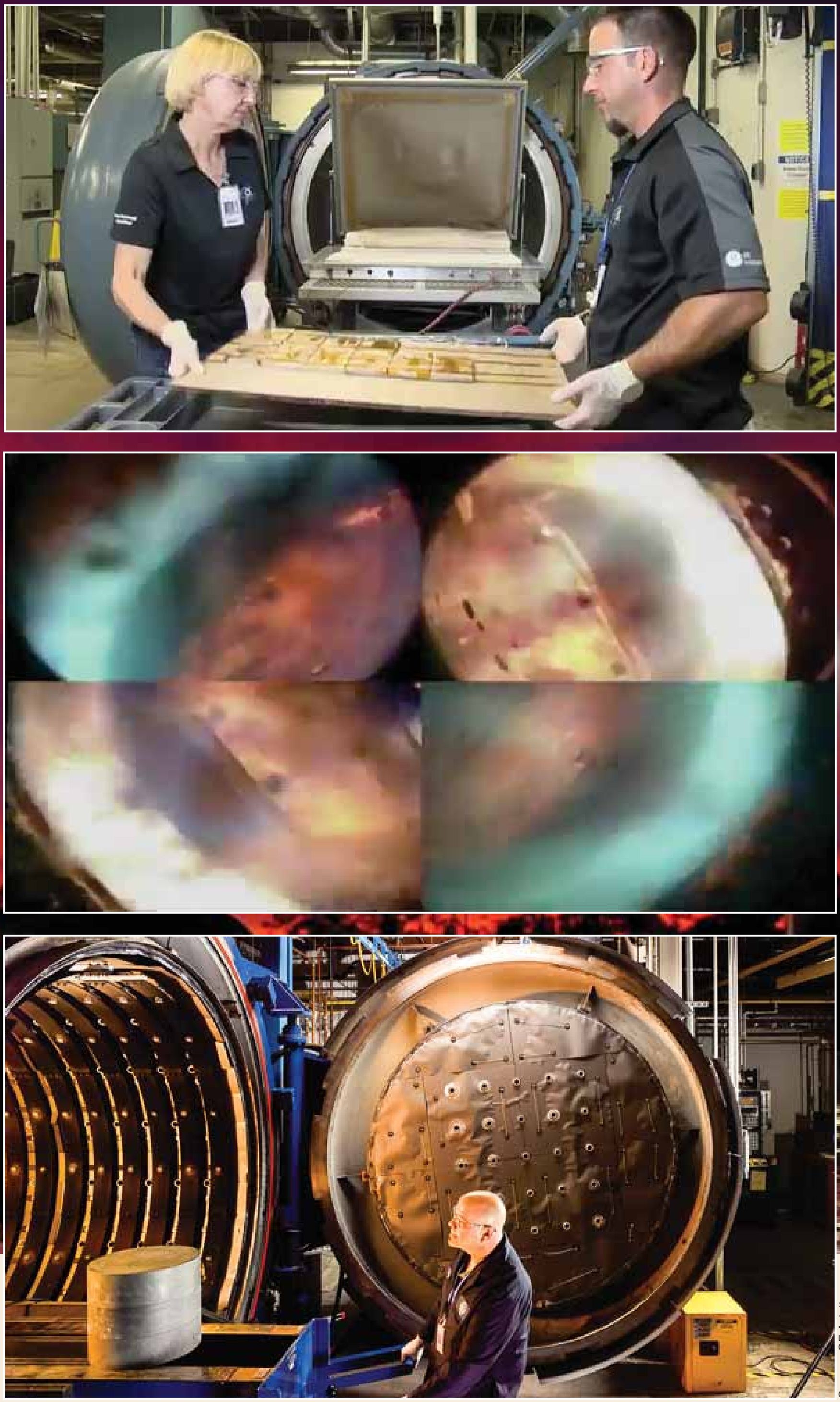
Ceramic-matrix composites (CMCs) comprise a ceramic matrix reinforced by a refractory fiber, such as silicon carbide (SiC) fiber. CMCs offer low density, high hardness and superior thermal and chemical resistance. That and their intrinsic ability to be tailored as composites make CMCs highly attractive in a vast array of applications, most notably internal engine components, exhaust systems and other "hot-zone" structures, where CMCs are envisioned as lightweight replacements for metallic superalloys.

Yet, despite more than 20 years of R&D, commercial successes for CMCs have been largely limited to missile structures, radomes and exhaust systems for fighter jets. Nevertheless, major development programs are currently underway, and there is growing investment in production-scale manufacturing. CMCs might well be at their tipping point.

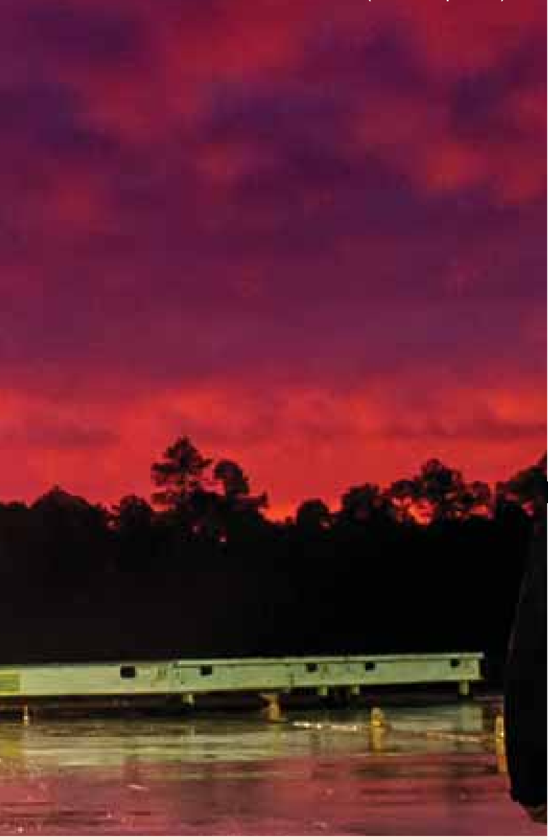
Today, CMCs can be produced using a number of fabrication processes: chemi-

ABCs of CMC production

During manufacture of CMCs at GE's Newark, Del. facility, the process begins much like any other composite, but after layups are cured in the autoclave (top photo), organic compounds are burned off (middle photo), leaving a near-net-shaped part made of porous ceramic-coated SiC fibers. These parts are then placed in a melt infiltration chamber where silicon is reacted with the remaining carbon to form the CMC (bottom photo).



Source: GE Aviation



cal vapor or liquid phase infiltration, hot press sintering techniques and polymer infiltration and pyrolysis (PIP). In addition, reinforcements can come in many forms: continuous fibers, short fibers, whiskers, particles or a combination. In fact, research has shown that low fracture toughness and crack growth resistance can be overcome through secondary reinforcement phases with particles, whiskers or even fibrous structures like nanofibers.

As an example of the latter, ANF Technology Ltd. (Tallinn, Estonia) is commercially producing a trademarked aluminum oxide nanofiber, called NAFEN, that reportedly can improve the ductility of CMCs, keeping Young's modulus high while increasing creep resistance and decreasing brittleness.

"Ceramics customers currently working with NAFEN are hoping for improvements in fracture resistance, impact toughness, abrasion resistance and structural reinforcement," says Tim Ferland, business development manager at ANF Technology. He reports that there are programs in place with several global accounts that are testing or planning to test the material with CMCs, although he adds that adoption of CMCs has been slow compared to the use of NAFEN

Source (both photos): COI Ceramics

Oxide CMC record-setters

The center body of the CMC exhaust nozzle molded for Boeing Research & Technology (BR&T, Huntington Beach, Calif.) is the longest oxide CMC part ever made (left), and the nozzle (the outer ring, above) is the largest diameter oxide CMC ever made.

in polymer composites and polymer paints and coatings.

"There's a lot of ground-swell activity going on, and as the industry becomes more knowledgeable about, and comfortable with, CMCs, the growth will continue," says Scott Richardson, general manager of CMC component manufacturer COI Ceramics Inc., an affiliate of space systems developer ATK (both in San Diego, Calif.).

According to Todd Steyer, a manager at The Boeing Co.'s Huntington Beach, Calif., operation, factors behind the timeliness of CMC development include stable properties and increased production volumes of ceramic fibers (oxide and nonoxide), a maturing supplier base that is using established manufacturing processes, and good performance results from full-scale demonstrators and prototypes. Steyer, who reviewed aerospace-related presentations from the 4th International Congress on Ceramics in the American Ceramic Society's (ACerS) *International Journal of Applied Ceramic Technology* (July 2013), serves as vice chair of the U.S. Advanced Ceramics Assn.

In fact, the demand for CMCs is expected to increase *tenfold* over the next decade, according to jet engine and aircraft systems manufacturer GE Aviation (Newark, Del.). GE made its intentions regarding CMCs clear in June when it announced plans to build a $125 million, 125,000-$ft^2$ (11,613m^2) manufacturing plant in Asheville, N.C., to produce CMC engine components (see "Learn More," p. 45).

Many people view GE's move as a game changer for CMCs. "GE has done more than just *talk* about CMCs; it made a serious commitment," says Tom Foltz, director of business development of Specialty Materials Inc. (Lowell, Mass.), which manufactures SCS-brand silicon carbide fibers. "It could have as much of an impact as anything related to applications on the future of the technology," he adds. "GE is going to be leading and pulling everyone along with them."

CMCs in the "hot zone"

GE's Global Research Center (Niskayuna, N.Y.) and GE Aviation, with its pilot-scale production facility in Delaware, have been developing and producing CMC technology — both the material and the machines used in its manufacture — for more than 20 years. The company tested a CMC turbine blade in GE's F414 engine in 2010 and also ran CMCs in the hot section of its F136 engine. More than 1 million hours of testing have been logged, including more than 15,000 hours in land-based gas turbines that are generating electricity. The company believes the material is flight-ready.

SiC CMCs can withstand temperatures greater than 2400°F/1316°C. This and their reduced weight (*one-third* the weight of nickel superalloys) make them attractive to engine manufacturers that are looking for weight reduction in the engine hot zones in pursuit of greater fuel efficiency. Additionally, CMC components have greater durability and heat resistance and, therefore, require less cooling air than the nickel-based superalloys that currently dominate gas turbines and jet engines.

"Removing cooling air allows a jet engine to run at higher thrust and/or more efficiently," GE Aviation claims. "Incorporating the unique properties of CMCs on a turbine engine increases engine durability and reduces the need for cooling air. These gains improve combustor efficiency and reduce fuel consumption."

Today's high-efficiency jet engines emit hotter exhaust gas — hot enough to exceed the limits of traditional materials, such as titanium and superalloys. In jet engine propulsion history, the average rate of technology progress for turbine engine material temperature capability has increased 50°F/10°C per decade, according to GE. However, with the introduction of CMCs, GE believes it will increase material temperature capability by 150°F/66°C in this decade alone.

Currently, the CMC high-pressure turbine shroud (a stationary ring that encircles the moving blades on the second stage of the high-pressure turbine)

Source: The Boeing Co.

CMC on track to commercialization

CLEEN team members at The Boeing Co. (Seattle, Wash.) inspect a CMC nozzle prior to engine testing. The nozzle will soon be installed on a 787 *Dreamliner.* Flight tests are expected in late 2013, with service beginning in 2016.

for the much-publicized Leading Edge Aviation Propulsion (LEAP) jet engine has undergone more than 20,000 hours of testing. It could mark the first use of CMCs in a commercial engine. The LEAP engine is being developed by CFM International, a joint venture between GE and Snecma (a subsidiary of Safran, Courcouronnes, France). Its first flight is expected in 2016.

The use of CMCs reportedly allows GE to shed hundreds of pounds of engine weight and improve thrust by 10 percent. The CMC shroud weighs approximately 1 kg/2.2 lb — *one-third* the weight of an equivalent nickel superalloy shroud. In terms of design, the weight savings multiplier effect is much more than 3:1 because everything down the chain is affected as well.

GE froze the design of the first two versions of the LEAP engine in June 2012. The LEAP-1A for the Airbus (Toulouse, France) A320*neo* began ground testing in September 2013 and is on track to enter service in 2016.

GE also is studying the use of CMCs for a variety of applications beyond the LEAP engine, including a CMC turbine blade upgrade on the F414, which powers the Boeing F/A-18E/F *Super Hornet* and the Hindustan Aeronautics Ltd. (HAL, Bangalore, India) *Tejas* light combat aircraft. Within the 2016-2018 time frame, GE expects to mold up to 800 CMC components per day to meet *current* CMC commitments.

CMC acoustic nozzle

GE isn't the only company turning to CMCs for commercial jet hot zones. CMC components, including a turbine blade track and an acoustic engine exhaust nozzle, are in development as part of the Federal Aviation Admin. (FAA) Continuous Lower Energy, Emissions, and Noise (CLEEN) program. The five-year, jointly funded R&D effort is focused on airframe and engine technologies that speed the reduction of aircraft engine fuel burn, emissions and noise.

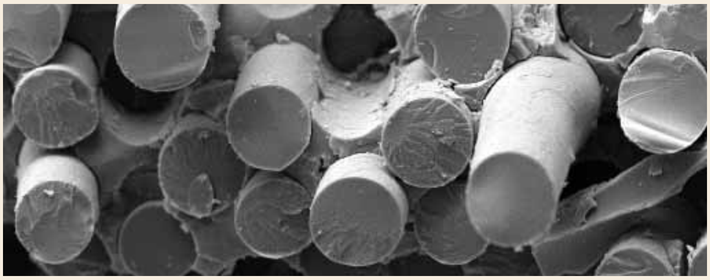
Boeing Research & Technology (BR&T, Huntington Beach, Calif.) has led development of the acoustic nozzle, which is designed to make engines quieter, lighter and more efficient. "The reason companies like Boeing have begun looking at alternative materials in the exhaust area is due to increasing temperatures," confirms ATK-COI's Richardson. "Existing material solutions may not be able to

Source: Lancer Systems LP

Precision & durability

This radial bearing with precisely machined lubricating grooves (left) was manufactured using CeraComp carbon-reinforced CMC, from Lancer LP (Allentown, Pa.), which reportedly prevents crack propagation. The bearing is targeted at down-hole drilling pumps. Lancer also manufactures CMC components for a variety of other markets, including weapon systems. Shown here (right) is a lightweight CMC rifle compensator with integrally threaded pressure vents.

Source (both photos): MATECH



CMC precursor

CMC supplier MATECH (Salisbury, Md.) is able to synthesize both SiNC (silicon nitro-carbide), shown here in spools, and SiC preceramic polymer and has scaled up its process to low-rate initial production. The preceramic polymer can be spun into green fibers and pyrolyzed into SiNC or SiC ceramic fiber. MATECH, which also weaves its own textiles, uses chemical vapor infiltration to manufacture CMCs in-house. A photo micrograph (SEM) shows the company's SiNC fiber in a CVI deposited SiC matrix.

meet thermal requirements in the coming years." Given that reality, Richardson says of the acoustic nozzle, "This is the largest component ever made in oxide CMCs, and marks a significant feat for CMCs."

Although BR&T conceived the vision and developed the design for the nozzle system, it contracted with ATK-COI to manufacture and deliver the two large CMC components that make up the nozzle. The outer ring, called the nozzle, measures approximately 5.25 ft/1.6m in diameter and is about 3 ft/1m long; the tail cone, which sits inside the front end of the nozzle, is approximately 7 ft/2.1m long (see photos, top of p. 40).

In terms of manufacturing, Richardson explains that he and his team look at the process *simplistically*. "It's generally akin to a polymer-based composite material in the front end," he explains. "Typically, you can use the same kinds of techniques in terms of forming — anywhere from hand layup to resin transfer molding." ATK-COI built the BR&T nozzle components using hand layup, after which the parts were cured. "That's typically where a polymer composite would be finished," Richardson notes. "In the case of CMCs, at this stage it must be converted to ceramic, which is done through either sintering or pyrolysis." In this case, ATK-COI used a sintering process.

The material system included a continuous filament alumina fiber (Nextel 610) from 3M (St. Paul, Minn.). ATK-COI mixes the matrix, or slurry, material in-house, and Boeing supplies the core material.

A major program milestone was reached in January 2013, when the nozzle was installed on the back of a Rolls-Royce (Reston, Va.) Trent 1000 engine rig at NASA's Stennis Space Center in Mississippi for accelerated testing (see photo, p. 38). The nozzle performed as expected during the 73-hour engine test, with no thermal or structural stress issues. In terms of service life, Richardson notes, the "specifications asked for 55,000 hours, which is what we tested to. Predictions indicate that the nozzle could continue in service well above that." The nozzle will be installed next on a Boeing 787 *Dreamliner*. Flight tests are expected in late 2013, with commercialization later this decade.

More CMCs ahead for engines

Elsewhere in engine development, specifically for narrow-body jets, Pratt & Whitney (P&W, East Hartford, Conn.), a United Technologies Corp., isn't as bullish about CMCs. The company has taken a decidedly different approach in handling thermal management, preferring to focus on the "advanced cooling" provided by its variable bypass engine, with adaptive fan design, and advances in nickel alloys. In fact, P&W has openly questioned the maturity of CMCs for aircraft engines and whether they will pay off in the short to medium term. Still, the company points to a long-term goal of resolving what it sees as "cost and reliability" issues with CMCs and believes the materials have the potential to enable gear-based turbofans to operate with greater fuel efficiency.

Rolls-Royce, on the other hand, has taken the plunge with its recent purchase of Hyper-Therm HTC Inc. (Huntington Beach, Calif.), which manufactures CMCs, such as C/SiC and SiC/SiC. "We expect CMCs will revolutionize the weight and performance of engines that currently rely on single-crystal super alloys found in today's most advanced engines," says John Gallo, Rolls-Royce North America's executive VP of operations.

Hyper-Therm has been working with CMCs for more than a decade. And although much of the current development and testing in CMCs has been

Source: Specialty Materials Inc.

SiC woven preform

Specialty Materials Inc. (Lowell, Mass.) manufactures a large SiC monofilament (SCS Ultra), which is shown here as a woven preform on the company's loom. Though the material doesn't lend itself to complex-shaped parts, it does offer high creep resistance at high temperatures.

done using small-diameter yarns (10 µm to 15 µm diameter), Hyper-Therm has collected considerable data on CMCs reinforced with a large-diameter silicon carbide monofilament, specifically SCS-Ultra, from Specialty Materials.

SCS-Ultra SiC fiber was initially designed for use in titanium aluminide metal-matrix composites, but it is reportedly effective in CMCs as well. Produced primarily in 5.6-mil diameters, SCS-Ultra contains very fine SiC crystallites (200 nm or less) and is stable at temperatures of 2500°F/1371°C and higher.

"A large monofilament like ours doesn't lend itself to complex-shaped parts," admits Specialty Materials' Foltz. "Yet, from a materials standpoint, we have the highest creep resistance at high temperatures of any SiC fiber." To date, the material has been used mainly to mold jet engine vanes and blades.

Notably, Hyper-Therm was contracted by the Marshall Space Flight Center (Huntsville, Ala.) to devise a cost-effective methodology for manufacturing axisymmetric CMC structures. This led to the development of the first-ever actively cooled, continuous fiber-reinforced SiC-matrix composite thrust chamber for liquid rocket propulsion systems. These devices are cooled with cryogenic liquid hydrogen to protect against combustion environments that are capable of reaching temperatures greater than 6500°F/3593°C. Hot-fire testing was performed at NASA Glenn.

CMCs for ultrahigh temperatures

For applications that face the most extreme environments — such as leading edges for hypersonic and supersonic vehicles that must withstand temperatures in excess of 2000°C/3632°F, corrosive atmospheric plasma and the shock of extreme temperature variations — typically nonoxide, ultrahigh-temperature (UHT) CMCs are required. Although much of the development work in the CMC industry has focused on oxide CMCs, nonoxides can be well suited for applications in solid rocket motor propulsion systems; missile structures and thermal protection systems; and profiles for hypersonic and supersonic vehicles.

"Whereas silicon-based or oxide CMCs are targeted at applications that require longer life (100,000 hours of cycle time and more), ultra-high-heat CMCs are employed where temperatures are much hotter but the mission durations are a lot shorter," explains Dr. Edward J.A. Pope, CEO of MATECH (Salisbury, Md.), a manufacturer of both oxide and nonoxide fibers and CMC components.

"Nonoxides are characterized by low porosity, wear resistance, high matrix density and extremely high-temperature capability," explains Bill Meiklejohn, president of Lancer LP (Allentown, Pa.). "They display the highest heat handling capability of all CMCs and derive much of their mechanical performance from the matrix," he adds.

"Our ultrahigh-heat CMC materials are designed for temperatures greater than 3000°F [1650°C] and reaching 5000°F [2760°C]," says Pope. "There aren't really many material systems of *any* kind that can withstand that temperature range, except for gas-heavy refractory metal alloys," he continues, "but those are heavy and can become ductile at the high-end of the temperature range. Plus, our

material has the advantage of being very lightweight in comparison." MATECH's nonoxide CMC's range from 2 to 3 g/cm^3 compared to 10 to 22 g/cm^3 for oxide CMCs.

The reportedly impressive qualities of UHT CMCs do come at a price. They are generally processed via chemical vapor deposition, and the raw materials can cost *10 times* as much as oxide-based systems, according to Meiklejohn. Nonoxide systems also require significantly *longer* processing times than oxide systems.

"We work primarily with the missile defense industry in ultrahigh-temperature applications," says Pope. Other UHT materials developed by MATECH include tantalum carbide (TaC) ceramic fiber and a hafnium carbide (HfC) ceramic fiber. Both are suitable for solid propellant rocket nozzles. The company also produces oxide materials and other CMCs for hot temperatures. With funding from the Air Force Research Laboratory (Wright-Patterson Air Force Base, Ohio), the company developed a stoichiometric SiC ceramic fiber, which is targeted at nuclear-fuel-clad tubes in light water reactors, gas turbine hot-section components and hypersonic leading edge materials. The company also produces silicon nitride/silicon carbide (SiNC) fibers that are melt spun in continuous 50- to 500-filament tow. Reportedly, the SiNC fibers have improved creep resistance and are chemically stable up to 1350°C/2462°F, with less than 2 percent oxygen content.

CMCs in petrochemical applications

Meanwhile, significant research into carbon fiber-reinforced SiC CMCs is yielding promising materials for hard-use applications, where strength, durability and ductility are every bit as important as heat management. Earlier this year, for example, Lancer purchased CeraComp, a carbon fiber-reinforced SiC CMC developed by Greene, Tweed & Co. (Kulpsville, Pa.). "We believe ceramics are going to be a significant growth opportunity for us in the future," says Lancer's Meiklejohn. Lancer already uses CMCs in small arms applications, with programs in place related to jet aircraft exhaust systems, and the company is now expanding CMCs into the oil and gas, chemical processing and power generation industries.

CeraComp was designed for greater fracture toughness, similar corrosion protection, and wear characteristics equivalent to, monolithic SiC ceramics used in sleeve bearings in magnetic coupled pumps. OEM pump manufacturers have used monolithic SiC bearings for stationary and rotating components in pumps for decades. Although it has been the preferred material, it is vulnerable to fractures caused by thermal and mechanical shock. A splintered piece of a fractured bearing, because of its hardness, can lead to catastrophic pump failure.

Using CeraComp, Lancer developed a high-pressure, high-temperature CMC bearing that it believes will have a longer life. Carbon fibers in the CMC prevent crack propagation, improving impact and thermal shock resistance. SiC particles are included to enhance the stability of the composite, improve wear resistance and reduce shrinkage of the SiC matrix during densification. The bearings are currently undergoing field tests.

Lancer also is finding applications for CMCs in its fiber-optics business. Lancer supplies harsh-environment op-

tical connectivity solutions to the energy, aerospace and military markets. The American Petroleum Institute's (API) *Specification* 6A, which requires wellheads used in oil and natural-gas extraction to withstand 1800°F/982°C while maintaining 5,000-psi pressure throughout, is providing a new opportunity for CMCs, says Meiklejohn. Conventional wellheads aren't surviving under the new standards, he points out. In answer, Lancer is building CMC containers that encapsulate the wellheads and protect them from heat. "We received an order within the last year to start a prototype and will begin testing in a month."

Meiklejohn believes Lancer will find an advantage as it optimizes its CMC manufacturing process, which uses PIP. "We're working to develop better chemistry to limit the amount of volatiles that come off during burn-off cycles in order to make the part denser after every PIP cycle," he explains. "We're also looking at optimizing the burn-off cycles by determining the optimal ramp-up time, cool-down cycle, and temperature. The more we can shorten the cycle time, the more cost-effective CMCs will become."

"Over the next year," he adds, "we're going to add people and we're looking at a new facility. A lot of that is wrapped around the growth potential we see in CMCs."

Roadblocks to overcome

A plethora of other CMC development programs abound worldwide: vanes for high-pressure turbines, advanced nuclear reactor components, self-healing CMCs for aircraft engine blades and vanes, structures for reusable thermal protection systems and more. The question is, how many of these programs will result in commercial applications?

Barriers remain. "The risk of introduction is the biggest roadblock," says ATK-COI's Richardson. "And the biggest part of that is the customer having confidence in the material system."

"CMCs are well suited for applications in the aerospace and defense industries, which are by nature conservative," says Meiklejohn. "Just as it took time to go from metal to composites, it will take time to go to CMCs … [and] for people to build confidence in these materials."

Cost continues to be an issue. "Ultimately, as we move into production, the volumes and the ability to work through lean activities are going to be huge for bringing down costs," says Richardson.

Meiklejohn agrees, adding, "When customers consider the time and cost associated with CMC processing, it slows down adoption of the material. If we can get the processing time down, it will open up a number of applications."

For now, everyone concurs that the investment by GE signals a changing tide for CMCs — one everyone is hoping will help them all scale the barriers. ■

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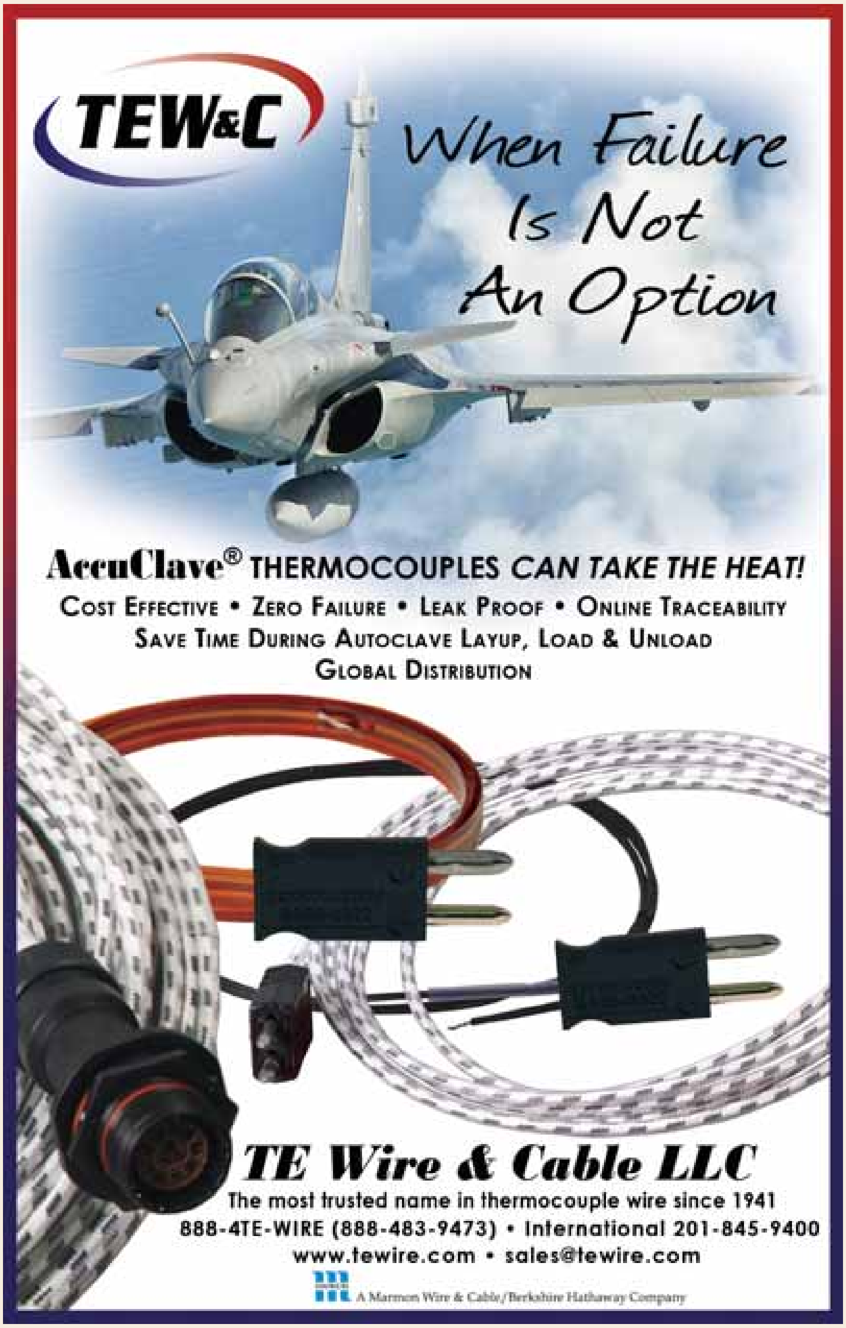

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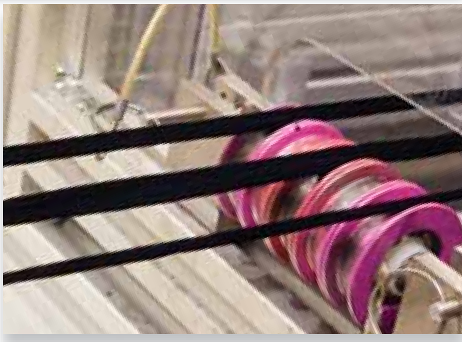

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APPLICATIONS

Software supplier aids parts producer with greater accuracy


Source: Crosby Composites

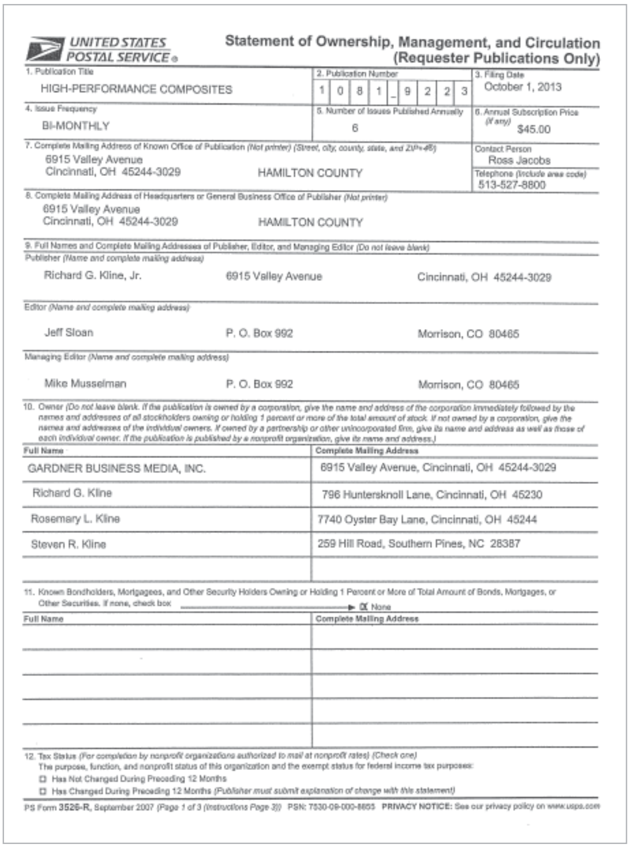
Paul Crosby founded Crosby Composites (Brackley, Northamptonshire, U.K.) 25 years ago when the use of composites in Formula 1 (F1) racing cars was just beginning. "It was obvious that these materials were an opportunity that would get bigger," he remembers, "so I started my own company."

He introduced digital modeling and CNC machining eight years ago, with the help of software supplier **Delcam Plc** (Birmingham, U.K.), despite his reservations about cost. Starting with PowerSHAPE for basic part and tool design, Crosby's designers found it easy to learn how to do complex modeling operations. PowerMILL — software that converts CAD models to NC toolpaths for multi-axis milling — was adopted on a 30-day trial, and Crosby never looked back.

Crosby says the software has helped produce F1 composite parts to levels of accuracy rarely seen in the industry. Part tolerances between ±0.1 and ±0.25 mm (±0.004 and ±0.010 inch) are a key differentiator for his business. Now a third Delcam software suite is helping ensure part accuracy. PowerINSPECT On-Machine Verification software enables rapid inspection of complex parts or tools by comparing them with the CAD model, and it is compatible with a variety of coordinate measurement machines.

Crosby explains that machined holes and pockets in carbon fiber composites tend to be undersized because the material relaxes slightly when cut, which is difficult to predict because not all of the fibers are cut in the same orientation. To overcome this problem, the initial machining operation is followed by inspection on the machine tool with PowerINSPECT, which shows if material needs to be removed while the required extra toolpaths are easily generated in PowerMILL. In addition to increased accuracy, all machining and inspection can be completed on the machine tool on a single fixture, eliminating the need to move the parts between fixtures, which can affect tolerances.

The first set of 17 parts produced with this method was fitted onto a F1 race car with *no misfits or rework*, reportedly the first time for such an outcome in that FI team's history. ■



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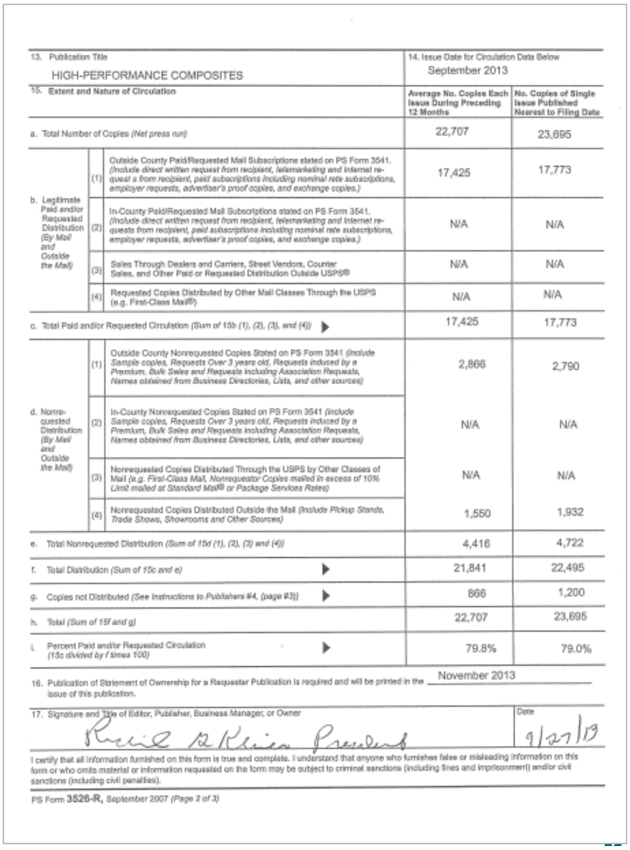

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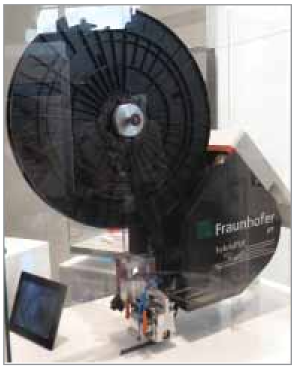
NEW PRODUCTS

Dry fiber tape placement with laser-based thermoplastic consolidation



Fraunhofer IPT (Aachen, Germany) introduced at Composites Europe 2013, in Stuttgart, Germany, a new automated tape placement (ATP) system that employs lasers for the placement of dry continuous fiber tapes with in-situ consolidation of thermoplastic resin matrix. The system reportedly offers out-of-autoclave processing, good temperature control, layup rates of about 1m/sec (3.3 ft/sec) and energy-efficient diode lasers. An infrared camera is used to control temperature at the head, and tape is offered in widths of 6 mm, 12 mm and 25 mm (0.24, 0.48 and 0.98 inch). Applications include open aerostructures, (wings and fuselage sections); closed structures, such as pylons and pressure vessels; tailored blanks; and composite repair. The system is being commercialized for Fraunhofer by **Advanced Fiber Placement Technology BV** (AFPT, Sprang-Capelle, The Netherlands). **www.ipt.fraunhofer.de/en.html; www.afpt.nl**

Laser heating for automated fiber placement

Automated Dynamics (Schenectady, N.Y.) reports that it has developed a laser-based resin heating technology for automated fiber placement of thermoplastic or thermoset prepregs. Called the Laser Heating System (LHS), it replaces infrared (IR) heating systems that are normally used for placing thermoset-based prepregs, as well as hot-gas heating systems that are used for placing thermoplastic-based prepregs. The system reportedly offers several improvements over traditional heating systems:

- Better process stability.
- Fiber placement rates three to five times faster than nonlaser systems (up to 0.5m/sec or 1.6 ft/sec for engineering thermoplastics and 1.2 m/sec or 3.9 ft/sec for thermosets).
- Closed-loop process temperature control, based on actual material surface temperature.
- Tighter process temperature control: ±10°C for thermoplastics and ±3°C for thermosets.
- Better heating efficiency, which means more heat energy is transferred directly to the prepreg.

Because laser energy is applied more efficiently to the prepreg, and because the closed-loop control keeps the surface temperature within a relatively small window, Automated Dynamics says the overall energy consumption of the LHS is about 60 percent less than hot-gas heating systems. Said to be proven in a production environment simulated in the lab, the technology is currently undergoing real-world production testing. The LHS will be a standard option on all Automated Dynamics fiber placement systems, and the company is working with other fiber placement system manufacturers to offer it as a retrofit option on their machines as well. **www.automateddynamics.com**

Olefin yarn commingled with other fibers

Innegra Technologies (Greenville, S.C.) has introduced for composites the new Innegra H line of fibers, comprising high-performance olefin yarn commingled with other high-performance fibers, including carbon, glass, basalt and aramid. The fiber is designed to increase durability and avoid the shattering effect of current lightweight composites. The new fibers can be used in a variety of processes and in a broad range of applications within several industries. These range from creating lighter-weight and impact-resistant sporting equipment to reducing the weight of automotive body parts. Innegra also anticipates interest from the luggage, marine, ballistics and protective-apparel industries. **www.innegratech.com**

Spread-tow product line extended

Chomarat (Le Cheylard, France, and Anderson, S.C.) reports that it is extending its line of carbon reinforcements with C-WEAVE SP, a new line of spread-tow carbon fabrics for composite parts with high aesthetic performance requirements, especially in the high-end automotive, sports and leisure, luggage and telephone markets. C-WEAVE SP spread carbon fabric is made with 200 g/m^2 3K fibers and is available in plain or twill weave. The fabric reportedly achieves a 99 percent spreading rate (compared to what Chomarat says is the usual average of 85 to 92 percent). At this rate, Chomarat says it is possible to manufacture carbon composite parts with a surface layer that is 20 percent lighter (compared to 245 g/m^2 3K fibers), with good surface quality and optimized aesthetics, performance and cost. Chomarat worked on the choice of raw materials, the production process and quality control, all of which are crucial selection criteria for this type of technically demanding product. **www.chomarat.com**

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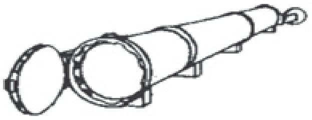

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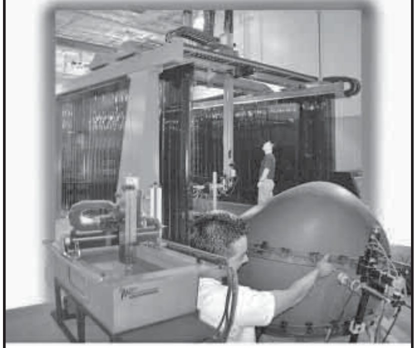

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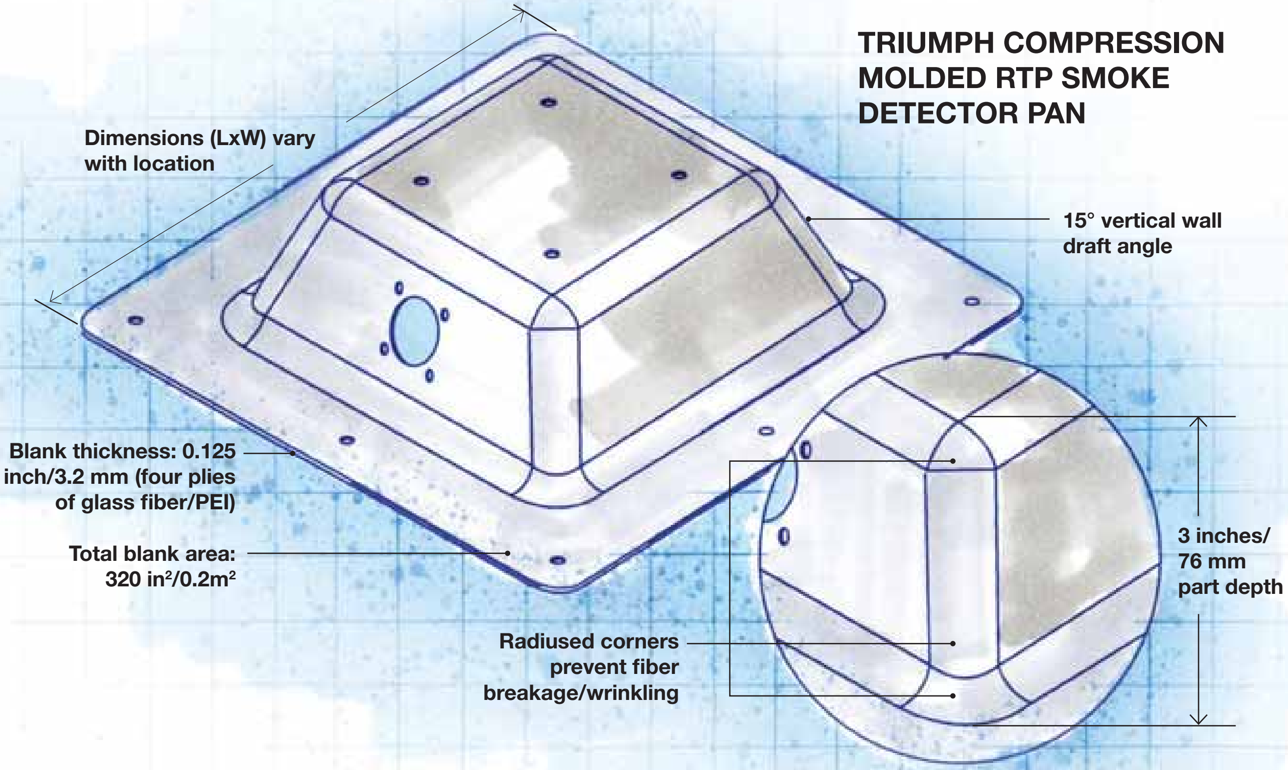
COMPRESSION MOLDING MASS

Compression molding is fast and efficient, but continuous-fiber design requires

There has been much talk in the aerospace industry over the past few years about the potential for use of thermoplastic composites in the aerostructures of future aircraft. Indeed, R&D efforts are underway in the U.S. and in Europe to assess the viability of a variety of carbon fiber-reinforced thermoplastics in everything from wing structures to fuselage sections to empennage components. If, and how much, thermoplastics will actually be used in primary and secondary commercial aerostructures remains to be seen. In the past decade, Airbus SA's (Toulouse, France) decision to incorporate thermoplastic composites into wing leading edges (see "Learn More") was big news, but was also the exception.

That said, thermoplastic composites, carbon and glass fiber-reinforced, have already won their way into commercial aircraft interiors in a variety of applications — some structural, such as brackets and clips, and some semistructural. An example of the latter, and a testimony to the lengths aircraft OEMs are now willing to go to lightweight their aircraft to enhance fuel economy, is Triumph Composite Systems' (Spokane, Wash.) continuous fiber-reinforced thermoplastic smoke detector pan. The tray-shaped composite component (see photo, p. 55) is inverted and installed in the aircraft ceiling in many places to provide a mounting space for onboard smoke detectors.

Triumph converted the pan from a hand layup/vacuum bag design. It's molded from a four-ply 0.045-inch/1.1-mm thick PEI blank supplied by Ten-



TRIUMPH COMPRESSION MOLDED RTP SMOKE DETECTOR PAN

DESIGN RESULTS

- Compression molded "smoke pan" designed for conversion from 2-D to 3-D form.
- Hat angle and plateau optimized to prevent part from shrinking against mold surfaces.
- Angle changes optimized with radii to minimize fiber wrinkling and maintain structural integrity.

OUT OF AIRCRAFT INTERIORS

optimization to avoid wrinkles and shrinkage.

BY JEFF SLOAN
ILLUSTRATION / KARL REQUE

Cate Advanced Composites USA (Morgan Hill, Calif.) under the Cetex brand. The total surface area of the pan is 320 in^2/0.2m^2 and it features a hat section that is 3 inches/76 mm deep. Although the pan is glass-reinforced, it illustrates many of the same design lessons Triumph has learned working with continuous carbon fiber.

Housed in a facility once occupied by a unit of The Boeing Co. (Chicago, Ill.), Triumph is a prolific compression molder. Nick Busch, R&D engineer at Triumph, says the company's smoke pan is a good example of what has become Triumph's specialty — converting labor-intensive, long cycle-time thermoset-based composite parts to highly automated, short cycle-time thermoplastic-based composites that are manufactured, primarily, via compression molding.

From flat blank to trimmed pan

The smoke detector pan begins as a flat sheet of continuous fiber-reinforced thermoplastic resin (right) that cam be formed via compression-molding, into the pan's complex shape (above.)

Source: Triumph

Bigger than it looks

Why go to the trouble for a part so small? The appeal of thermoplastics is understandable: Ease of handling, ease of processability, recyclability, toughness and, notably, no lengthy and expensive cure in an autoclave. Further, aircraft interiors present unique challenges that revolve primarily around fire, smoke and toxicity (FST) mitigation: In case of a crash or onboard fire, aircraft interior components must not only resist burning, but must also self-extinguish after flame source is removed. According to U.S. Federal Aviation Admin. (FAA) standards, most aircraft interior components must not allow a flame burn length of more than 8 inches/203 mm. Further, after removal of the flame source, the flame on the component may not persist for more than 15 seconds.

Compression molding, too, has strong appeal, particularly for aerospace manufacturers who are frustrated by the process inconsistencies inherent in hand-layup, autoclave-based molding processes. Compression molding of thermoplastics typically starts with a preconsolidated blank, usually consisting of several plies of carbon or glass fiber fabric (unidirectional or woven) oriented to meet the mechanical requirements of the application. The reinforcements are infused with a thermoplastic resin, which in aerospace applications is likely to be an engineered material: polyetherimide (PEI), polyphenylene sulfide (PPS), polyetheretherketone (PEEK) or polyetherketoneketone (PEKK).

Although preconsolidated blanks can be manufactured in-house, they also are available from established third parties. Triumph's pan blanks, for example, are supplied by TenCate Advanced Composites USA, and vary in size, depending on the size of the final part. The molder, then, can order and receive raw materials with a defined and consistent fiber volume fraction and thickness. Additionally, RTP blanks, unlike thermoset prepreg, require no refrigeration and can be stored at room temperature indefinitely.

2-D becomes 3-D

In preparation for molding at Triumph, a blank is usually placed in a frame or attached to a carrier sheet that helps keep the blank properly positioned and oriented in the mold. Frames and carriers also offer cycle-to-cycle positional consistency, a key factor in part repeatability. Next, the blank, on its frame or carrier, is transferred robotically to a preheater (infrared or other heat source) that heats the blank to more than 600°F/315°C, thereby softening it in preparation for molding. The time required for preheating depends on the size and thickness of the blank (usually 0.010 to 0.250 inch or 0.254 mm to 6.35 mm), as well as the resin type, but can take as long as 10 minutes. After preheating, the blank is shuttled into a mold (the mold tools are held at an elevated temperature, typically below the T_g of the material), which immediately closes on the blank and forces the now-soft material to assume the shape of the mold. Robotic handling systems and a prescribed, consistent preheating process also ensure repeatability.

After forming, the part is cooled to harden the matrix and then demolded. Typically, and unlike a thermoset


Source: Triumph

Compression mold at the ready

The compression mold, with the forming tool at top (note the generous draft on the tools vertical surfaces) awaits the arrival of the continuous fiber-reinforced thermoplastic blank.

composite part, a thermoplastic blank is designed with sacrificial material on its edges to provide a gripping surface for the positioning frame. This material is removed postmold via machining or trimming to bring the part to its final dimensions. (Also, Busch points out, any porosity problems in thermoplastic parts tend to occur near those edges.) This step can be followed by drilling and/or other finishing steps.

Design challenges

As with every composites manufacturing process, compression molding is ideal for some applications, but not all. Undercuts, sharp angles and complex curvatures are at best difficult if not occasionally impossible. Further, converting an existing part from infusion or a similar process to compression molding, as Triumph does regularly, is more complicated than simply transferring CAD files.

Because compression molding involves the conversion of a flat, effectively 2-D blank into a complex 3-D part, there are, says Triumph's Busch, certain design rules that must be followed and limitations that must be respected. The rules grow out of the fact that the process induces forces that tend to produce fiber bending, stretching, buckling and wrinkling during the conversion from flat to contoured forms. Many of these principles are illustrated in the smoke pan, which presents several challenges that were met by not readily obvious design solutions.

First, says Busch, with the exception of L- or C-brackets, vertical part walls are strongly discouraged because, as a thermoplastic material cools, it shrinks and "grabs" tooling surfaces. A part with vertical walls thus tends to grip the mold surface against which it was formed, making part removal difficult. The rule of thumb is to design vertical walls with a draft angle of at least 2°. "We like drafted walls better than vertical walls," he says. As is apparent in the illustration on p. 55, Triumph's smoke detector pan features a hat section with 15° slopes. Further, says Busch, any hat or pyramid shape like the one on the smoke pan should terminate in a flat surface and not reach a peak.

Second, because continuous glass and carbon fiber tend to wrinkle and buckle when formed around highly concave or convex surfaces, and because such wrinkling compromises the structural integrity of the part, angle changes must be carefully designed and managed. On the smoke pan, for example, a prescribed, curved radius is used to transition fiber and material from one angle to another at the top and the bottom of the hat section, minimizing stress on the fiber and maintaining structural integrity.

"When you go from 2-D to 3-D," says Busch, "you have to think about what happens when something goes around a corner."

Triumph's design software is used to simulate fiber bending as much as possible, but, says Busch, "usually we just rely on trial and error." As a result, Triumph has developed extensive and proprietary design guidelines that help the company optimize a design for thermoplastic compression molding.


Source: Triumph

Demolded and ready for trimming

Cooled and demolded, the part shows the marginal material that permitted the blank to be suspended and held in precise alignment with the tool prior to mold closure.


Source: Triumph

Trim and fit

Shown here after trimming to final dimensions, the pan is ready for drilling and finishing steps.

Another factor Triumph has to consider, says Busch, is the processing temperature of the resin. Some thermoplastics require temperatures as much as 100°F/38°C hotter than others, which adds time to the heating cycle. In addition, with so much heat buildup in the part, managing part cooling becomes a more critical concern so as to avoid postmold warpage.

Ultimately, notes Busch, one of the great limiting factors that prevent aerospace parts manufacturers from embracing thermoplastic compression molding is tooling cost. "But," he says, "you have to look at the full picture to see what the value is." Such value is built into every stage of the process: High automation, short cycle times and enviable process consistency. Busch says that for the smoke pan, the cost/benefit cutoff for compression molding is about 115 parts/month. Further, Triumph requires only two blank configurations to mold 10 unique part numbers. Most importantly, the smoke detector pan underscores the greatest benefit of conversion from a thermoset layup-based to compression-molded version: a production cycle time savings of 75 percent — a factor any aircraft designer will find not difficult to convert to a dollar value. ■

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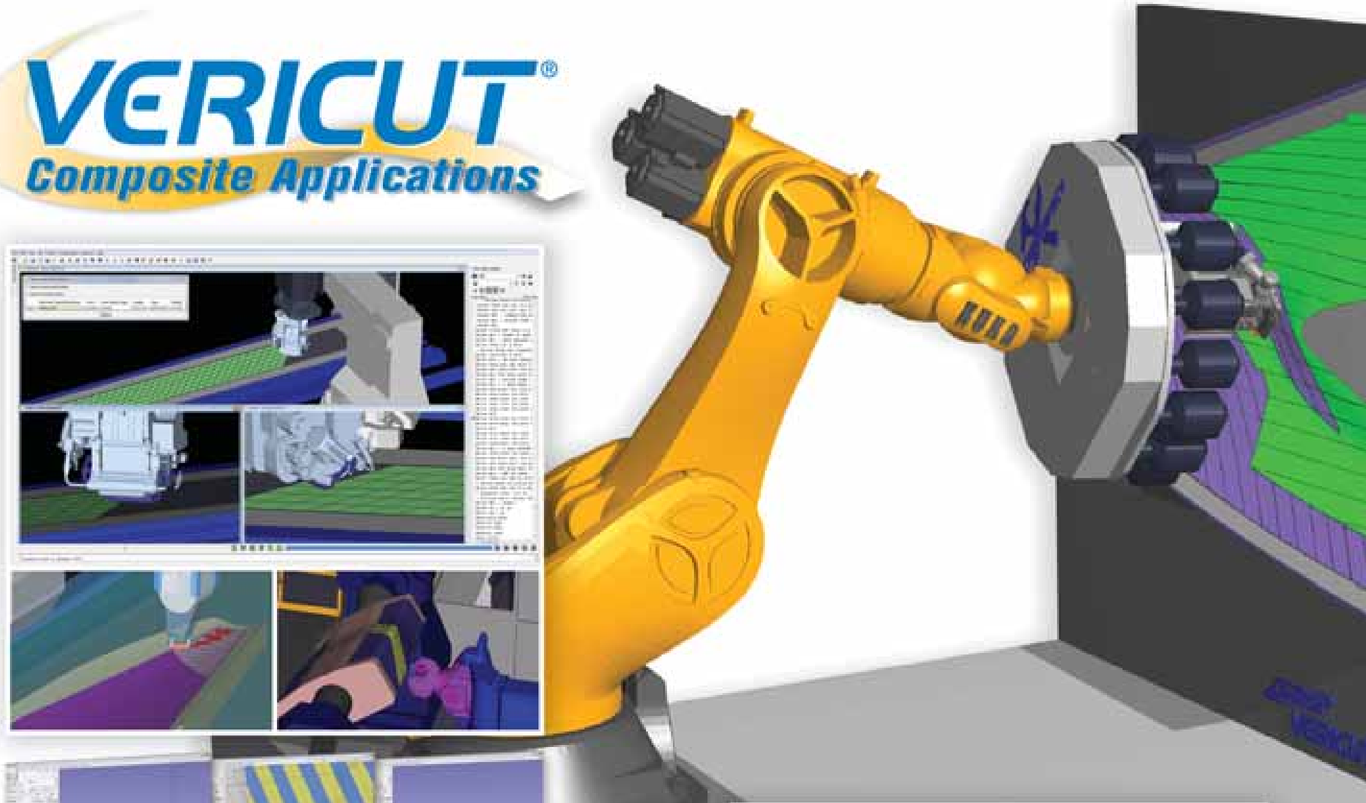
CFRTP is used, for example, to form the wing leading edges on the Airbus A320/340 and A380 aircraft. See "Thermoplastic composites gain leading edge on the A380," *HPC* March 2006 (p. 50) or visit http://short.compositesworld.com/A0RYPVJa.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