U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Fiber Reinforced Polymer Composite Manufacturing Workshop

January 13, 2014

Participant Provided Discussion Starter Presentations

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Discussion Starter Instructions

In preparation for the breakout session discussion and to kick-off the conversation, participants were invited to submit one slide on a specific technology or set of technologies related to one of the focus areas. Participants were asked to avoid presenting on a specific organization and product, but rather, provide an assessment of the technology to be based on the participant's technical expertise and background.

Participants were provided the following framework for the single slide discussion starters.

With respect to the potential objectives for composites manufacturing as outlined in the DOE RFI to have impact to clean energy and industrial applications to reduce cost, increase production rate, lower energy and increase recyclability of fiber reinforced polymer composites:

- Please identify a specific key technology that has the potential to help achieve these objectives and which focus area you are addressing.
- What is the state of the art for this technology? TRL/MRL level?
- What are the key technical limitations/challenges to the technology today?

Participants were asked to only provide content that was approved for public dissemination and were notified the information would be shared as non-attributed data. Submission of the slide by a participant to the workshop organizers provided DOE permission to distribute the information provided publically.

Manufacturing Process Technologies Blue Teams A and B

(e.g. lay-up techniques, out of the autoclave, novel cure techniques, resin infusion, pultrusion, tooling, machining, other)

Marine to Transportation Leveraging SBIR Technology

Lightweight Technology- The Future of Transportation

N09-049 Advanced Combatant Craft for Increased Affordability
Phase II and Phase III SBIR
40-60% Weight Reductions
Shock Mitigating Structures
Low Cost FRP Technology
- Advanced Preforms
- Advanced Coatings/Resins
- E-Glass Fibers
- 2lb PU Foam

Marine Composites Industry Advantages
- High Performance
- Light Weight
- Low Cost - Very Cost Sensitive Market
- Material Costs vs Aerospace Materials
- Manufacturing Process Ideal for
  - Prototype/Prof of Concept
  - Low Volume Runs

Marine to Transportation

60% Weight Reduction from Steel/Wood RV Chassis-Floor

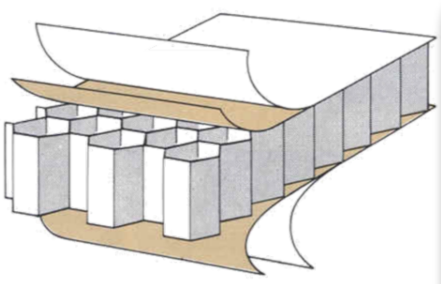
32% Weight Reduction from Steel Bus Floor

Challenges:
Molding Processes for Volume Scale Up

- Limited Production
- Moderate Volume
- High Rate

SLOW PRODUCTION METHODS

- While the #1 factor preventing CFRP (Carbon Fiber Reinforced Polymers) from becoming a design material of choice it is the cycle time of traditional manufacturing processes that is the major inhibitor of high end fiber reinforced composite materials.
- Alternative Out-of-Autoclave, OOA, are resulting in near 75% reduction in processing time with a commercial price reduction of 30%.
- However, additional development work is required to develop resin matrices that will permit the process to produce parts in 2 minutes.



Composite materials have been used by the automotive industry since the 1960s, but only in small quantities. Several attempts have been made to introduce large scale composite applications, but cost and manufacturability have limited their success.

Out of Autoclave Technologies

- Key Technology: Out of Autoclave (OoA) Curing/Consolidation Technologies (not materials, but new processes) for Laminates and Sandwich Stuctures made from Thermoset and Thermoplastic Prepreg (e.g., SET™ by Vistex Composites, QuickStep, RapidClave™ by Globe Manufacturing)
  - Reduces cost and lowers energy by eliminating the cost- and energy intensive autoclaving step for layup conoslidation and curing (arguably, the Achilles heel of advanced composites manufacturing)
  - Increases production rate, since production isn't tied to an expensive autoclave with fixed volume and long temperature ramp up and ramp down cycles
  - Reduces waste, since less vacuum bagging materials are typically needed.
- MRL Level: 8-9 (Pilot line capability and low rate production demonstrated)
- Key Technical Limitations/Challenges:
  - Automation of tooling design process (SET)
  - Scaling up process to larger parts (SET, Quickstep)
  - Equipment cost (Quickstep, RapidClave)

Blue Team – Manufacturing Process Technology

- **Cobonded/Cocured/Secondary Bond Structure**
  - **Surface preparation**
  - **Low cost 3-D woven preform technology (cobond)**
  - **Process variation control**
  - **Adhesive performance**
  - **Inspection methods**
  - **Path to certification**
  - **Sustainability of composite structure**
- **Automated Fiber Placement**
  - **Enhanced slit tape material behavior prediction for programming**
  - **Low cost slitting and spooling**
  - **Improved heating with closed loop control and data logging**
  - **Shortening process development span for new laminate configuration**
  - **In-situ flaw detection**
- **New and innovative materials, processes, and tooling transition to production**
  - **Shorten the cycle time**
  - **Material properties availability**
  - **Low cost fiber and resin systems**
  - **Shorter processing cycles (thermosets and thermoplastics)**
- **Out-of-Autoclave Technology**
  - **Primary structure applications**
  - **Innovative laminate curing methods to shorten process cycle**

Emerging Composite Manufacturing Technologies for Automotive

2011
2012
2013
2015?
?

Highly filled chopped FG components 60%+

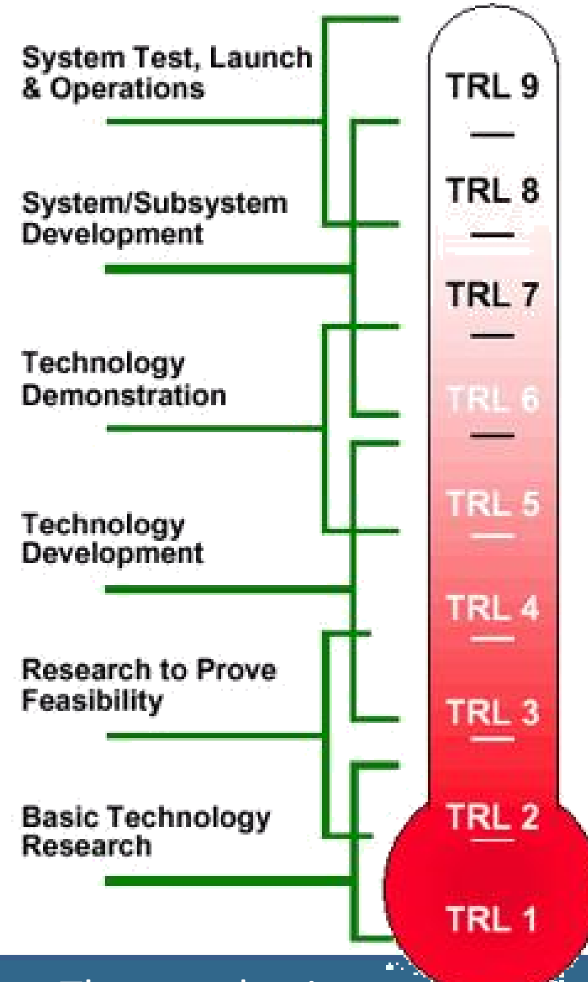
Hybrid metal + composite structures

High Pressure RTM processes (Epoxy/PU)

LFT/Short fiber + Tape/Fabric/Mat TP

Out of autoclave prepregs

High V_f in-situ polymerization of AP PA6 TPC



***Airbag module (KraussMaffei)**

Long-Fiber Thermoplastic over-molding enables high volumes for continuous reinforcements

Pultrusion Challenges

Develop glass reinforcements with increased stiffness and strength properties in both longitudinal and transverse orientations

Develop pigment and resin chemistries that are resistant to ultraviolent rays in outdoor applications

Develop a fire, smoke and toxicity (FST) resin with mechanical properties equal to vinyl ester resins

Blue Team: Manufacturing Process Technology

Fine Tuning Manufacturing Influences Cost Efficient Manufacturing

- Maximizing composites' impact in high volume, lower cost applications is best achieved by investment in both glass (increasing performance) and carbon (lowering cost) fiber technology
- For glass fiber manufacturing, mechanical performance increases of 10-15% have been achieved in recent years and it is realistic to expect that performance limits can be pushed to 20-25+% in 5-7 years if further melting technology is pursued
  - New refractory materials, metal alloys for bushings, and melt processes are needed to accommodate higher melting temperature glass compositions
- The wind industry has already embraced the use of composites; however, the length of the blade is limited by current material performance, and within cost constraints of the wind industry.
  - Once new materials are developed, high throughput and low cost composite processes for wind blades or automotive components will increase adoption
- A lack of a cross-industry, consortia-based dialogue to combine these tools with a top-down design approach is a barrier that can begin to be addressed by today's audience

AUTOCOMPOSITES

Blue Group:

Despite technical challenges, the key to high-volume FRP composite manufacturing is selecting the highest-value-add applications, aligning the supply chain around them, and getting started now

- The supply chain in turn scales up and producers have the impetus to make disruptive investments in auto-specific material and manufacturing technology

- Composite manufacturing processes exist today (MRL level 8-9) that are suitable for high-volume production (>50,000 units per year)

- What's missing?

  - A high-volume commercial application each link in the supply chain can commit to and invest toward
  - Proving out a specific part for high-volume production
  - Making the up-front investment in high-volume production

CENTERS OF INTEREST TO DOE FRP COMPOSITE MANUFACTURING WORKSHOP PARTICIPANTS

- Swagelok Center for Surface Analysis of Materials
- Advanced Manufacturing and Mechanical Reliability Center (AMMRC)
- The Solar Durability and Lifetime Extension (SDLE) Center
- Metallography Laboratory

SELECT FRP PROJECTS AND RESEARCH INTERESTS

- Polymer synthesis and structure-property relationships of polymer nanocomposites
- Synthesis and characterization of electro-spun silk-like polyurethane nano-fibers
- Three-dimensional electro-spun alginate nano-fiber mats
- Formation of homogeneous polymer/nano-fiber composites
- Stimuli-responsive MEMS polymer nanocomposites
- Inducing modulus changes in polymer nanocomposites
- Mechanically gradient nanocomposite films
- Microtensile testing of mechanically-dynamic polymer nanocomposites
- Polymer nanocomposites for electric energy storage.
- Synthesis of diamond nano-powders
- Alginate–Polyethylene Oxide Blend Nanofibers
- Modeling of nanofiber thermal and mechanical properties

Carbon Fiber Composite Manufacturing Challenges…….

Low Cost Carbon Fiber ($3-$5/lb)

Alternative precursor materials (commodity PAN, lignin, polyolefin)

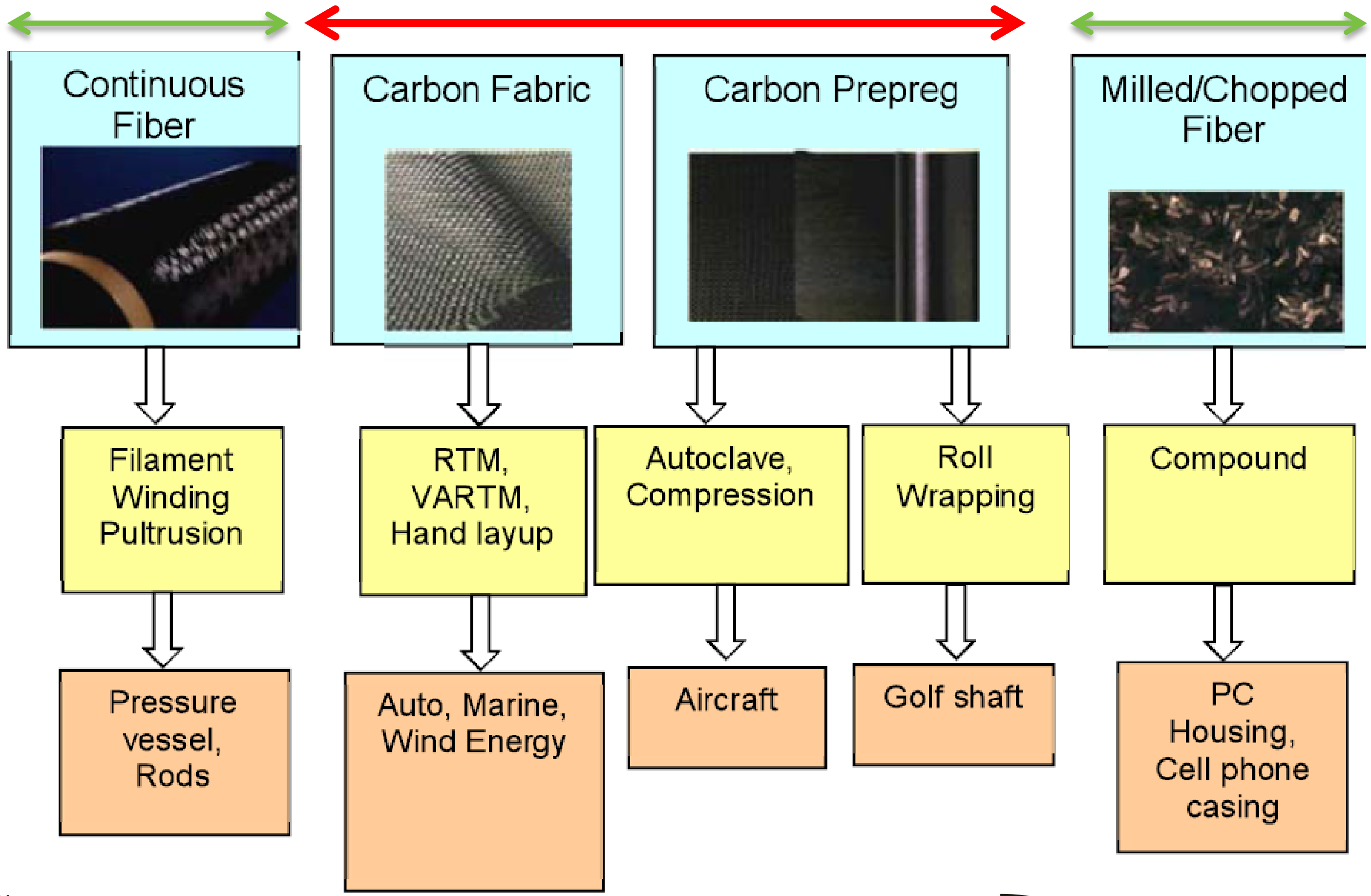
Processing (Plasma Oxidation, Microwave Assisted Plasma, Advanced Stabilization, Surface Treatment)

Cycle Time Reduction (<5 min for mass prodn.)

Robotics Layup

Induction Process (Plasan)

Low viscosity fast curing resins (Dow Chemical)



Source: Lucintel (2013)

Cheaper raw material, faster manufacturing process, low part cost

Expensive raw material, slow manufacturing process, high part cost

Technology Pathway

Affordable, Hi-throughput Manufacturing

Automotive		Wind, Oil & Gas, etc.
>100k upa**	*Volume**	1-10k upa**
~1 meter	*Length**	~10-100 meter
10 → 1 minute	*Cycle time**	10 → 1 hour

Source: BMW via CompositesWorld

***** Order of Magnitude***

***** units per annum***

Source: Fives (formerly MAG)

- **Automated unit operations**
- **Processes consistent with structural optimization, hybridization**
- **Affordable materials/formats and scrap minimization**
- **Adaptable tooling**

New processing methods for *graphene-reinforced* nanocomposites

The Promise: ***Graphene*** is the stiffest and strongest material in the world, and it exhibits high thermal and electrical conductivity.

The Limitations: Graphene is too expensive (~$600,000/kg), and poor matrix bonding and dispersion cause the composite properties too fall short of predicted values.

Key Technology

- Develop new methods to mass produce graphene through mechanical exfoliation of inexpensive graphite
- Develop methods to functionalize graphene to promote covalent bonding to the polymer matrix
- Explore in situ processing methods that combine graphite conversion to graphene and graphene functionalization into a single composite processing method

State-of-the-Art

- Lab scale demonstrations but no commercialized or scalability studies

Challenges

- Large scale graphene production is primarily done through chemical processes and mechanical exfoliation is mainly done on the micro-scale
- Functionalization requires an additional chemical processes and may result in decreased properties
- Significant research funding is needed to develop comprehensive combinatorial manufacturing processes

One-step processing methods for thermoplastic nano-FRPs and FRPs

The Promise: ***Nano-FRPs and FRPs*** offer a lightweight alternative with many property benefits (specific strength, corrosion resistance).

The Limitations: Most nano-FRPs and FRPs must be processed in multiple steps to achieve adequate dispersion and distribution of the reinforcing agent within the matrix, followed by part fabrication.

Key Technology

- Develop new methods to mass produce nano-FRPs and FRPs in one processing step to lower manufacturing and energy costs
- Develop single screw extrusion and injection molding methods that do not require a pre-compounding step
- Explore multi-scale reinforcement (nano/micro carbon fiber) of an FRP to provide a wider range of property benefits

State-of-the-Art

- Mixing and part fabrication is typically achieved using twin screw extrusion (or a batch process) followed by injection molding

Challenges

- Achieving good dispersion and distribution of the reinforcing agent (especially nano)
- New mixing element designs for single screw extrusion and injection molding
- Significant research funding is needed to develop one-step combinatorial manufacturing processes

hierarchical multi-scale reinforced polymer matrix composites

The Promise: A hierarchical arrangement of reinforcement at multiple scales should result in increased strength, functionality, and opportunities for optimization for multiple applications.

The Limitations: Lack of fundamental understanding from modeling, scaling, and multi reinforcement processing technique development.

Key Technology

- Develop methods to introduce nano-reinforcement into polymers with the aim of using these nano-reinforced polymers in further composite manufacturing processes at larger scales such injection molding, 3D printing, pultrusion, etc....
- Develop reliable modeling techniques that account for both process and mechanics for the design hierarchical composites

State-of-the-Art

- Nature provides many examples of using hierarchical design to yield optimal performance from available constituents.

Challenges

- Some research is demonstrating and producing similar results but it has not been achieved with high performance materials or on a large scale

The Promise: ***Recycled RFPs*** offer a low cost, plentiful source for raw materials, and when combined appropriately, high specific strength for structural applications that are corrosion resistant and maintenance-free.

The Limitations: FRPs using recycled polymer as the matrix are not time-tested in the field, as are traditional materials.

Key Technology

- Develop new methods to model long-term properties of recycled FRPs
- Explore carbon nano fiber and inexpensive graphene reinforcement to create recycled nanocomposites

State-of-the-Art

- Bridge demonstration projects at US Army bases and small-scale use as railroad ties

Challenges

- Acceptance of a new material in general construction applications
- Development of a reliable method to determine the allowable design stress for a specific material and application so that the material behaves creep resistant over a long time period
- Significant research funding is needed to develop lower cost manufacturing processes, reliable predictive models, design guides for end users, and new nanocomposite recycled FRPs

High Performance Composite Manufacturing

Autoclave Processing

Advantages:
+ High quality parts

Disadvantages:
- Expensive
- Resource-intensive
- Slow and inflexible

New processes must address disadvantages but <u>maintain</u> part quality and consistency.

Vacuum bag-only consolidation using ovens or heated tooling

+ Lower capital and operating costs
+ Improved production flexibility, rate
- **Defect reduction strategies for effective, consistent processing**

In-situ process monitoring and adaptive cure control

+ Fundamental understanding
+ Adaptive processing for optimal quality and energy use, lower scrap rates
- **Accurate, reliable, implementable monitoring methods**

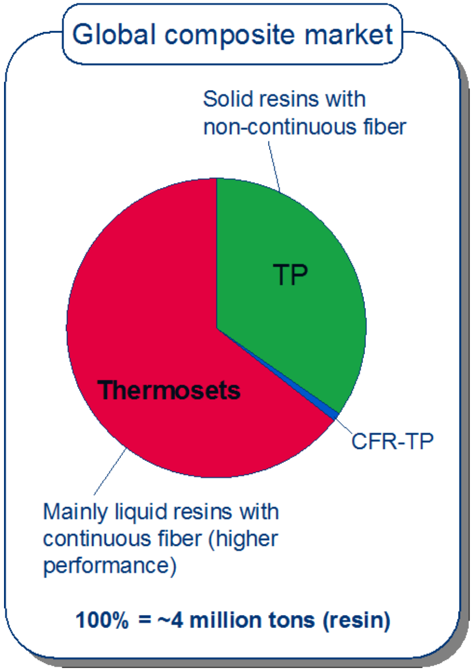
Reduction, reuse and recycling of scrap material

+ Reduction in material demand
+ Recovery of embodied energy
+ Novel applications for high performance materials
- **Process control for reduced scrap**
- **Cost-effective reuse, recycling methods**

Fundamental Research → **Scale-Up Studies** → **Technology Transition**

Hybrid Thermoset-Thermoplastic Systems?

	Advantages	Disadvantages
Thermoset	**Liquids at RT** **Better wet out**	**Non-recyclable** **Inability to reprocess/form** **Slower mold times**
Thermoplastic	**Thermoformable** **Recyclable** **Faster mold times** **Easier joining**	**Solids at RT** **Difficult wet out** **Traditionally, short fiber only**



- **Recyclability**
  - Methods (physical or chemical)
  - Material recycled (matrix and/or fiber)
  - Mechanism of recycle (matrix pyrolysis vs. “clean” depolymerization)
- **Repairability**
  - Time/energy savings versus new
- **Fit into existing manufacturing equipment**

Mfg Processes

Reducing the Cost of Composites

Processes for Manufacturing

- Out of autoclave
- Rapid cycles
- Large tow processing
- Simplified tooling

Advanced Materials

- Enhance processability
- Enhance performance and efficiency to reduce raw material usage
- Enable repairability

Tooling Technologies

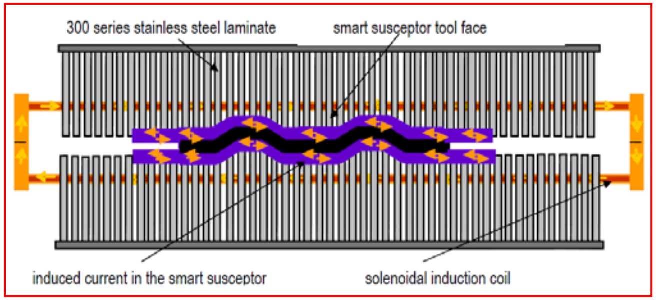
- Reduce manufacturing & assembly steps
- Minimize secondary processes
- Enable fabrication of maximum structural efficiency
- Reduce part count

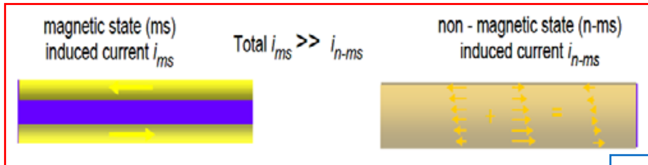
Design for Material Optimization and Manufacture

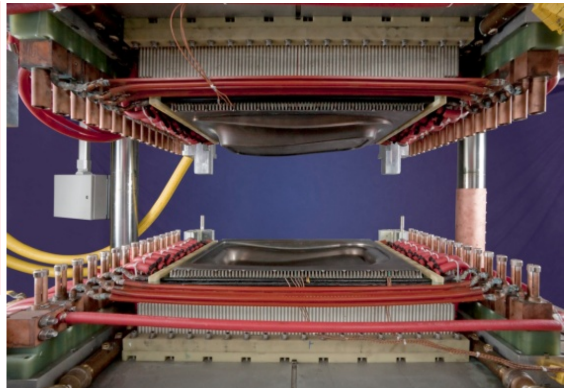
- Maximize material utilization
- Material cost should reflect product needs and market
- Sophisticated analysis techniques
- Reduce design uncertainty to maximize use of material potential

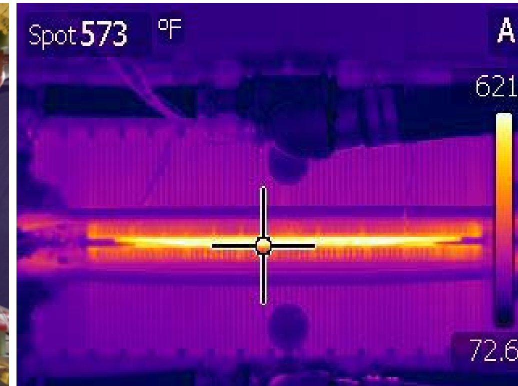
Reducing the cost of composites

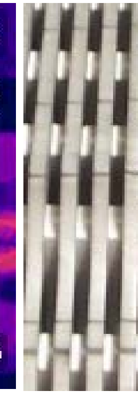
1. More applicable for broad range of markets and applications
    1. Advanced Materials
        - Enhance processability
        - Enhance performance and efficiency to reduce raw material usage
        - Developed for repairability
    2. Processes for manufacturing
        - Out of autoclave
        - Rapid cycle
        - Large tow processing
    3. Advanced design for material optimization and manufacture
        - Maximized cost/performance of fibers
        - Sophisticated analysis techniques
        - Reduce design uncertainty to maximize use of material potential
    4. Tooling technologies
        - Reduce manufacturing / assembly steps
        - Minimize secondary processes
        - Enable fabrication of maximum structural efficiency
        - Co-curing





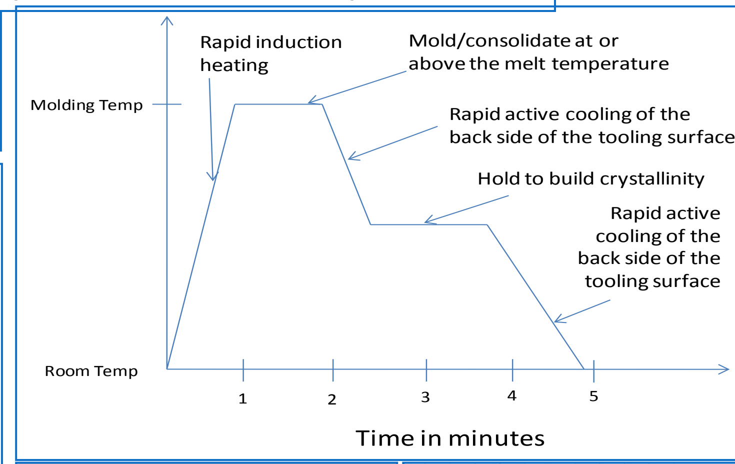


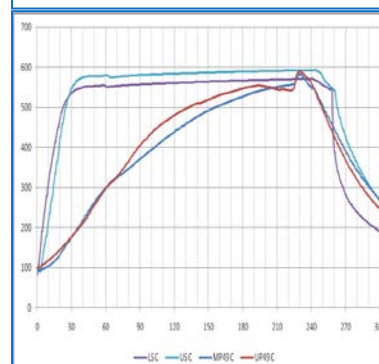


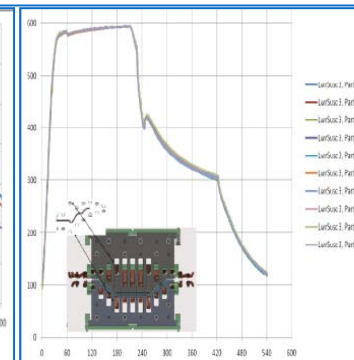


Mold surface - Heated by induction - Cooled by Air/water

Research funding provided by DOE – AMO GO-18135
(Information from - Final Technical Report)







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Enabling Technologies and Approaches Red Team

(e.g. design methods and databases, analytical tools, nondestructive evaluation, damage tolerance, joints, repair, other)

Enabling Technologies and Approaches
Red Team

- ICME is *Integrated* Computational Materials Engineering
  The integration of materials information, captured in computational tools, with engineering product performance analysis and manufacturing process simulation.
- Current level of development: Generally TRL 3-4, with selected (few) examples at TRL 7 and beyond
- Key technical limitations/challenges
  - Need for open demonstrations of the integrated approach
  - Democratizing tools and especially integration approaches
  - Developing open datasets, data management approaches and standards
  - Growing the small community of specialists trained in ICME techniques

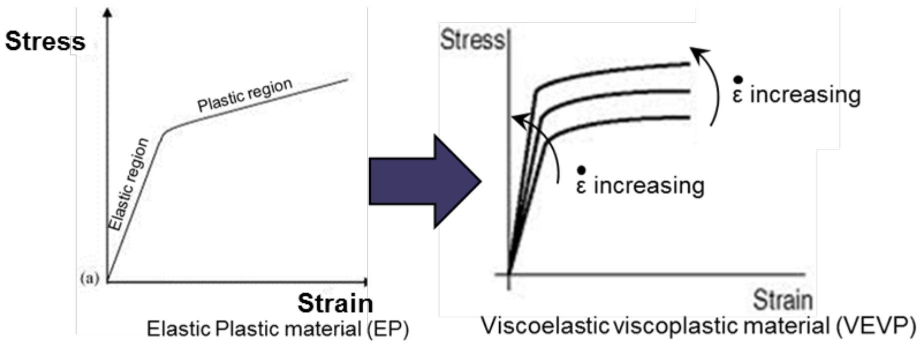
Reducing Cost of Wind Energy

- Primary metric for wind energy is **Cost of Energy** ($/kWh)
  - 10% longer wind turbine blade captures ~ 20% more energy
  - 10% longer wind turbine blade weighs (costs) ~ 33% more
- Composite blades have lengthened economically by:
  - Incorporating new glass fiber and carbon fiber materials with improved material properties
  - Incorporating more structurally efficient designs (thick airfoils, swept blades, flat-back airfoils)
- Continued blade improvements will require:
  - Materials with improved specific-strength, specific modulus, and specific fatigue-life per dollar
  - A move from safe-life to damage tolerant design methodology incorporating improved models that sufficiently represent damage growth and residual properties
  - Improved manufacturing process and inspection technologies to ensure manufactured part meets the design requirements

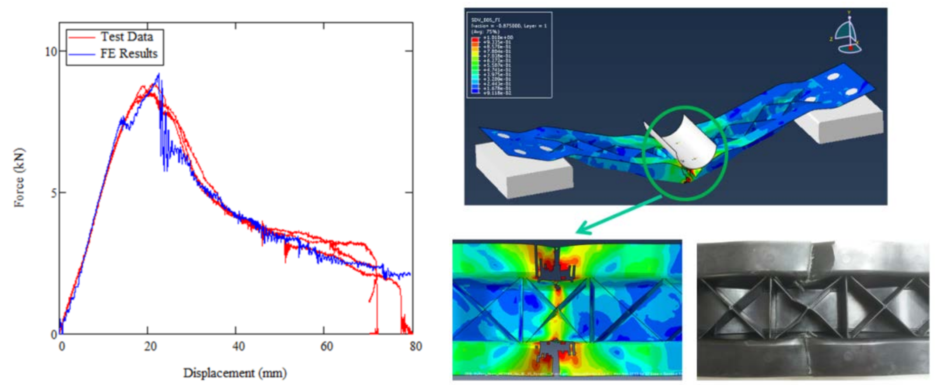
Enabling Technologies – Modeling and Simulation Tools

- Composite Design process requires simulation to failure of large parts.
- Extension of metal based failure criteria is needed.
- Elastic-plastic laws need to be extended to include viscoelasticity.
- Quasi-static, High-rate (collision), and Fatigue under different loading modes, needs to be modeled.
- Material laws for weld-lines and bond-lines are needed.

Viscoelasticity



Failure Prediction



Need Advanced Material Laws for Multiphase Time-dependent Fiber Reinforced Polymer Composites

Automated Fiber Placement

- Automated Layup up composite material- typically pre-impregnated material
  - Gain strength and improved light weighting by utilizing fiber direction
  - High speed layup and machining is required to meet production rates
- Applications;
  - Wind blade shells & Spar Caps
  - Urban mass transportation vehicles
  - Containers for compressed liquid (oil, gas, etc.)
- TRL 9; equipment is already used in aeorspace production.
- Key limitations/challenges: costly material has been the road block thus far, however, IMT has utilized less expensive carbon and glass prepregs as we work with material suppliers. Development should continue!

Red Team: Enabling Technologies

Design Tools that Impact Manufacturing

- In the automotive industry, engineering design software does not include composites in material databases, nor is this information broadly shared across OEMs.
- There are some design tools that incorporate manufacturing processes, but these are more prevalent in markets such as aerospace.
- The development of a more universal comprehensive materials and products database for a range of users and markets has huge implications.
  - Integrating manufacturing steps that reduce energy, increase production rate, and enable the design of low costs solutions is the goal
- Limitations exist in evaluating the long-term durability of composites that could impact design and manufacturing plans.
  - Integrating composites durability across to a range of environments, and incorporating design and manufacturing efficiencies
  - Target durability criteria including fatigue (wind energy) and impact (automotive) would provide enhanced energy efficiencies
- A lack of a cross-industry, consortia-based dialogue is a barrier that can begin to be addressed by today's audience

Nanomaterials such as carbon nanofibers are significantly more cost effective compared to carbon nanotubes, and are mass produced

1. Incorporation of *carbon nanostructures* (e.g. carbon nanofibers, CNTs, graphene) for matrix modification and functionalization that can serve the purpose of self-sensing, lightning strike mitigation, damage sensing, fire suppression, EMF shielding etc.
2. Synthesis of carbon nanostructures with *high rate production* in open atmosphere that can cover very large areas and existing structures
3. Use of carbon nanostructures with the ability to tune the properties of and employ *low cost matrices* in fiber composites

Carbon nanomaterials have the mechanical strength of some of the strongest commercial grade carbon fibers, and much higher interfacial adhesion properties that can improve the interfacial shear strength

1. Investigate nanostructural level multifunctional mechanisms and how these mechanisms relate to macroscopic performance
2. Inquire methods to functionalize nanomaterials for optimal adhesion and dispersion control so that *design margins* (related to cost effectiveness) can be reduced. Relatively high *design margins* are major barriers preventing the introduction of new composites and a more widespread use of modeling
3. Experiment with the compatibility of nanostructures with matrices (eg at the level of individual nanofibers) and employ the measured mechanical properties in computational models to design and then synthesize matrices with *tunable* mechanical behavior to implement *cost effectiveness*

Production of layered fiber reinforced or monolithic composite materials with for adaptable design space and tailored functionality with time and cost effective manufacturability and in-situ repairability

Composites Virtual Factory Hub Overview

- Concept Validations
- Tool use in problems
- Specific requirements

- Feedback on tools
- New tools needed

OEM's

Composites Community

Composites Virtual Factory HUB

Powered by HubZero® Technology

- Virtual manufacturing simulation
  - Commercial tools
  - Emerging tools
  - Prioritized needs analysis
- Composites community dialogs
- Web access to computing power

- Data Sets

- Requirements

- Individuals: expert to novice
- Companies: OEM to Tier 1-2

- Innovations

- Display simulation tools
- Beta Versions of new

- Powerful simulation tools

- New codes
- Needs analysis
- User education

Tier 1 and Tier 2 Suppliers

Commercial Software Providers

- Organize Hub by:
  - Complexity of tool
  - Manufacturing process
  - Function
  - Material system

Objectives

1) Engage OEM, Tier 1, Tier 2 communities
2) Provide a platform to use tools needed for composite materials in manufactured products
3) Provide a pathway to develop optimum manufacturing processes

Key Outputs

- Integrated OEM/Tier 1/Tier 2 Community
- Simulation software
- Integrated suites for each process
- Enhanced Tier suppliers
- Direct comparison of manufacturing processes
- Optimum solutions

- Sponsored by:
  - Consortium memberships
  - Government Agencies
  - User fees
  - Royalties returned to Hub

Characterization and Nondestructive Testing of Manufactured FRP, towards Certification by Analysis

Focus Area: RED (Enabling Technologies)

Define *allowables* versus *defects*

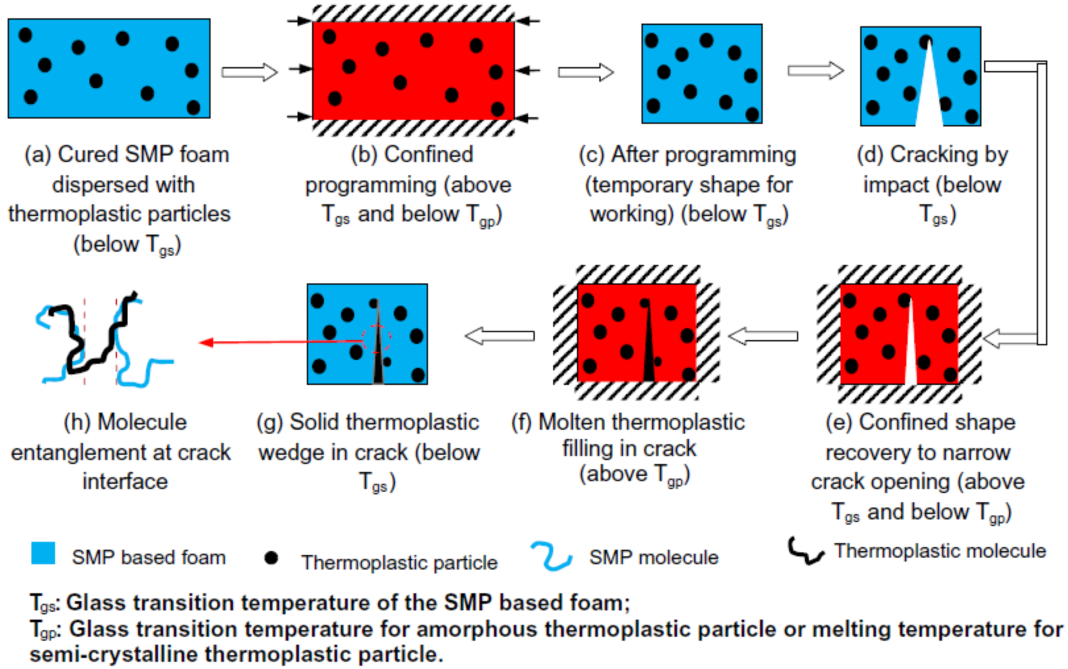
- How does the presence of an unintended discontinuity in manufactured FRP affect its future performance?
- Need to classify unintended discontinuities and set bounds on acceptability
- How? By experimentation including micro-/macroscopic characterization, linked to damage progression modeling

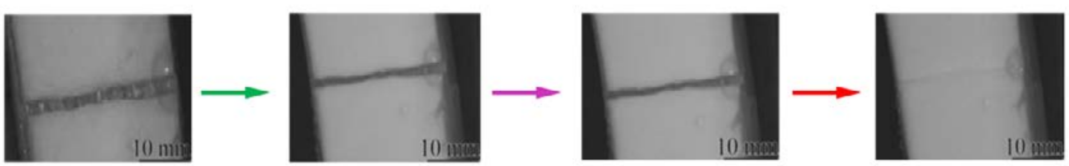
Models and NDE development

- Develop and validate models of damage/degradation progression
- Link damage/degradation to observable material parameters
- Develop NDE techniques to measure those observables e.g.
  - IR spectra, THz & microwave imaging/spectra, dielectric loss
  - Ultrasonic attenuation & non-linear measurement approaches

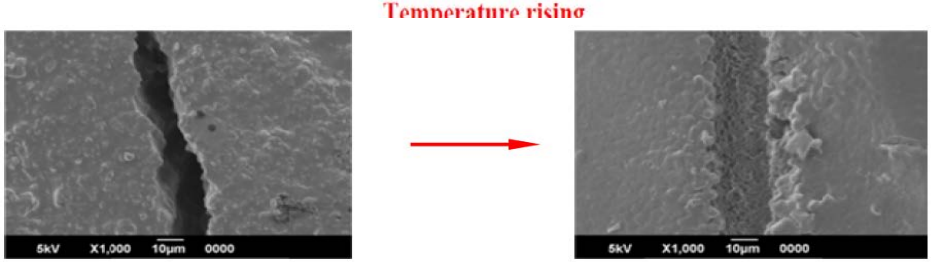
TRL 1-3, MRL 3
Challenges: Results will vary by material system; need to find universal approaches

Bio-inspired self-healing and bio-inspired joint for coupling dissimilar composites

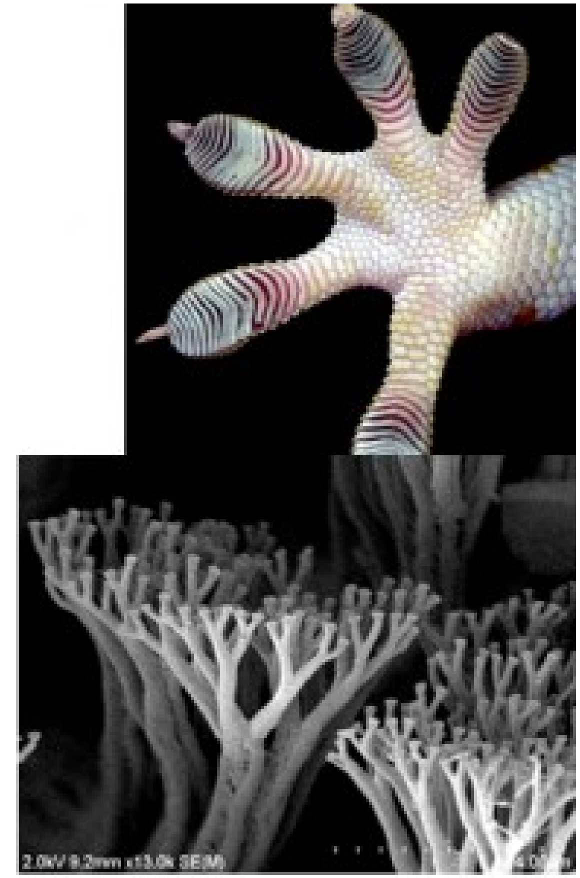




Temperature rising



(b) SEM images of healing process



A gecko foot hair inspired stimuli-responsive coupler for joining dissimilar composite

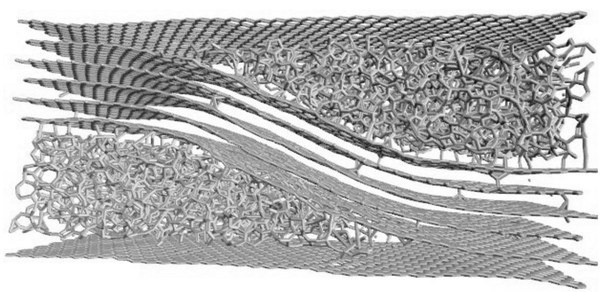
http://creationrevolution.com/2010/12/walking-on-ceilings/

G. Li and N. Uppu. *Composites Science and Technology*, 70(9):1419-1427, (2010).

G. Li, H. Meng, and J. Hu. *Journal of the Royal Society Interface*, 9(77): 3279-3287, (2012).

Simulation & NDE Needs

- **Simulation** ⟷
  - **Length scale from nm (carbon crystallites and flaws in fibers) to 100 m (turbine blade)**
  - **Time scale from milli-seconds (chemical reactions) to hours (turbine blade curing)**
  - **Processes, mechanics, interfaces, etc.**
- **NDE**
  - **Desirable to cover entire length scale but μm - mm dominant**
  - **Non-contact 3D NDE auto parts in < 1 min**
  - **Factory floor, real-time, in-line, 6σ reliability**
  - **Address multiple materials, part sizes, complex geometries**



Left: Graphical representation of carbon fiber basic structural unit with all dimensions < 10 nm (source: Rice University)

Right: Fabrication of 75 m wind turbine blade (source: Siemens)

Mass Manufacturing of Modular Composite Panels for Energy Efficient Building Systems

Vision: Zero energy consumption in 10 years

Mission: to reduce energy consumption by 60% thru material (shell panel) production and daily operation, and also reduce construction wastage by 50%

USDOE Building Technologies Office – Whole Building Approach Focus Area

Building envelope, next generation attic and roof systems

Objective: to cost-effectively develop and manufacture advanced composite modular wall panel and roof systems (no truss) for buildings

1. Mass produce durable, strong and stiff composite panels made of glass and/or natural fibers and resins with low embodied energy by Pultrusion or High Temp Infusion

2. Easily installed modular panels with built-in joint integrity

3. Produce sandwich panels for extreme thermal resistance and superior fire performance

4. Introduce modular panels with photovoltaic cells

5. Panels with utilities

6. Roof panels with no shingles but skid resistant surface

7. Roof panels with no separate gutter system

Game Changing Technologies

The market competitiveness and cost-effectiveness of the proposed product will be achieved through: 1) modular design; 2) energy saving system with lower embodied energy in production and lower daily energy consumption; 3) waste reduction; 4) mass manufacturing; 5) minimization of field work; and 6) use of recycled materials.

Summary: Prefabricated modular roof panel system will include insulation, shingles, joining mechanism with finished ceiling, gutters, colors of choice, even solar panels or roof openings for sun light, and other green building features

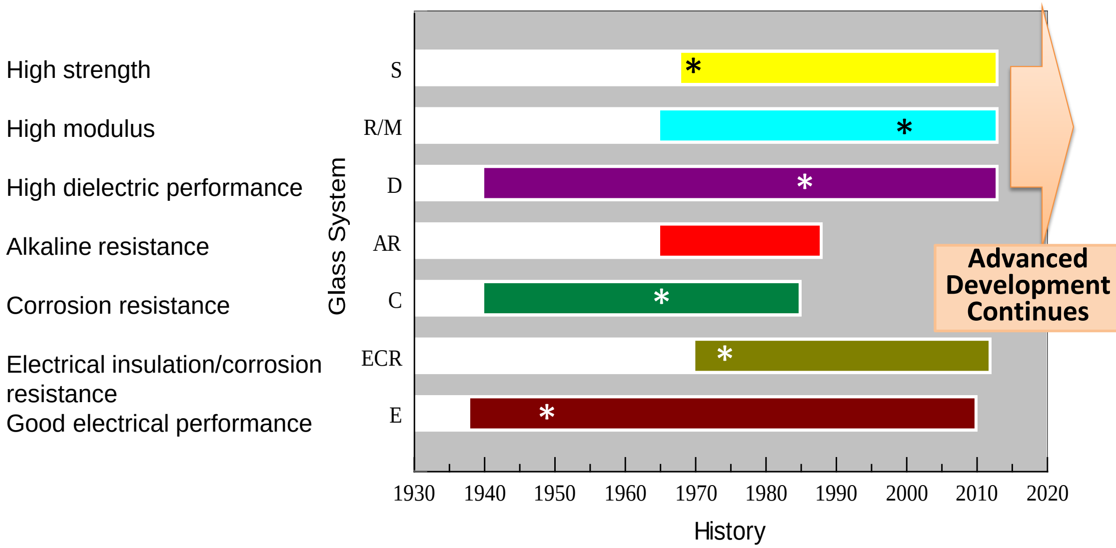
Recycled and Emerging Materials Green Team

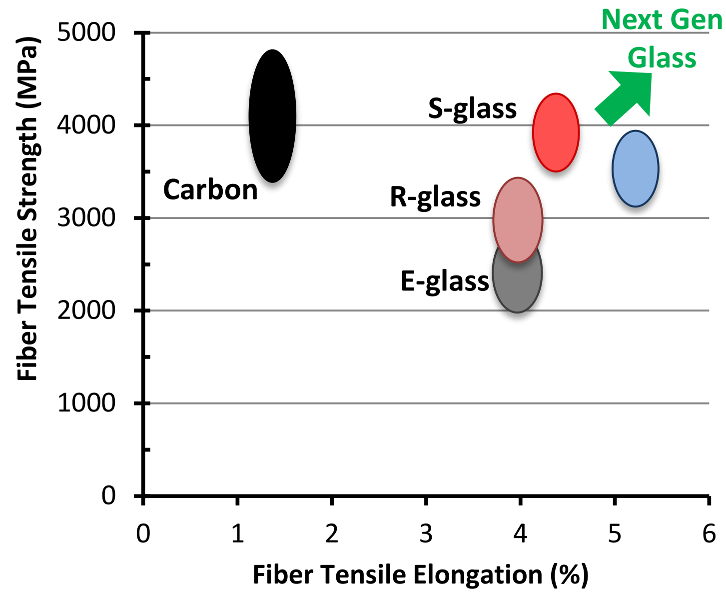
(e.g. recycling carbon fiber, renewable precursor materials, advanced glasses, nanomaterials, other)

Recycled and Emerging Materials
Green Team

- Advancement of **Resin & Curative Technology** for fiber reinforced composites is key part of **Process Optimization**
  - Faster Feed Rates, Quicker Cure, High-Volume Production
  - Improved Toughening & Adhesion, Lighter Weight
- Innovative Products Support Clean Technology through Synthetic & Renewable Materials
- Align Efforts with **Key Material & Health Challenges**
  - Carbon fiber, graphene, succinic acid, glycerol, 3-HPA
  - Bis A, Styrene, Cobalt, Formaldehyde, Isocyanates
- Use “Open Innovation” to Connect & Develop with Academic, Government & Industrial Partners in our Core Chemistries & Markets
- Must understand market triggers for commercialization of renewables
  - $ Value Δ vs. Parity
  - How can incentives help – “Energy Star” program, Wind PTC and set-asides

Advanced Glass Fiber Compositions





Composite market size and requirements are driving advanced fiber compositions**

** "High-Performance Glass Fiber Development for Composite Applications," Hong Li, Cheryl Richards and James Watson, *Intl. J. of Applied Glass Science* (2013).

- TRL: 4, MRL: 3
- Key technical challenges:
  - Higher processing temperatures (required for high-performance fibers)
  - Scalable melt technologies with reduced capital

Thermoplastic Composite Materials

Coordination and Integration of Continuous Fiber Thermoplastic Materials within Commercial/Automotive and Military Aerospace Industries

Aerospace Industries requirements:

- Low Cost Tooling
- Recyclability
- High Impact Strength
- Rapid Production

Common practices in the Commercial/Automotive Industries

Coordination between Industry/Trade Organizations to expand the utilization of Thermoplastic Composite materials in the above referenced industries

Green Team: Recycled & Emerging Materials

Technical Challenges to meet market needs

- Successful composites recycling strategies include grinding and pyrolysis. Recycled composites have been used in Europe in the cement kiln process as fuel and repurposed in some new technology parts.
  - These applications are low value and low volume
- Economics of the recycling process and final repurposed products are challenges to meet DOE's 80% recyclability goal, as well as industry, institutional, and end-use market factors.
  - New strategies or process improvements are needed to meet economic drivers
- Technology-market development is needed to overcome limitations in:
  1. Developing energy efficient processes to separate polymer resins from fiber reinforcements
  2. Restoring original mechanical properties to recycled fiber reinforcements
  3. Developing new products using recycled composites.
- A lack of a cross-industry, consortia-based dialogue to combine these tools with a top-down design approach is a barrier that can begin to be addressed by today's audience
  - OEMs to dictate cost and performance requirements and the recycling value chain to obtain control over the material scrap streams

Carbon Fibers are Recoverable from Polymer Matrix Composites

- Process research conducted has established the technical and economic feasibility of reclaiming carbon fiber from composite substrates
- Two processes were developed:
  - ✓ Thermal decomposition reclaims carbon fiber from thermoset and thermoplastic substrates
  - ✓ Solvent dissolution reclaims carbon fiber from thermoplastic substrates
  - ✓ Process conditions (e.g. residence time and temperature) are optimized based on substrate composition
- Physical properties of the reclaimed carbon fibers are adequate for chopped fiber applications

Ref. Jody, B.J., J.A. Pomykala, E.J. Daniels, and J.L. Greminger, "A Process to Recover Carbon Fibers from Polymer-Matrix Composites in End-of-Life Vehicles," JOM (August 2004.)

Torrefaction: Emerging Materials

Torrefaction involves heating plant or wood biomass, in a low-oxygen environment, liberating water, volatile organic compounds (VOC's), and hemicellulose (HC) from the cellulose and lignin.

Torrefied materials can be used for the following:

- **Bio-Plastics:** One can blend torrefied material with polymers to make stronger, lighter and water-resistant plastics.
- **Metallurgical Coal Alternative:** US Steel has found that torrefied wood chips can displace metallurgical coal in the coking process.
- **Bio-Compound Extraction**: Torrefaction can extract high-value bio-compounds, from genetically-modified bio-crops, while also torrefying the remaining biomass.

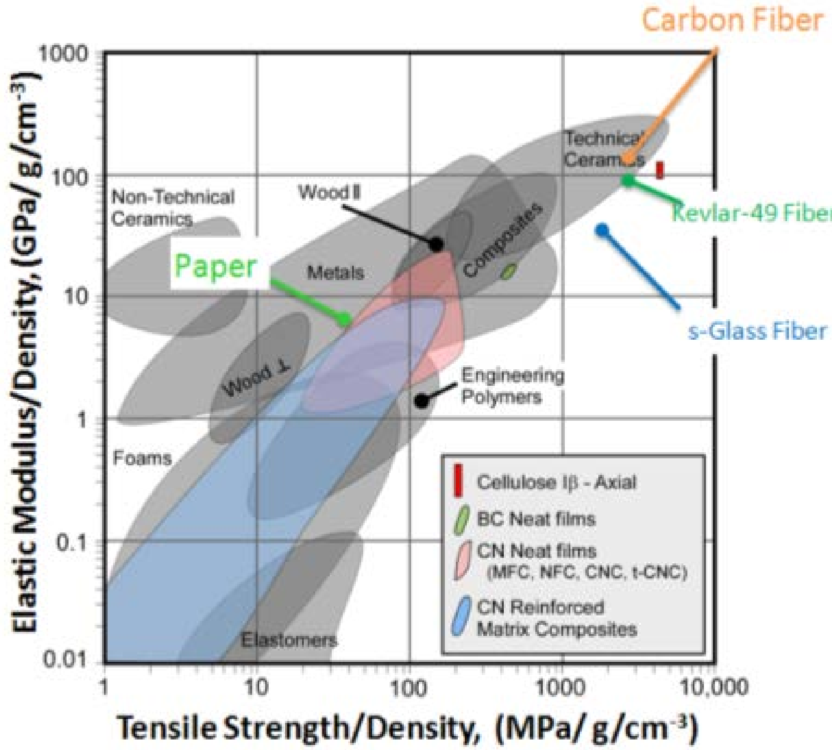
Cellulosic Nanomaterials in Composites

BENEFITS

- High strength and stiffness
- Potential for lightweight, high-performance composites
- Can be made compatible with polymer
- Scale up quickly to produce commercial quantities
- Low cost of production relative to carbon fiber and glass fiber – projected $1 per lb approx
- Natural, renewable material not produced from fossil sources
- Favorable LCA compared to reinforcement alternatives

TRL 2-5:

- Research underway worldwide



Nanocellulose has specific strength and stiffness comparable to alternatives.

Reference: Moon, Robert J., et al. Cellulose nanomaterials review: structure, properties and nanocomposites, *Chem.Soc. Rev.*, *Royal Society of Chemistry*, Critical Review, 2011. DOI: 10.1039/c0cs00108b.

Nanomaterials enable higher performance products and reduce manufacturing energy usage

Recycled and Emerging Materials – Green Team

- Nanomaterials are an emerging technology that can help reduce energy usage and increase production rate in CFRP manufacturing
- Enable higher performing and differentiated products
- Enhance mechanical, thermal, electrical properties allowing for weight savings and multifunctional structures (tougher, lighter, more durable components), substantially lower life-cycle energy consumption
- Thermal/electrical – enhanced through-thickness conductivity can enable decreased cure times, integration as cure detection sensors, embedded heaters for OOA, QC inspection
- TRL – 7 integration into some products on the market already
- MRL – 6 some doing pilot scale/low-rate initial production
- Key challenges – process integration difficulty, need higher production volumes, lower cost, and compatible form factor for CFRP, greater clarity on EHS regulatory environment

Alternative Carbon Fiber Precursors

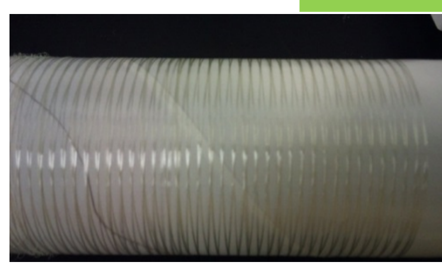
- **Alternative carbon fiber precursors need:**
  - **Low cost feedstock**
  - **High carbon yield**
  - **Low cost to produce precursor fiber**
  - **Multiple sources (either in resin or fiber form) with order 1M ton potential scale**
  - **What are the new chemicals, materials, & processing sciences beyond current fiber forming polymers as precursors?**

- **> 95% of industrial CF currently made from PAN**
  - **≥ 500 ksi tensile strength**
  - **≥ 33 Msi tensile modulus**
  - **24k – 80k continuous tows**

Precursor	T/MRL
Textile PAN	4 - 6
Melt-spun PAN	2 - 3
Polyolefin	3 - 4
Functional lignin	4
Structural lignin	2 - 3

Polyolefin pellets

Lignin powder



10-filament, melt-spun PAN tow

Textile PAN precursor (source: FISIPE)

Recycled & Emerging Materials

- **Recycled carbon fibers need:**
  - **Part production technologies suited to nontraditional feed formats**
  - **Reformatting technologies**
  - **Recovery of carbon fiber tow would be a huge breakthrough**
  - **May require surface re-engineering**

Reclaimed carbon fibers (source: Adherent Technologies)