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Institute for Manufacturing and Sustainment Technologies

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A U.S. Navy Manufacturing Technology Center of Excellence

QUARTERLY 2006 No.1

iMAST Engineers Recipient of DMC 2005 Defense Manufacturing Technology Achievement Award

iMAST research engineers were recently honored as part of a team that received the Defense Manufacturing Technology Achievement Award. This annual award is given to project teams from the government and/or the private sector who are most responsible for a specific innovative manufacturing technology achievement.

This year's award recognized a Navy Manufacturing Technology project that is addressing a design challenge using composite-to-steel adhesive joints for the DD(X), the U.S. Navy's next generation multi-role surface combatant. Project team members included participants from industry, academia, and other Navy centers. Plans are underway for implementation of the technology by several Navy shipbuilders. Bath Iron Works and Northrop Grumman Ship Systems have been active team members and participants in all aspects of the project since its inception. To ensure that manufacturability and implementation is fully within the capability of manufacturing personnel, full scale test articles were built at Northrop Grumman Ship Systems under normal operating conditions.

Deputy Under Secretary of Defense for Advanced Systems and Concepts, Ms. Sue Payton (center), presents iMAST researchers Terri Merdes and Kevin Koudela their DMC Defense Manufacturing Technology Achievement Awards.

In addition to iMAST, the project team included Bath Iron Works, Northrop Grumman Ship Systems, Navy Joining Center, the Composites Manufacturing Technology Center of Excellence (South Carolina Research Authority), Boeing, and the Naval Surface Warfare Center-Carderock. Details on this project are available at http://www.dodmantech.com/award/index.shtml.

Defense Manufacturing Conference 2005 was held in Orlando, Florida. This annual effort continues to be a premier event for the DoD, other government agencies, academia, and industry to network and share achievements in technology transition and manufacturing programs. "Manufacturing in the Changing DoD Environment" was the theme of this year's conference. To support that theme the conference focused on gaining senior leadership participation across industry, DoD, and academia. Panel sessions, concurrent forums, and high-level keynote speakers promoted the exchange of technical information. Congressional representatives also continued to highlight various manufacturing-related issues involving the all-important defense industrial base. Presentations by iMAST members included: Doug Wolfe (Smart Thermal Barrier Coating Designs with Increased Reflectivity and Lower Thermal Conductivitiy for High Temperature Turbine Applications), Jeff Banks (Demonstration of Embedded Health Management Technology for the HEMTT LHS Vehicle), Tim Eden (F/A-18 F404 Fretting and Low Cycle Fatigue Amelioration), Charles Tricou (Overspray Elimination Through Development of High Transfer Efficiency Painting Technologies), and Ted Reutzel (Laser Paint Stripping of Composite Helicopter Rotor Blades).

Next year's conference will be held 27-30 November in Nashville, Tennessee. For more information, visit the Navy ManTech web site at http://www.onr.navy.mil/sci_tech/industrial/mantech/.

Focus On Advanced Composite Materials

Report Documentation Page

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DIRECTOR'S CORNER

The Year Begins

Welcome back! 2006 is in full swing and work is proceeding efficiently. We had a very successful Defense Manufacturing Conference. The presentations were professional and instructive. The contact with participants provided many valuable prospects. The teaming of research facilities with the defense contractors and the government has proven to be the successful route toward implementation in Manufacturing Technology.

The Applied Research Laboratory at Penn State not only supports the Institute for Manufacturing and Sustainment Technologies (iMAST). We have active projects funded through other Navy ManTech Centers of Excellence. A primary example is the DDX Composite to Steel Joint. We are working with the Composites Manufacturing Technology Center and the Navy Joining Center on this project. We participate in several projects with the Center for Naval Shipbuilding Technology. I believe the partnering with other centers improves the chances of implementing technologies.

This year is an exciting year for ManTech. Next fiscal year, the President is requesting the building of two DDX platforms. With the investment of significant ManTech resources, the DDX program has the potential to save millions of dollars over a multiple ship build. Both collarless construction and the composite-to-steel joining are likely candidates for implementation.

Our feature article discusses a promising material that can expand the use of composites in various applications. Composites have long been lauded for their corrosion resistance and low weight-to-strength ratio. One of the drawbacks has been the operator contact time. Manufacturing composites often requires extensive manual labor. Dr Greg Dillon describes a material undergoing research. Identifying a material that is corrosion resistant, retains sufficient strength, and is formable in complex curvature applications will have significant impact on costs of future DoD systems.

This newsletter marks the last one for our loyal and efficient staff assistant, Lori Mowery. She is retiring from ARL after more than 27 years of service at Penn State. We wish her fair winds and following seas!

Bob Cook

Editor's Note: Due to the unfortunate passing of our publications director, Kevin Fox, we were not able to produce our final two newsletters last year. Mr. Fox's passing was a significant loss to the Applied Research Laboratory. We now have a new team on board and are slowly getting back to normal. Your understanding is appreciated.

MATERIALS PROCESSING TECHNOLOGIES · **MECHANICAL DRIVE TRANSMISSION TECHNOLOGIES** · **LASER PROCESSING TECHNOLOGIES** · **COMPLEX SYSTEMS MONITORING TECHNOLOGIES**

ADVANCED COMPOSITES MATERIALS TECHNOLOGIES · **NAVY/MARINE CORPS REPAIR TECHNOLOGIES** · **MANUFACTURING SYSTEMS TECHNOLOGIES**

Focus on Advanced Composite Materials

New Materials Technologies for Advanced Forming Processes

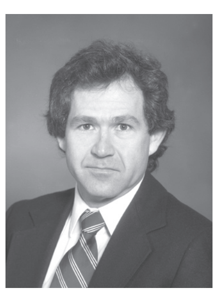
by Gregory P. Dillon, Ph.D.

Background

Automated forming technology represents a cost competitive alternative to established lay-up fabrication methods for a wide range of military and commercial applications. Initiatives at Boeing, Lockheed Martin and Northrop Grumman Corporation over the last decade have availed of the potential of forming technology to greatly reduce operator contact time, with attendant human health, as well as process economic benefit. Basing most process developments on single or double diaphragm forming of flat laminated uncured prepreg materials, these programs have yielded process time reductions on the order of 50% relative to conventional approaches. The desire to extend this benefit to a larger spectrum of components has spurred renewed interest in automated forming, both from process innovation and materials development standpoints. It is the realization that material parameters can have an overriding impact on part formability that has encouraged the development of new material systems.

The principal process limitation, imposed by material physics, that impedes the broad application of forming technology, is the occurrence of laminate wrinkling. This mechanism occurs primarily when compressive forces in a deforming laminate reach a level that cannot be adequately counteracted by the support forces provided by the diaphragms. Prediction of the precise stresses that cause laminate wrinkling is a complicated problem since (in the uncured state) prepreg material is a combination of highly elastic fibers in a viscous matrix resin and, as such, constitutes a complex visco-elastic system with all the recognized temperature and rate dependencies. However, it has been shown that successful forming of complex components depends on the inducement of desirable deformation modes such as in-plane and inter-ply shear, in preference to the nuisance buckling modes that are most noticeably manifested as laminate wrinkling. Unfortunately, the higher the levels of the former modes that are required to form a given component the more likely the latter will be induced instead. Since in-plane and inter-ply shears scale with part complexity (double curvature), expedients that reduce the required levels of these shears are likely to improve formability.

Hexcel Corporation has developed a new material form, designated Stretch Broken Carbon Fiber (SBCF), in which the fibers that comprise a fabric or prepreg have essentially been broken in random fashion. This offers the potential to allow extension along the axis of the fibers and thus reduce the likelihood of laminate wrinkling. The basic idea behind the material form, as it applies to forming technology, is that required shearing deformations are relaxed by the availability of an additional deformation mode. Therefore, the likelihood of inducing wrinkling modes is reduced. A development program is underway that involves Hexcel Corporation, Penn State's Applied Research Laboratory, Boeing, Northrop Grumman, and Rensselaer Polytechnic Institute. The goal of the project is to characterize the deformation mechanics of the material and select suitable applications in which its unique properties may be exploited to economic benefit. The activity is funded by the Office of Naval Research, with the Naval Air Warfare Center functioning as the program technical monitor.



PROFILE

Gregory P. Dillion is the deputy head of the Composite Materials Division at Penn State's Applied Research Laboratory. He is also the department head for Advanced Technology Development within the Composite Materials Division. As a research engineer Dr. Dillon conducts research in the area of composites processing, as well as material characterization and performance. Prior to joining ARL, Dr. Dillion was principal engineer in the Advanced Development Department of the Engineering and Technology Division at Northrop Grumman. Dr. Dillon was also assistant director of the composites and polymer processing program at the Massachusetts Institute of Technology from 1989 to 1994. Published widely in the area of advanced composites, on topics including environmental resistance, novel cost-effective processes, and cost modeling, Dr. Dillion's research interests also include the influence of processing sequence on composite architecture and resultant impact on performance.

Born and raised in Ireland, Dr. Dillion holds a B.S. degree in material engineering as well as a Ph.D. in composites from the University of Limerick. Dr. Dillion can be reached at (814) 865-5879, or by e-mail at: <gpd2@psu.edu>.

Development Program

The approach to characterization of material behavior and ultimate transition to appropriate application had three key components. Tests were devised and conducted that determined the effect of expected process parameters on material deformation. Resultant data were used in the development of a numerical modeling capability that, when fully refined, will allow the impact of component geometry on formability to be determined. Lastly, a series of demonstration components were selected based on the potential for successful materials implementation to positively affect process economics. Thus a truly concurrent engineering / development approach has been adopted.

Material Testing

Initial uniaxial tensile tests were carried out by Hexcel Corporation and the results showed conclusively that the material stretched in a very orderly fashion and that optimal forming temperatures were in the region of 116°C. These early tests, while uncovering a number of important factors relating to the deformation behavior of the SBCF material forms, did not truly represent the multi-axial stresses encountered in conventional forming processes. In order to overcome these limitations a biaxial pressurization or 'bulge' test was developed and a device fabricated at the Applied Research Laboratory. This test unit is comprised of a 25.4 cm diameter pressurization chamber, above which a layer of high temperature bagging material and test ply stack is clamped in place using a serpentine cross section ring and four large toggle clamps. A linear variable displacement transducer was placed at the center of the sample along with a control thermocouple. Heat was applied using a heat gun that was connected to a controller, and temperature and central displacement data was captured using a data acquisition system. Pressure was set to a desired level (0.1 to 0.3 MPa) and applied by opening a valve to admit air to the shallow pressurization chamber. A large test matrix was designed to determine the effects of material type, pressure, temperature and laminate lay-up geometry on stretching behavior.

A preprinted grid pattern was applied to the top surface of all samples, in order to determine the spatially varying deformation profile from each of the tests. This grid consistent of four concentric circles of 3.18, 6.35, 9.53 and 12.7 cm, and diametral lines spaced at 22.5°. Data collection was conducted at these spacings in order to provide for convenient cross calibration with late model outputs.

Three test temperatures were chosen for evaluating the materials. Room temperature (21°C) was used as a reference to allow for determination of temperature trends. The intermediate temperature (77°C) was selected to represent current limitations of known implemented forming technologies, while 116°C was believed to be optimal, based on prior universal testing. Figures 1 and 2 show data for SBCF materials that contain AS-4 and IM-7 carbon fibers generated at 77°C. At this temperature the AS4 material is seen to be much more deformable than the IM7. This confirms the trend seen in initial uniaxial tests. Note however, that increased pressure brought about deformation in the IM7 system that was similar in magnitude and, significantly, stability to that exhibited by the AS4 material at lower pressures. This is a very important result, since it shows that process configurations that provide pressures in excess of that supplied by vacuum (such as in an autoclave) could be used to form this widely utilized material.

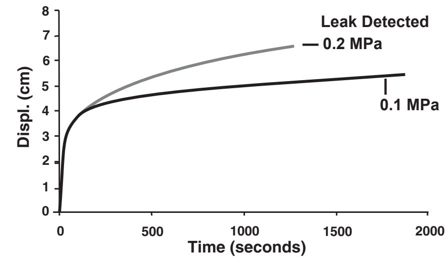


Figure 1. Effect of pressure on deformation of (0/90)S AS4 unidirectional tape at 77°C.

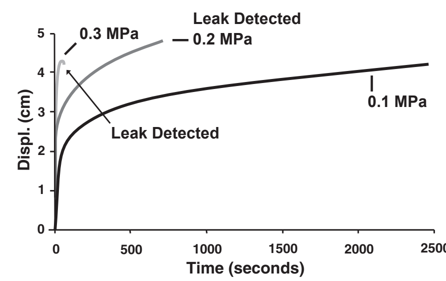


Figure 2. Effect of pressure on deformation of (0/90)S IM7 unidirectional tape at 77°C.

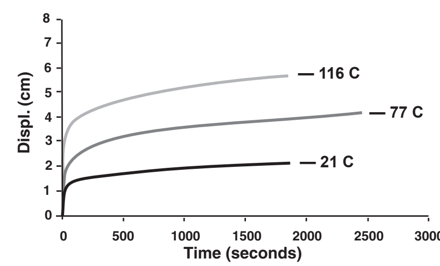


Figure 3. Effect of temperature on (0/90)S IM7 unidirectional tape at (0.1 MPa).

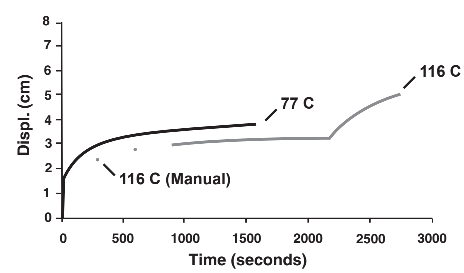


Figure 4. Effect of temperature on 1 ply samples of AS4 woven material at 0.1 MPa.

Figure 3 shows a temperature study conducted using the IM7 material under a pressure of 0.1 MPa. Note that at the higher temperature the maximum deflection corresponds to a diametral strain of about 13%. However it is again significant that this material achieved these relatively high strains under the high temperature test condition.

Woven AS4 prepreg materials were also tested, and the results of a temperature study are shown in Figure 4. Note that the data trends agree very well. In the case of the 116°C test the pressure was increased to 0.2 MPa after about 35 minutes of testing and further deformation occurred. However, significant sample slippage was noted at this stage, though leakage did not appear to occur. The result confirms a trend suggested in the early uniaxial tests i.e. the higher temperatures yield lower deformations with the fabric material forms. While in general it is noted that the woven material is much less formable than the corresponding unidirectional tape, this inverse temperature correlation is the most striking feature of material behavior. It is believed that the lower strains exhibited by the woven systems may be explained by an effective pinning mechanism imposed by the tow cross over points. The temperature effect is less easily explained, however. It is feasible that when the locking mechanism is induced, the pressure applied from beneath may simply squeeze out the resin, thus reducing the lubricant effect of the matrix material. This may be particularly damaging from a deformation standpoint where a natural locking mechanism exists and might therefore explain why a similar effect is not observed in the aligned fiber systems.

The grid patterns applied to the samples were used to track the spatially varying deformation profiles for each material system. Results for tests carried out on AS4 and IM7 unidirectional materials are shown in Figures 5 and 6 respectively. The figures show the radial increases in the individual grid segments (note that these radial line segments were originally 3.175 cm long). The data show two important results. Firstly, it is evident from both experiments that little deformation occurs close to the perimeter, though occasionally minor deformation is noted. While

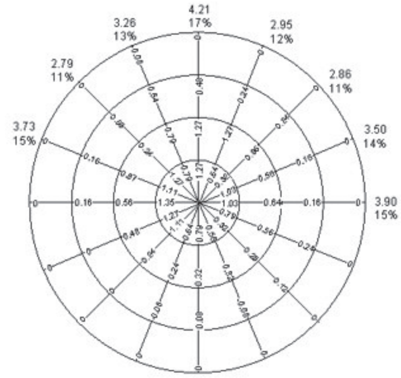


Figure 5. Deformation profile for AS4 (0/90)S. Sample Tested at 77°C and at 0.1 MPa.

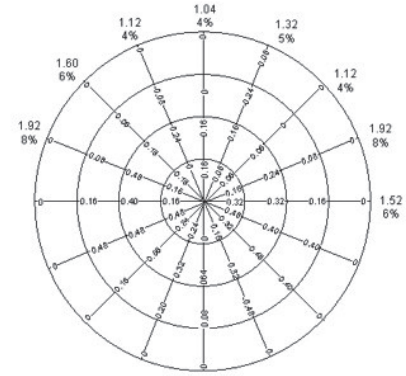


Figure 6. Deformation profile for IM7 (0/90)S. Sample Tested at 77°C and at 0.1 MPa.

this was predictable, as properly clamped fibers cannot move and deformation should be confined to fibers that do not span the test area, it also proves that sample slippage did not occur during these tests. Secondly the deformation is seen to be very localized across the samples. Note that the data are presented such that the top surface ply orientation is vertical in the figures. The numbers presented at the ends of the diameters are the summations of the deformations (and strains in parentheses) across each of the lines. Negative values of deformation are caused by localization of fiber pull bringing grid points closer together rather than pulling them apart. The results also show the greater formability already highlighted for the AS4 system. It is also apparent that the strain is concentrated at the center of the samples and reduces with radial distance. This has critical implications from a processing standpoint as it essentially determines the regions of zero deformation at a clamped perimeter (important for stamping operations) and potentially assists in the determination of minimum feature-to-feature distances in complex components. The data collected in the fashion described provide important input to finite element modeling activities.

Process Modeling

Rensselaer Polytechnic Institute has used the LS Dyna dynamic code as a platform for the development of a numerical modeling capability. Initial efforts were devoted to reproducing the experimental results of the biaxial 'bulge' tests carried out at ARL. Several tensile, creep and stress relaxation tests were conducted in order to capture the necessary material parameters needed to calibrate the model. While some dynamic damping issues remain, the characteristic curves presented in the biaxial test curves given above were successfully reproduced. The curved c-channel data, used in process trials conducted at Northrop Grumman, has also been modeled and the simulated material deformation is shown in Figure 7. This tool allows the impact of process geometry on

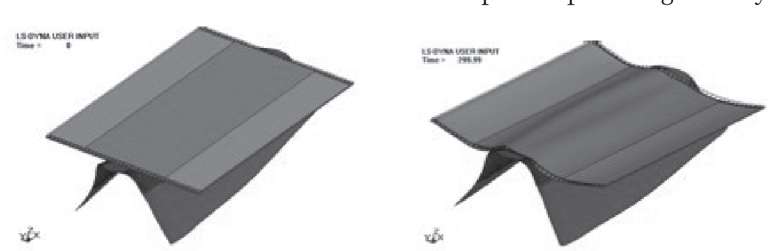
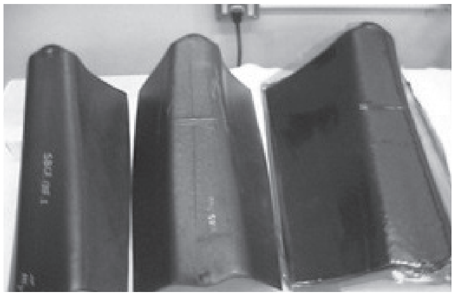


Figure 7. Numerical model of deformation sequence during forming of curved C-Channel.



Part A. Part B. Part C.

Figure 8. Curved C-Channels made by a double diaphragm forming process using stretch broken and continuous fiber prepreg material forms.

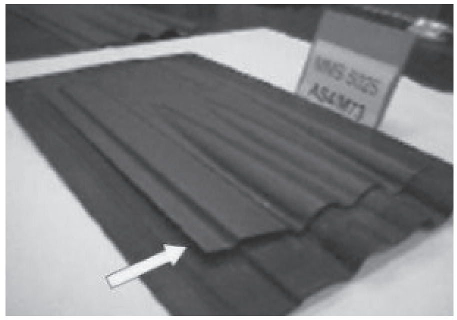


Figure 9. Fairing Made with The Baseline Material Showing Warpage Relative to the Cure Tool.

material deformation sequence to be determined, and it is this sequence, in combination with the constitutive behavior of the material, that determines the processing stresses.

Forming Process Trials

The material characterization tests described above provided strong evidence that the SBCF material forms were capable of achieving significant stretch under realistic forming conditions. Therefore a number of processing trials were conducted in order to determine the forming characteristics of SBCF material in comparison to continuous fiber systems. Three complex geometries were selected that were representative of current aerospace requirements. A curved c-channel was selected as a shape that, on the basis of prior work, was believed to be beyond the capability of conventional forming technology when processing continuous fiber materials. A variable cross section sine wave fairing was also selected, as this incorporated features that could only be successfully formed if local deformation was permitted, and a beaded panel was selected to represent a class of aerospace components that cannot be formed now and are too expensive to produce by hand lay-up.

Curved C-Channel Process Trials

A series of curved C-Channels were made by a double diaphragm forming process using stretch broken and continuous fiber prepreg material forms. The resulting parts are shown in Figure 8. The C-Channel part made from continuous fiber unidirectional prepreg material was unsuccessful. Wrinkles developed on the surface after forming. The same part configuration was made using SBCF material and formed without wrinkles. This appears to be due to the improved formability of the SBCF material.

Part A. was made from SBCF material and formed with no wrinkling or fiber distortion. Parts B and C were made from continuous fiber material and developed wrinkles during the forming process. Since identical forming parameters were employed in processing all parts, these trials strongly suggest that the fiber axis stretch that is afforded by the SBCF material reduces the required levels of in-plane and inter-ply shears that led to the laminate wrinkling on the equivalent continuous fiber parts.

Fairing Process Trials

The fairing incorporates local complex features that represent a particular challenge for automated forming processes. The first part was made from the standard continuous fiber material. Significant part warpage was noted after cure as shown in Figure 9. Warpage occurs in composite parts when internal stresses are locked in during the curing process. By comparison, little part distortion was noted when the same part was processed using the SBCF material, as shown in Figure 10. It is not clear at this stage why apparently greater shape fidelity is noted on parts that are processed using the stretch broken material forms. It is possible that in the critical stage prior to solidification the discontinuous materials allow micro deformations that relieve internal stresses imposed by the differential contraction of the fibers and resin. Reduced part distortion could have enormous impact on composite production costs, as assembly processes would be proportionately impacted. This effect may provide an unexpected benefit from the application of SBCF materials. Wrinkles were seen to develop around tight radii and compound curvature areas with the baseline continuous material. These are indicated in Figure 11. By comparison the SBCF

Figure 10. Fairing made with SBCF material showing very little warpage.

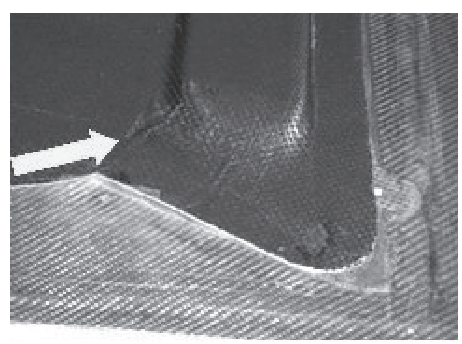


Figure 11. Fairing made with baseline material. Detail shows wrinkling in the area of complex curvature.

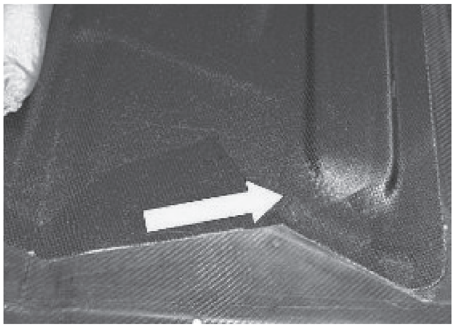


Figure 12. Detail Of The Fairing Made With SBCF Material Shows No Wrinkling in the Complex Curvature Area.

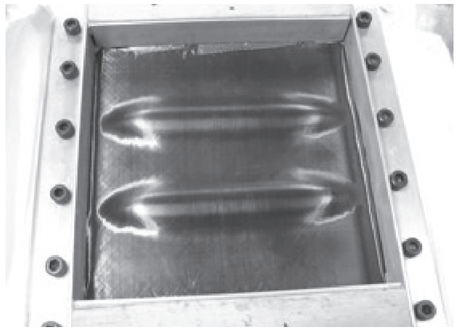


Figure 13. Beaded Panel Formed Using a Perimeter Clamp at a Pressure of 0.7MPa.

material, once again, showed a very clean surface in the same location, as seen in Figure 12.

The results shown in Figures 11 and 12 provide the best evidence to date that stretch broken materials allow successful forming of parts that might be otherwise unavailable to the technology.

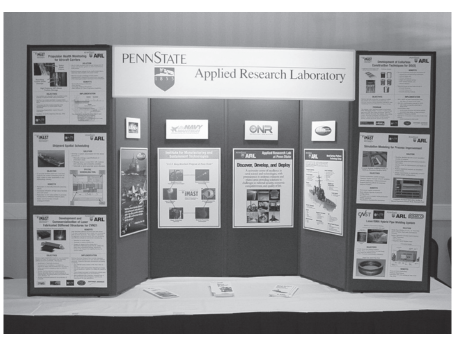
Beaded Panel Process Trials

At the suggestion of Sikorsky Aircraft, additional process trials were conducted using a beaded panel geometry that is representative of a range of helicopter fuselage stiffening components. In these trials a different approach was adopted. Departing from a process configuration that is representative of conventional double diaphragm forming, panels were made using a full perimeter clamp. In this way the material was forced to stretch, thus assuring that the unique deformation characteristics of the material are exploited. Compressive forces, which are the primary cause of laminate wrinkling, are completely eliminated. The panel shown in Figure 13 was formed with a pressure of about 0.7 MPa. While full conformance to the component geometry was not achieved, laminate wrinkling was effectively suppressed, and transition of this relatively simple autoclave based forming technology to emerging platform production is a realistic possibility.

Conclusions

A material characterization and process modeling program was conducted that allowed the deformation characteristics of a new class of composite materials to be determined. Building on automated forming technology that has been shown to significantly reduce part production costs, process technologies are being developed that will allow this new material to be used to form parts that cannot be made by existing methods. This may have a significant effect on fleet maintenance and sustainability, as the benefits of composite materials may be exploited in components that are currently believed to be too complex for application of such light high performance materials.

INSTITUTE NOTES



Relevant Research and Results . . . Yesterday, Today, and Tomorrow

iMAST Attends Shiptech 2006

Members of iMAST recently participated in the annual ShipTech forum in Panama City, Florida. Sponsored by the Office of Naval Research Navy ManTech Program Office, the forum addresses the domestic shipbuilding industry, its supplier base, the U.S. Navy Program Offices, and the U.S. Navy-sponsored shipbuilding research programs. The forum further provides the ability to exchange information on shipbuilding technical developments. ShipTech features advances generated respectively by the National Shipbuilding Research Program and the Navy ManTech Program through its Centers of Excellence and related shipbuilding initiatives. The overriding objective of the information exchange is to reduce total ownership costs of naval ships, while enhancing the competitiveness of the domestic shipbuilding industry.

iMAST participation included an exhibit booth. iMAST's Rich Martukanitz also served as a moderator for the panel discussion on "Technology Transition from ManTech to Industry". This particular panel discussion focused on collarless construction. iMAST's Mark Traband and Dan Finke also presented a poster titled: "Metamodel-Driven Production System Analysis Using Simulation". Next year's forum will be held January. Check future iMAST calendars of events for more detailed information as it becomes available.

CALENDAR OF EVENTS

2006			
11–14 Jan.	Surface Navy Association Symposium	★★★★★★★ *visit the iMAST booth*	Crystal City, VA
1 Feb	Capitol Hill Innovation in Action	★★★★★★★ *visit the iMAST booth*	Washington, D.C.
5–7 Feb.	Tactial Wheeled Vehicles Conference		Monterey, CA
4–6 Apr.	Navy League Sea-Air-Space Expo	★★★★★★★ *visit the iMAST booth*	Washington, D.C.
9–11 May	American Helicopter Society Forum 62	★★★★★★★ *visit the iMAST booth*	Phoenix, AZ
1–2 Jun.	Johnstown Showcase for Commerce	★★★★★★★ *visit the iMAST booth*	Johnstown, PA
5–7 Jun.	Navy Opportunity Forum		Washington, D.C.
12–15 Jun.	Mega Rust 2006 Marine Coatings & Corrosion Conference		Norfolk, VA
13–14 Jun.	M2AB Meeting: Ground Combat/Combat Service Support Vehicles		State College, PA
26–29 Jun.	U.S. Coast Guard Innovation Expo		Tampa, FL
31 Jul.–2 Aug.	ONR Naval-Industry R&D Partnership Conference	★★★★★★★ *visit the iMAST booth*	Washington, D.C.
16–18 Aug.	ARMTech Showcase for Commerce	★★★★★★★ *visit the iMAST booth*	Kittanning, PA
12–13 Sep.	ARL Penn State International Workshop on Advanced Coatings Technologies		State College, PA
12–14 Sep.	Marine Corps League Expo	★★★★★★★ *visit the iMAST booth*	Quantico, VA
9–11 Oct.	AUSA Expo		Washington, D.C.
23–26 Oct.	Expeditionary Warfare Conference		Panama City, FL
Oct.TBA	DoD Maintenance Conference		TBA
27–30 Nov.	DMC 2006	★★★★★★★ *visit the iMAST booth*	Nashville, TN

Quotable

"A fundamental rule in technology says that whatever can be done will be done."
— Andrew Grove

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