CompositesWorld.com

CompositesWorld

Next-Generation Composite Materials & Processes

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Agenda

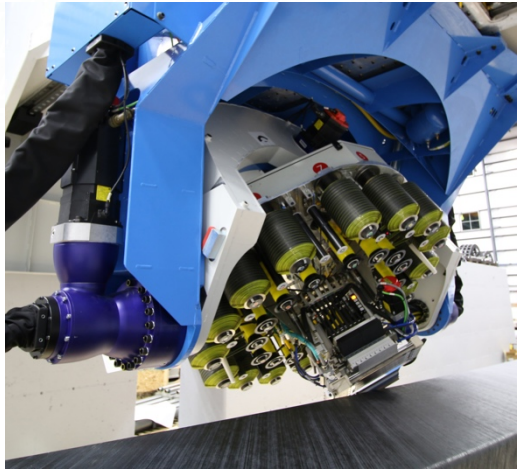
- Jeff
  - Where are we?/We are here
  - Continuous fiber AM
  - OOA aerostructures
  - High-volume RTM
  - Narrow tapes ATL
  - Novel preforms/preforming
- Ginger
  - Sensors for process monitoring
  - Pin-based tooling systems
  - Thermoplastic epoxies
  - Fiber-reinforced concrete
  - Hydrogen propulsion in aerospace
- Hannah
  - Graphene in composites
- Q&A

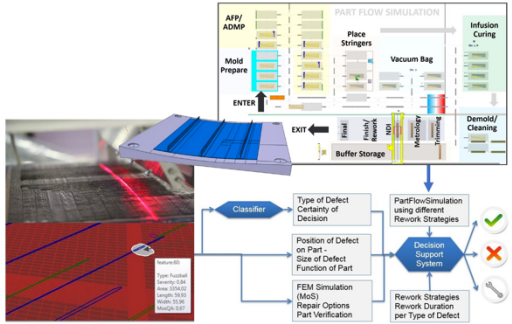
CompositesWorld

- Mission:
  - Provide in-print, digital and in-person coverage of the global composites manufacturing industry, including the design, tooling, fabrication and finishing of composite parts and structures.
- Products
  - Printed magazine (monthly)
  - CompositesWorld.com
  - CW Today newsletter (3 times/week)
  - CW EXTRA newsletter (2 times/month)
  - CW Talks: The Composites Podcast
  - CW Webinars
  - Carbon Fiber conference (17-19 November)

Where are we?

- Composites, the first 40 years:
  - Birth and early-stage development
  - Rapid materials and process development
  - Low-volumes dominate
  - Supply uncertainty (esp. CF)
  - Tribal knowledge; lack of broad application
  - Manual manufacturing processes dominate
  - Marine, some defense, aerospace, sporting goods
- The last 15 years
  - Adolescence, early adulthood
  - Aerospace breakthrough: A380, 787, A350, F-35, 777X
  - Automotive increments: BMW, Audi, Ford, Corvette, EVs
  - Wind turbine blades breakthrough
  - Continued M&P dynamism
  - Supply stability
  - Gradual shift away from manual processes
  - Persistent tribalism, but wider adoption

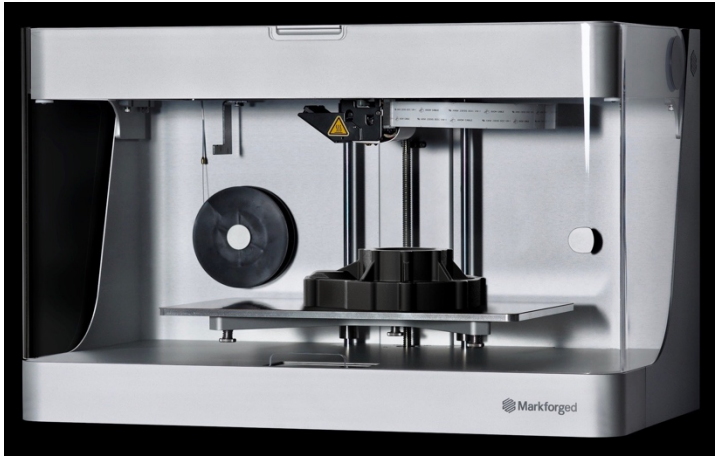




We are here

- The next 20 years:
  - Adulthood, middle age
  - Higher volumes in all end markets
  - Full industrialization, widespread automation
  - Manual processes, interventions minimized
  - Process control, in-situ QC, repeatability, consistency
  - Data harvesting, data integration, service portalization
  - Design tools evolved (no more margin of error)
  - Qualification acceleration
  - Sustainability, efficiency
- Markets
  - Aerospace: New single-aisles; electric, hydrogen propulsion; eVTOLs; hypersonics; space transport
  - Automotive/ground transport: EVs
  - Wind: Longer, more durable, less expensive blades
  - Architecture: Fiber-reinforced concrete, building structures

Continuous fiber AM



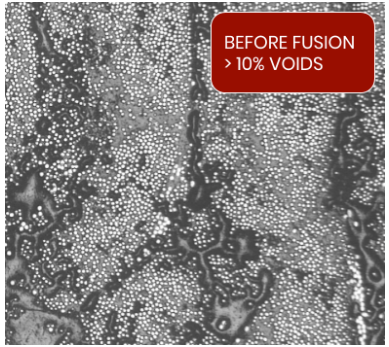
Markforged's Mark Two desktop printer applies continuous fibers in additive manufacturing. Markforged was first to market with a continuous fiber system in 2014. Source | Markforged

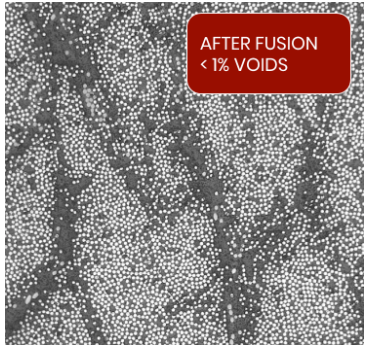
- Merging of traditional additive manufacturing concepts with highly engineered automation and application of continuous fiber reinforcements
- AM meets AFP
- Suppliers and technologies represent a range of capabilities, specialization
- Complex software/controls; machine learning
- Highly dynamic, high-innovation environment
- Strong potential for disruption
- Applications:
  - B2C products
  - B2B finished parts

Continuous fiber AM (cont'd)

Photo from 9T Labs news regarding Setforge cooperation.
Source | 9T Labs

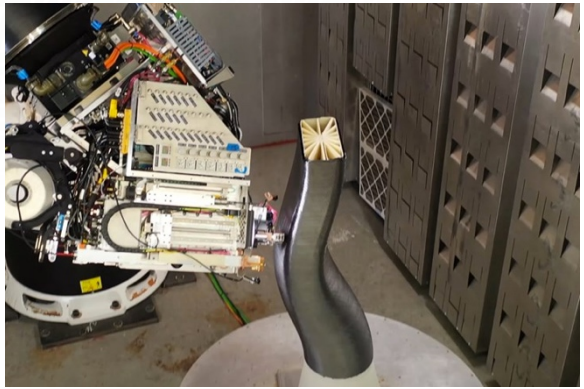
- 9T Labs (Zürich, Switzerland)
  - Red Series technology suite
  - fibrify design software
  - Two-step fabrication: Build Module (FDM preforming), Fusion Module (consolidation)
  - Fibers: Carbon (Hexcel AS4)
  - Resins: PA, PEKK
  - <1% porosity, 60% FVF



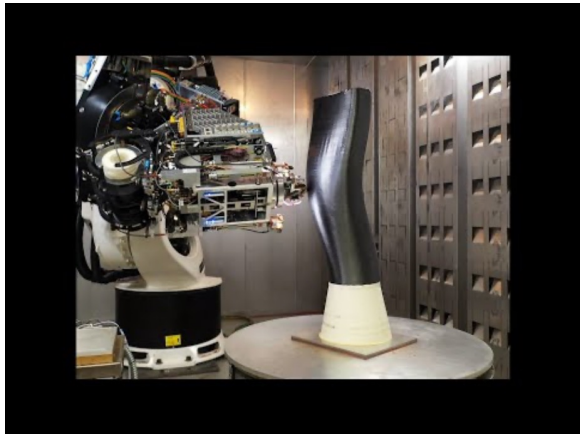


Source | 9T Labs

Continuous fiber AM (cont'd)



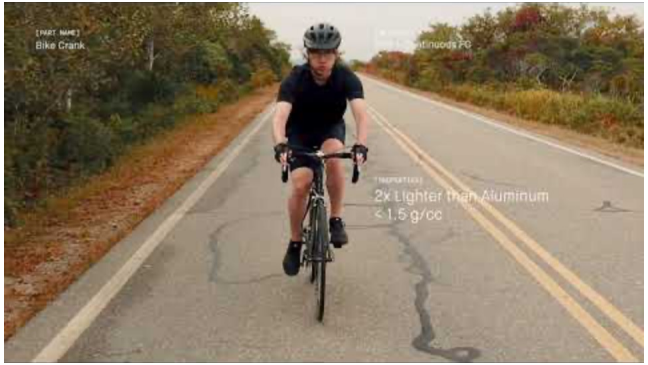
Electroimpact's SCRAM. Source | Electroimpact



- Electroimpact (Mukilteo, WA, US)
  - Manufacturer of AFP and ATL systems for aerospace
  - Scalable Composite Robotic Additive Manufacturing (SCRAM)
  - "True" 3D printing
  - 6-axis robotic system
  - Tool is built up on heated build platform via fused filament fabrication (FFF)
  - Tool is overwrapped with continuous fiber thermoplastic tape, with laser heating for consolidation
  - Tool is washed out
  - Process is ideal for applications where laying up continuous fiber is geometrically impossible or otherwise difficult
  - Resins: PAEK, PEKK, PEEK, PA, ABS
  - Fibers: Carbon, glass, boron

Watch on YouTube

Desktop Metal Fiber additive manufacturing system. Source | Desktop Metal



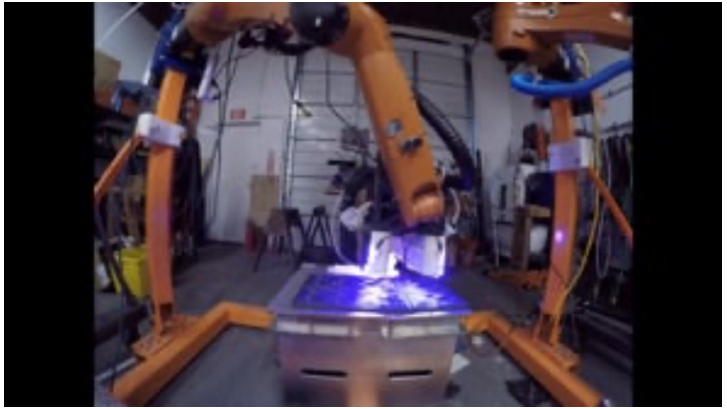
Watch on YouTube

Continuous fiber AM (cont'd)

- Desktop Metal (Burlington, MA, US)
  - Fiber LT/HT products (shipping 4Q 2020)
  - 2.5D fused filament fabrication (FFF) combined with in-situ tailored thermoplastic tape placement (AFP)
  - Two printheads, one for chopped fiber-reinforced FFF, the other for AFP
  - No secondary consolidation required
  - Offers ability to "overmold" aerospace grade prepreg tapes with high fiber volume content and low porosity
  - Entry-level and advanced control capabilities
  - Build envelope: 310 by 240 by 270 mm
  - Fiber LT: PA6/CF/GF
  - Fiber HT: PEEK/PA6/CF/GF
  - <1% porosity, 60% FVF
  - Resins: PEKK, PEEK, PA
  - Fibers: Carbon, glass

Continuous fiber AM (cont'd)

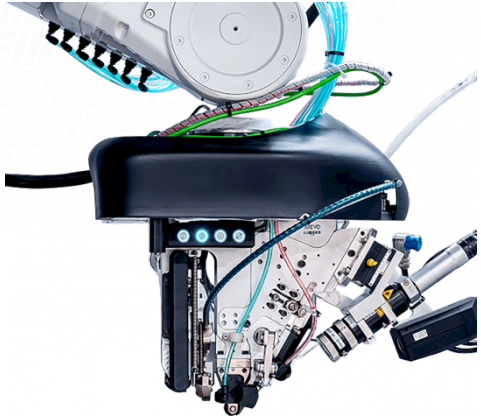
Orbital Composites' multi-robot Orb 1 3D printing platform. Thermoplastic printhead and 1-by-1-meter build platform. Source | CW



Watch on Vimeo

- Orbital Composites (San Jose, CA, US)
  - Orb 3D printing platform
  - Orb 1, first unit, features multi-robot (Kuka) system working on 1-by-1-meter build platform
  - Highly modular, highly scalable
  - Printhead on each robot deposits material
  - Robots programmable via desktop slicing software that integrates with Orb OS software to coordinate robot printhead behavior
  - Designed for integration into Industry 4.0 environment
  - Standard 1.75- and 2.85-mm extrusion heads
  - Resins: PLA, PA
  - Fibers: Carbon

Continuous fiber AM (cont'd)



Arevo DED extrusion head.
Source | Arevo

- Arevo (Santa Clara, CA, US)
  - Direct Energy Deposition (DED) technology
  - Extruder on printhead; 6-axis robot
  - 1-by-1-by-1-meter build volume
  - <1% porosity; 50% FVF
  - Resins: PA, PEEK
  - Fibers: Carbon
  - Early 2020, new CEO, Sonny Vu
    - Launch of Superstrata bicycle
    - Facility in Vietnam with 12 DED systems
    - B2C product that signals B2B parts manufacturing service commitment (in addition to machinery sales)
    - Eventually: Multiple global locations to provide B2B 3D printing manufacturing services

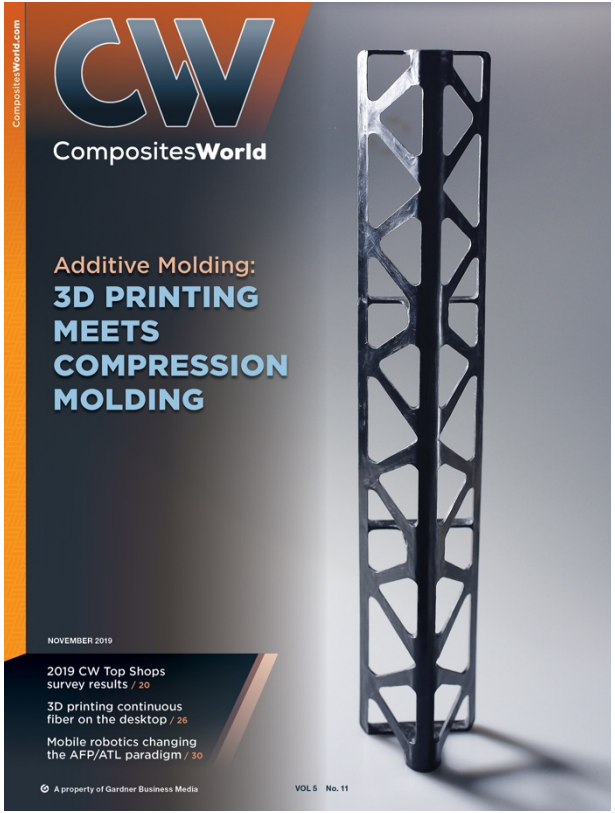
Arevo Superstrata bicycle, featuring frame and fork fully 3D printed with continuous CF by Arevo.
Source | Arevo

Continuous fiber AM (cont'd)

CEAD standalone extruder head. Source | CEAD

- CEAD (Deft, Netherlands)
  - CFAM Prime system, AM Flexbot, standalone extruder
  - All systems centered on extruder with continuous/discontinuous fiber option
  - Mounts on CNC machine
  - Very large parts fabrication; 4 by 2 by 1.5 meters, 15 kg/hr
  - Four heat zones
  - Resins: Most thermoplastics
  - Fiber: Glass or carbon (continuous or discontinuous)

AM Flexbot on 6-axis robot, building, finishing F1 mold. Watch on YouTube. Source | CEAD



Arris truss component. Source | Arris

Continuous fiber AM (cont'd)

- Arris Composites (Berkeley, CA, US)
  - Additive Molding technology
  - Combines additive manufacturing with compression molding
  - Highly automated batch process
  - Dry fibers either in tow or tape format
  - Fibers are drawn, prepregged, cut, shaped, placed in mold
  - Multiple layers of cut tapes/tows per mold
  - Mold is inserted into compression molding machine for consolidation
  - B2B manufacturing service model
  - No planned machinery/equipment sales

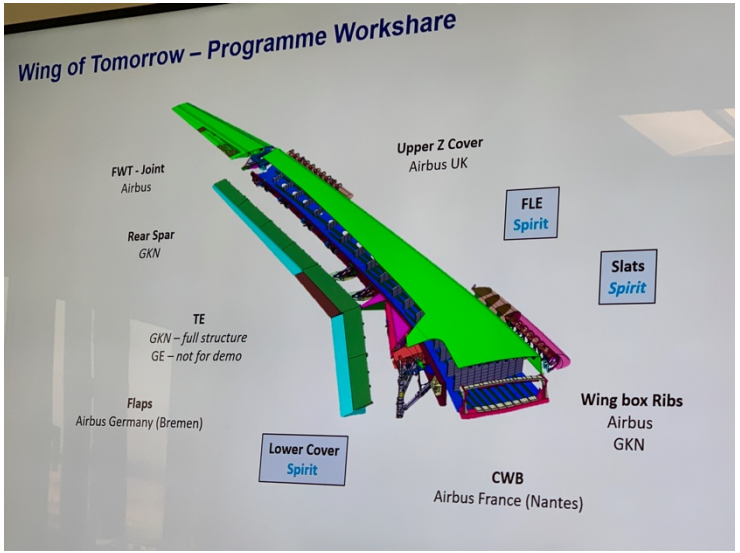
CF3D printhead.
Source | Continuous Composites

Continuous fiber AM (cont'd)

- Continuous Composites (Coeur d'Alene, ID, US)
  - CF3D technology
  - Printhead mounted on 6-axis robot, stationary or rail-mounted
  - Continuous dry fiber impregnated in-situ (UV) with snap-curing thermoset resin
  - Moldless capability
  - Complex geometries, freedom of design
  - Recent investment from Arkema
  - Fibers: Carbon, glass, aramid, optical, metallic
  - Resins: Epoxy
  - 50-60% FVF

Watch on YouTube.

OOA aerostructures



- Airbus Wing of Tomorrow Programme
  - Launched 2015
  - Explore the best materials, manufacturing and assembly techniques, as well as new technologies in aerodynamics and wing architecture
  - Multifunctional team that will select and develop a range of innovations in preparation for full-scale demonstrations
  - Reduced equipment and tooling costs along with faster production throughputs — particularly for possible use in a high-volume, single-aisle commercial aircraft program
  - Emphasis is on out-of-autoclave (OOA) materials and processes, including liquid resin infusion and resin transfer molding
  - Partners: Airbus (UK, France, Germany), GKN Aerospace, Spirit AeroSystems (Europe), Northrop Grumman
  - Subscale demonstrators developed by Spirit (lower wing skin) and GKN (rear spar), with full-scale articles to come by early 2021

OOA aerostructures (cont'd)

17m WOT lower wing skin mold at Spirit AeroSystems (Europe) in Prestwick, Scotland. Source | Spirit AeroSystems (Europe)

17m WOT lower wing skin mold with heated lid.
Source | Spirit AeroSystems (Europe)

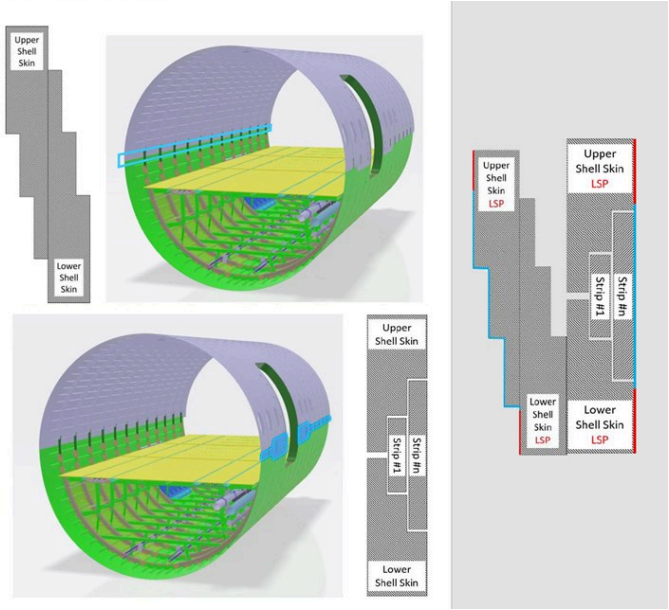
- Airbus Wing of Tomorrow Programme
  - Spirit AeroSystems (Europe), Prestwick, Scotland
    - Lower wing skin
    - Traditionally made via automated tape laying (ATL) with autoclave cure
    - WOT will assess feasibility of liquid resin infusion for high-rate production (60+ shipsets/month)
    - Spirit's Intelligent Resin Infusion System (IRIS) being deployed; suite of technologies
    - Important to process is specialized mold temperature control technology
    - Automated NCF placement also being developed
    - Sub-scale (7m) skin already produced
    - Full-scale (17m) skin to be fabricated early 2021
    - Cooperative with National Composites Centre (Bristol, UK)

OOA aerostructures (cont'd)

GKN Aerospace Global Technology Center, opened July 2020.
Source | GKN Aerospace

- Airbus Wing of Tomorrow Programme
  - GKN Aerospace, Filton, UK
    - Rear spar, single piece
    - A350 spars (34m) built via AFP in three sections fastened together
    - WOT will assess feasibility of resin transfer molding (RTM) for high-rate production (60+ shipsets/month)
    - Expect TRL 5/6 by mid-2021
    - NCF dry fiber formats, high-rate deposition, fully closed mold
    - 4m spar already produced, based on a section taken from full-length 17m spar
    - Full-scale (17m) spar to be fabricated early 2021; tool due to GKN spring 2020
    - WOT effort £9 million investment by GKN
    - New Global Technology Center (Bristol, UK), 50,000m^2, 40% dedicated to WOT, full-scale forming and assembly

OOA aerostructures (cont'd)



Overlap joint and butt strap joint configurations for joining two thermoplastic fuselage structures.
Source | Clean Sky 2

- Multifunctional Fuselage Demonstrator (Clean Sky 2)
  - 8m fuselage barrel made of welded thermoplastic composite structures
  - Several projects, work packages
  - STUNNING project: Lower thermoplastic fuselage, multi-functional
    - Led by GKN Fokker with partners
    - 8m long, 4m wide, 2-2.5m radius (single-aisle scale)
    - Lower half due to Fraunhofer IFAM by end 2021
    - Join fuselage halves: Butt strap joint (left side) with conduction welding vs. Overlap joint (right side) with ultrasonic welding
    - Frame coupling: Resistance welding
    - Ongoing work focused on fuselage assembly structures (Fraunhofer) and welding automation (TU Delft, SAM|XL)
  - Upper fuselage: Work led by DLR; CW is working on details

OOA aerostructures (cont'd)

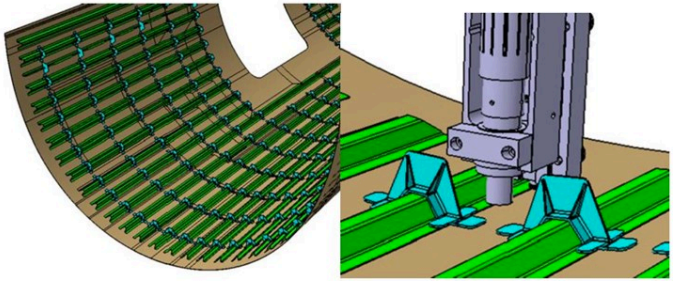
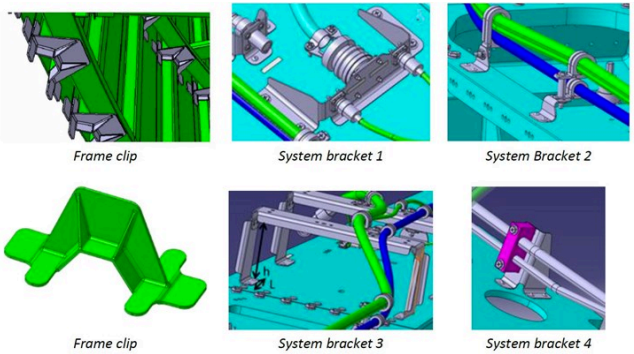


Figure 2: Stringers and clips welded to a thermoplastic fuselage



- Multifunctional Fuselage Demonstrator (Clean Sky 2)
  - MECATESTERS project: Welding (induction and conduction)
    - Induction welding: KVE Composites
    - Conduction welding: GKN Fokker
    - Toray AC LM PAEK UD vs. Solvay PEKK UD
    - Vary temperatures and pressures; assess for voids, defects
    - Fatigue resistance testing, crack propagation
    - Evaluate welding of compression molded brackets made with short-fiber materials
    - Lower fuselage: 13 frames, 36 stringers, 500 frame clips, 270 system brackets

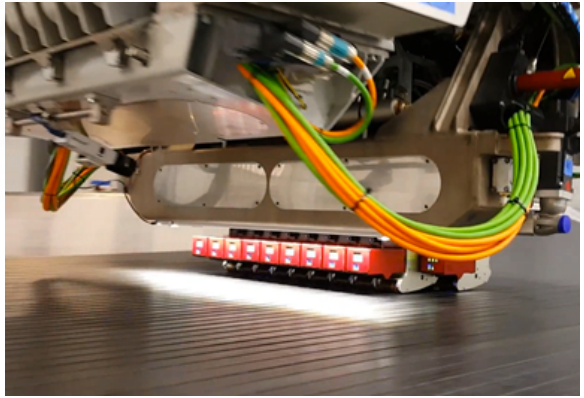
High-volume RTM

Spirit AeroSystems' resin transfer molded Airbus A320 spoiler, finished, assembled and painted. Source | CW

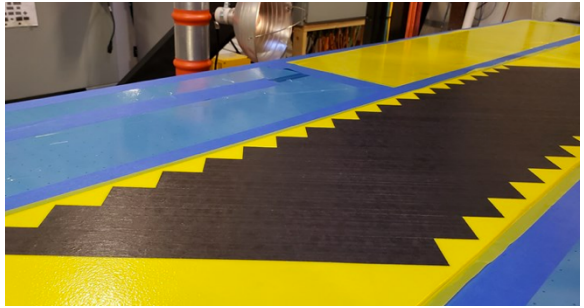
One of seven Coexpair RTM presses that Spirit has installed. The resin injected is Hexcel's RTM6 epoxy. Source | CW

- Airbus A320 spoilers
  - 5 per wing, 10 per plane; 1.8 meters long, 0.7 meters wide
  - Currently fabricated via hand layup; shim-dependent
  - One of few wing components not redesigned since plane entered market in 1987
  - Airbus made decision to switch to drop-in replacement fabricated using resin transfer molding (RTM)
  - Design optimized with help of Spirit AeroSystems (Europe) in Prestwick, Scotland
  - Spirit also did process engineering — cutting, kitting, preforming, molding, trimming, assembly, painting
  - Highly automated, minimal manual labor production line
  - Designed to produce 65 shipsets/month
  - 30% cost savings, raw material to wing installation; weight neutral
  - Fibers: Teijin NCF
  - Resin: Hexcel RTM6 epoxy

Narrow-tapes ATL



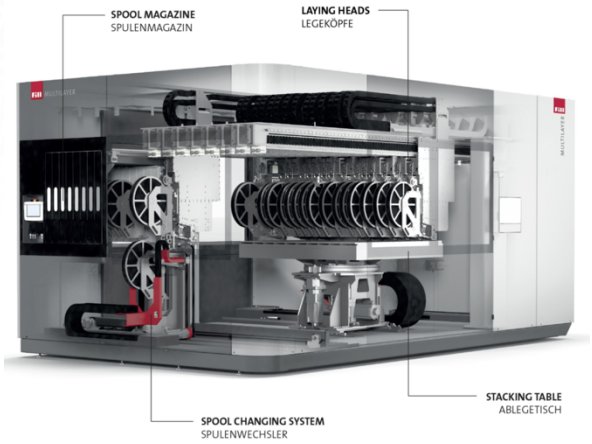
The Fives Lund SLALOM ATL lays down 1.5-inch carbon fiber tapes. Watch on YouTube. Source | Fives Lund



Crenulated 1.5-inch carbon fiber tapes. Watch on YouTube. Source | Fives Lund

- Fives Lund SLALOM ATL
  - Automated tape laying (ATL) typically uses tapes 3, 6 or 12 inches wide; favors moderately contoured structures
  - Automated fiber placement (AFP) typically uses tows 0.125 to 0.5 inch wide; favors complex curvatures
  - ATL tapes difficult to cut at the boundary; risk of material waste
  - AFP sequential cuts allows crenulation at boundaries; less waste
  - Question:
    - Is it possible to develop narrower tapes that use traditional tape allowables, provide boundary crenulation and more conformability?
  - Answer: Yes, with 1.5-inch tapes, each independently actuated
  - Programmable laps and gaps, depending on allowables
  - 19-lane system used to make 787 wingskins by MHI (Japan)
  - Future: Faster laydown (4.5 m/sec) for 60+ rate
  - Applications: Stringers, spars, wing skins, stabilizers
  - Short on-tool-time of 2-3 days

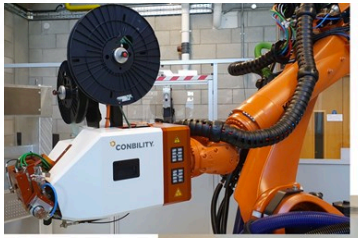
Novel preforms/preforming



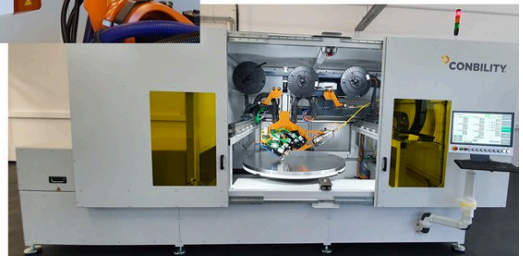
- Fill Gesellschaft Multilayer
  - Multi-spool placement of dry or prepregged tapes
  - Each spool independently actuated/controlled
  - Thermal bonding between layers via ultrasonic welding on each spool
  - Fully automatic spool change; up to 8 spares
  - 1.6-by-1.6m build area
  - 50-mm tape width
  - Subsequent, separate consolidation required

Watch on YouTube

Novel preforms/preforming



Conbility's PrePro 3D *(left)* AFP head and PrePro 2D automated cell *(below)* for in-situ consolidation of tailored laminates. Source | Conbility

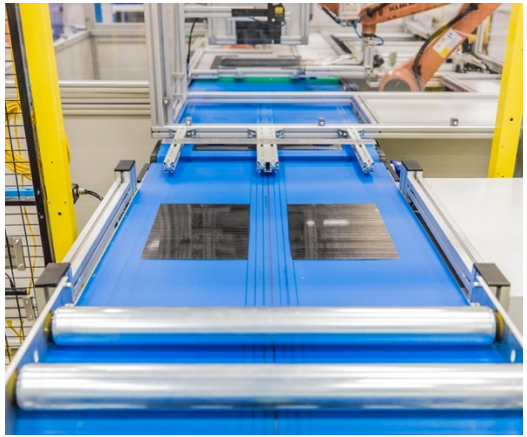


- Conbility PrePro technology
  - *In-situ* consolidation of tailored thermoplastic composite laminates
  - PrePro 3D, mounted on 6-axis robot
  - PrePro 2D, enclosed work cell
    - 3-spool applicator (scalable to 6 spools)
    - 25-mm-wide tapes (scalable to 100 mm)
    - 1.5m table (scalable to 2.0m)
    - 4-kW laser
    - Cut-and-add on-the-fly
    - Secondary consolidation step obviated by in-situ process
    - Targets laminate production for injection overmolding

Watch on YouTube

Novel preforms/preforming

Conveyorized trays in the Digital Composites Manufacturing Line (DCML). Source | SABIC



Consolidated laminates head to trimming and inspection. The system can produce four laminates per minute. Source | SABIC

- Airborne/SABIC/Siemens/Kuka Digital Composites Manufacturing Line (DCML)
  - Near-net-shape flat laminates from UD thermoplastic tapes
  - Layup, consolidation, trimming, digital/visual inspection, automated release, packaging
  - Conveyorized trays pass beneath feeder units
  - Feeder unit deposits a tape ply of specific dimensions, orientation into the tray; tray advances to next station
  - Plies accumulate to build laminate
  - 15 plies per laminate
  - Laminate stack welded together then transferred to consolidation
  - 4 laminates/minute throughput
  - Resins: PC, PE, PP, PEEK
  - Fibers: Carbon, glass, hybrid
  - Applications: Consumer electronics

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Next-Generation Composite Materials and Processes

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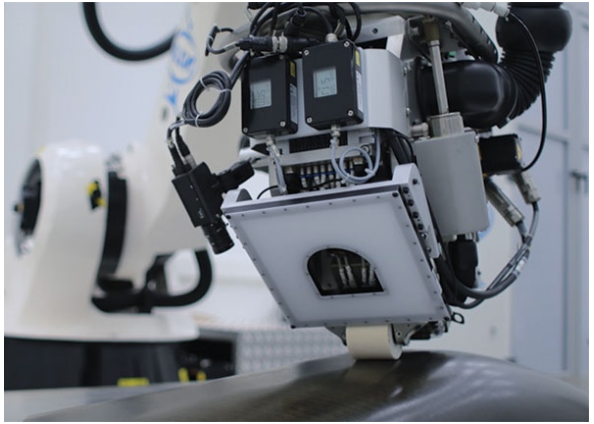
- Sensors for process monitoring
- Thermoplastic epoxy
- Pin-based tooling systems
- Carbon fiber-reinforced concrete
- Hydrogen in aviation

Sensors for process monitoring

AFP

- Fives Cincinnati/Lund – Flightware and profilometer
- Danobat – Profactor
- MTorres – Airbus InFactory Solutions, Profactor
- Electroimpact – Aligned Vision (777X wing)
- Coriolis – Edixia
- Coriolis – Apodius at NLR via SuCoHS project
- Electroimpact – Real-time In-Process Inspection Technology



SOURCE | Hexagon and SuCoHS Project, Sep 2019 by project coordinator Tobias Willie (DLR)

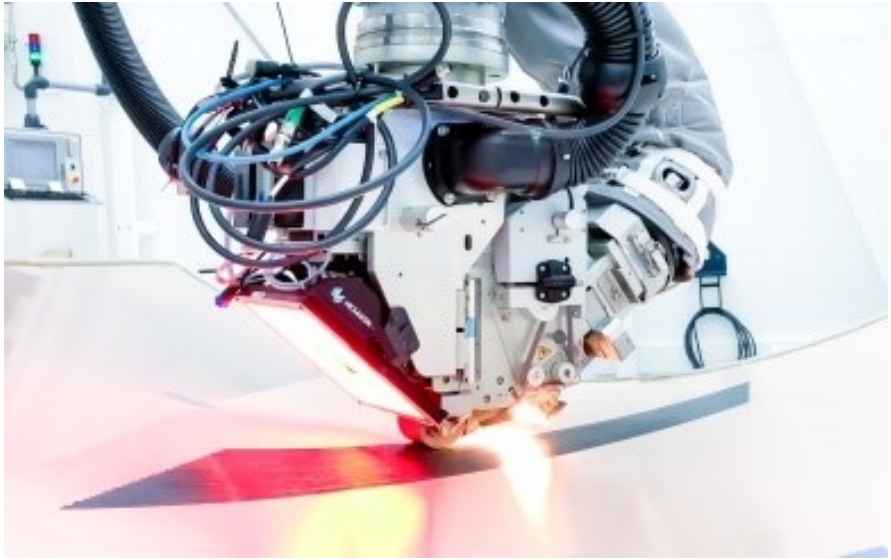
Coriolis – Apodius at NLR via SuCoHS project

- Sustainable Cost Efficient High Performance Composite Structures demanding Temperature and Fire Resistance
- Vision sensor mounted onto AFP head
- Detects gaps, twists, FOD, tow start/end positions
- Inline system for speeds >400 mm/s (24 m/min)
- For complex geometries as well as flat panels

SOURCE | SuCoHS Newsletter #3

AFP process monitoring

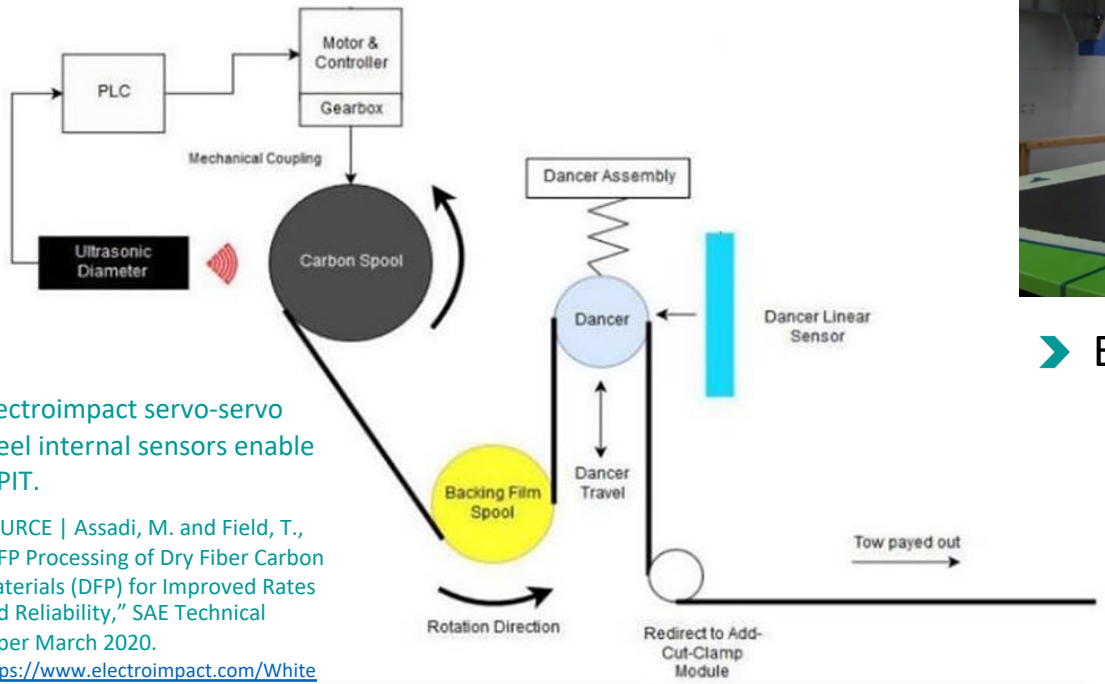
- Coriolis – Apodius at NLR via SuCoHS project
  - Vision system measures differences in the height profile of the lay-up material.
  - It allows the system to pick up every feature on the part's surface, even one micrometer thick, such as backing paper.
  - Provides in-situ quality feedback and process status in real-time.
  - Composites 4.0 capability — add lay-up process and quality data to digital twin – also loop back to simulation for more accurate prediction.
  - Successfully demonstrated with new thin-ply toughened (20% PES) cyanate ester tape developed by FHNW and North Thin Ply Technology.



Apodius AFP Inspection System at NLR facilities in Marknesse.
SOURCE | Alexander Leutner, SuCoHS Newsletter #3 – Interviews, July 2020

n|w University of Applied Sciences and Arts Northwestern Switzerland

AFP process monitoring



Electroimpact servo-servo creel internal sensors enable RIPIT.

SOURCE | Assadi, M. and Field, T., "AFP Processing of Dry Fiber Carbon Materials (DFP) for Improved Rates and Reliability," SAE Technical Paper March 2020. https://www.electroimpact.com/WhitePapers/2020-01-0030.pdf

Electroimpact – RIPIT

- Real-time In-Process Inspection Technology
- Servo-servo creel internal sensors
- Detects tow slips >.050 inch
- Detects add or cut placement error ±.050 inch
- Increased tension control for higher DFP rates (>100 m/min)

Sensors for process monitoring

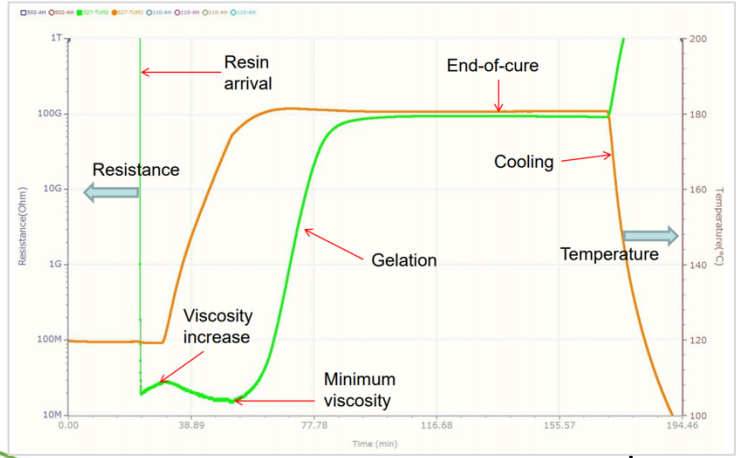
Cure

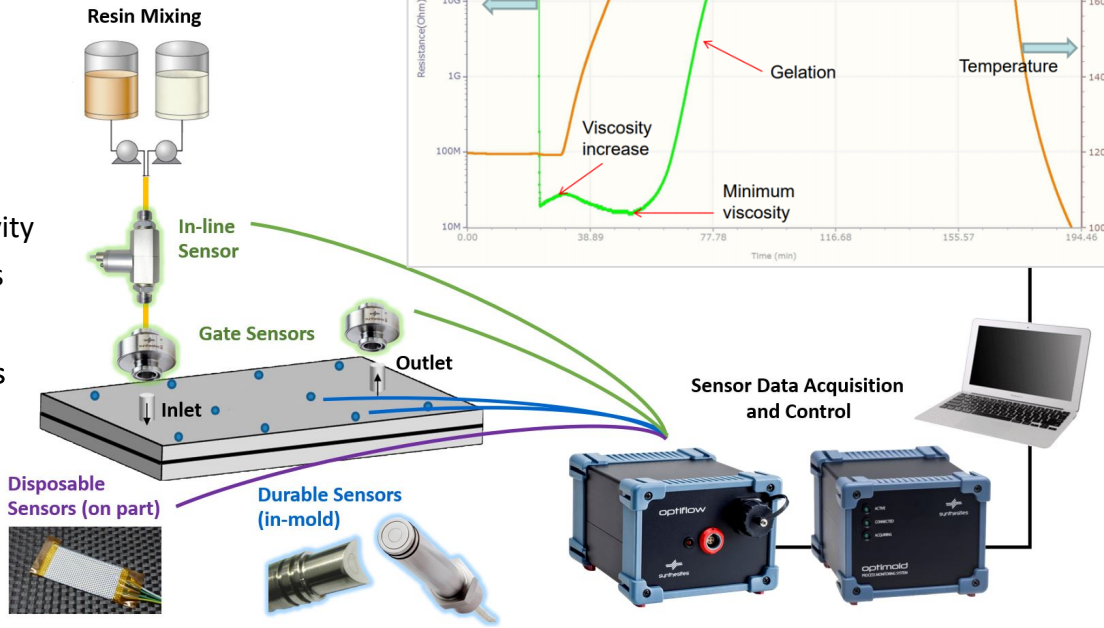
- Netzsch, Lambient – AC dielectric
- Synthesites – DC dielectric
- Luna Innovations, Technobis – Optical fiber

Synthesites

- Dielectric analysis (DEA) - resin electrical resistivity
- Resin flow + temp + electrical resistance sensors
- Real-time estimating viscosity, Tg, degree of cure
- Used/certified for production by wind blade mfrs and Bombardier for A220 resin infused wings

Typcal RTM6 cure cycle as measured with Optimold



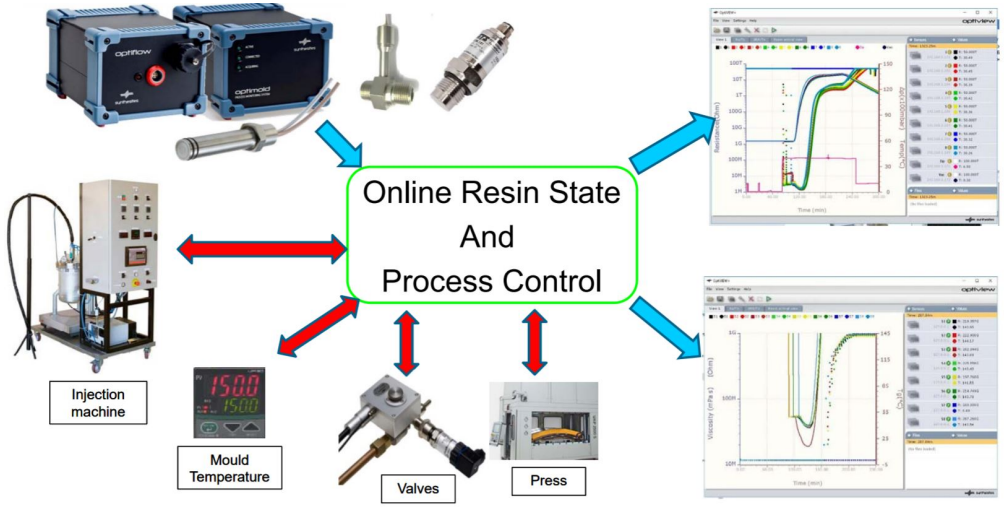


OPTIFLOW and OPTIMOLD units

SOURCE | "DC dielectric sensors for industrial composites production", *CW* blog Feb 2020.

RTM process monitoring

- Synthesites
  - Process control
    - Feed lines open/close based on resin arrival data
    - Heating/cooling and pressure based on resin viscosity
    - Stop cure cycle based on Tg
  - Can reduce cure times by >30%
    (e.g., RTM6 from 2 hrs @ 180°C to 70 min)

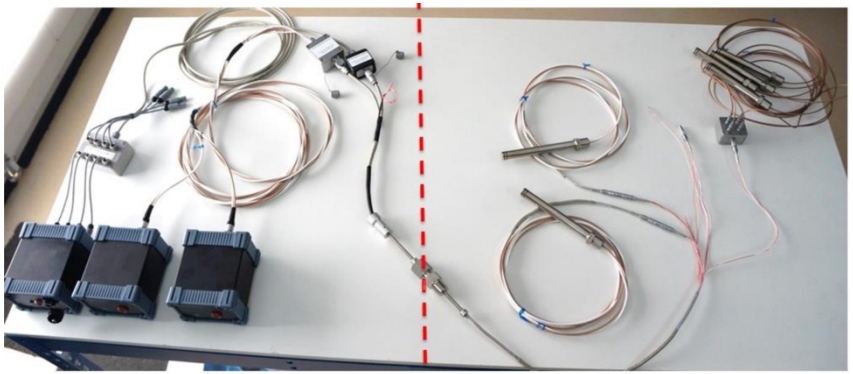


SOURCE | Nikos Pantelelis., "Material characterisation: From R&D to production, a case study," EuroNanoForum, June 2019.

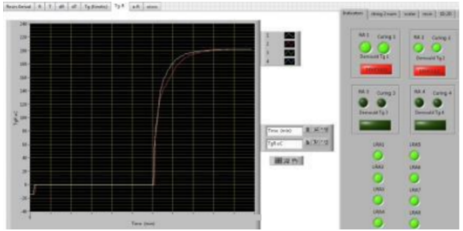
- Working w/ wind blade mfrs to start cooling after target Tg reached in 5 key locations
- Real-time Tg estimation vs. DSC after demolding
  — mean difference 1.6°C isothermal, 2.2°C non-isothermal

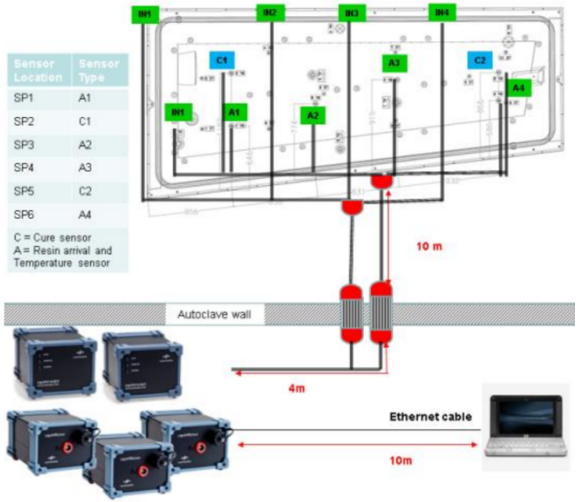
Infusion process monitoring

- Synthesites
  - Demonstration at Bombardier Belfast for ECOMISE project
  - Real-time Tg prediction and demolding at targeted Tg



Outside of the autoclave | Inside of the autoclave





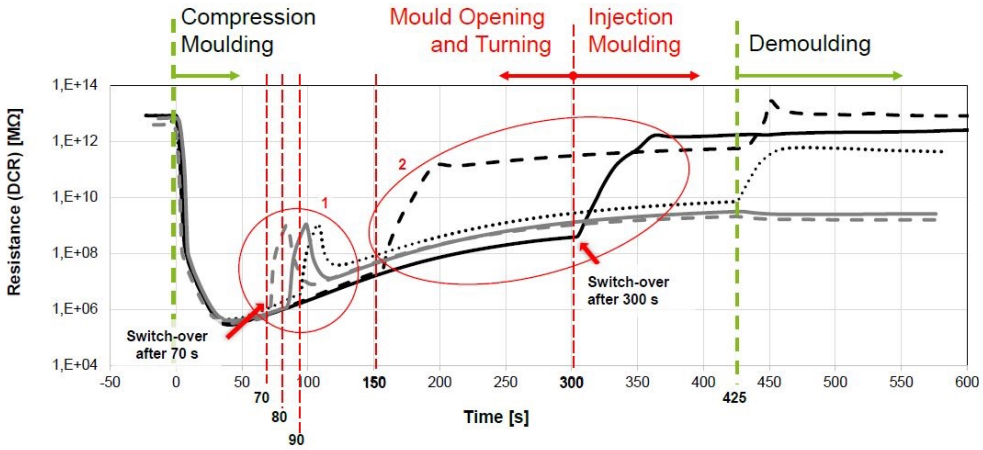
Sensor Location	Sensor Type
SP1	A1
SP2	C1
SP3	A2
SP4	A3
SP5	C2
SP6	A4

C = Cure sensor
A = Resin arrival and Temperature sensor

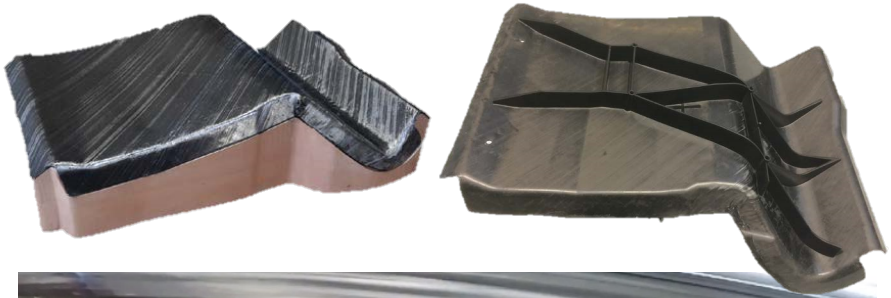
SOURCE | Nikos Pantelelis., "Cure monitoring of high-temperature resins for enhancing the manufacturing of advanced composites", EASN Conference "Innovation in Aviation & Space", Sep 2019.

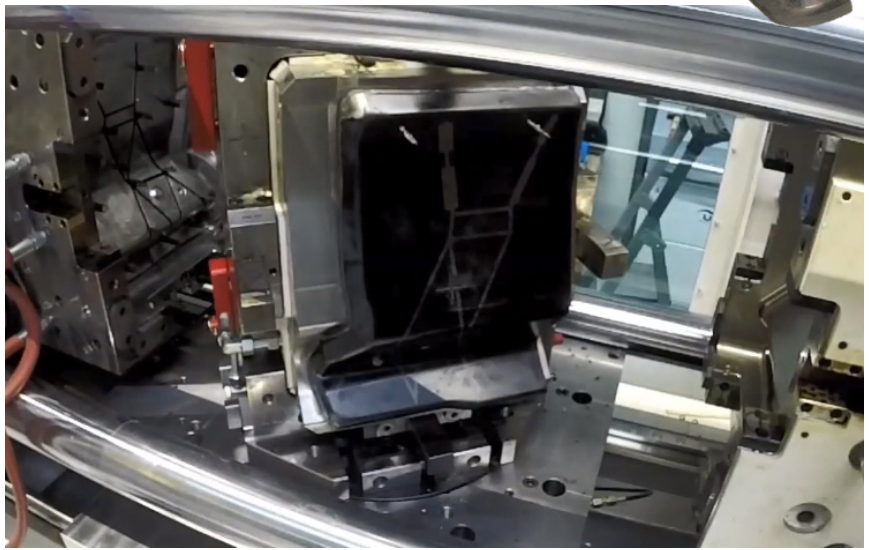
Prepreg process monitoring

- Synthesites
  - 50% reduction cure time of FML (GF/epoxy prepreg)
  - OPTO-Light thermoplastic-overmolded CF/epoxy prepreg



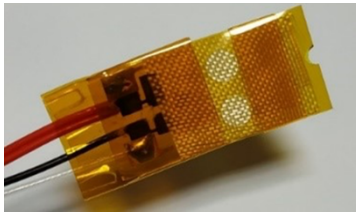
SOURCE | "Thermoplastic overmolded thermosets, 2-minute cycle, one cell", ***CW*** March 2019

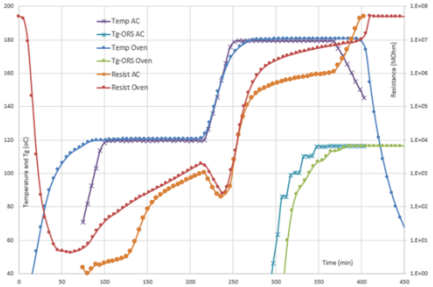


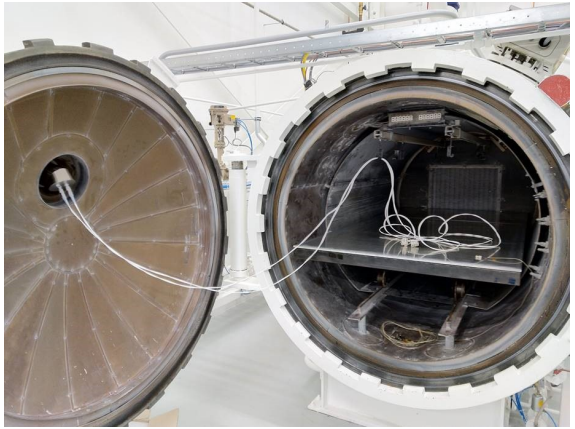


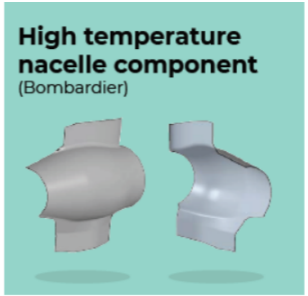
High-temp monitoring

- Synthesites' developments in SuCoHS project
  - High-temp disposable sensor for thin-ply and durable sensor used in direct contact with carbon fiber up to 300°C first ➡ ultimately 350°C
  - Self-sensing technologies to use carbon fibers in the composite for sensing process and structural properties
  - Successful trials with Cytec 5250 BMI, PES-toughened cyanate ester (PFA, thermoplastics)









- Reduce # subparts and part complexity
- Tg < 335°C

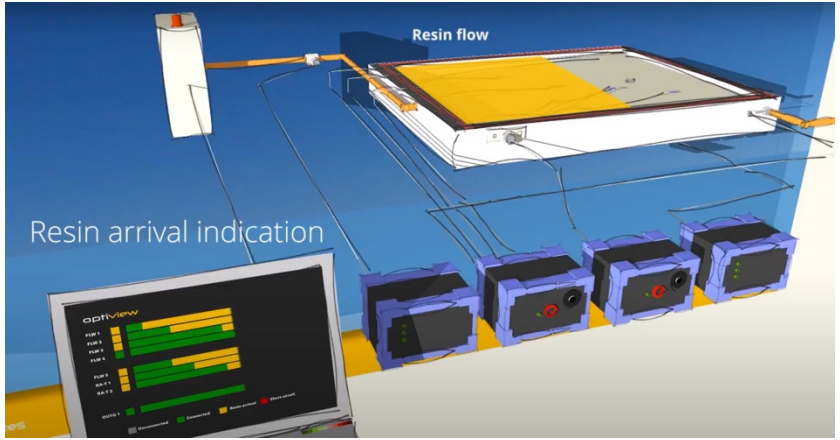
- Avoid Ti. APU housing
- Tg < 300°C
- Fire resistance, damage tolerance

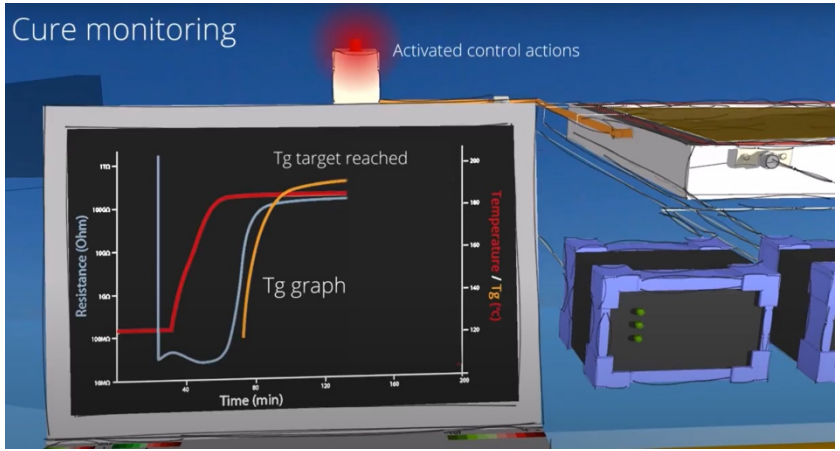
- New structure concept
- Higher performance, lower cost
- FST

SOURCE | Nikos Pantelelis., "Cure monitoring of high-temperature resins for enhancing the manufacturing of advanced composites", EASN Conference "Innovation in Aviation & Space", Sep 2019. and SuCoHS Newsletter #3 – Interviews, July 2020

4.0 Process Control

- Synthesites
  - Check resin quality and adjust process accordingly
  - Detect accurately resin arrival at critical locations
  - Open/close valves based on sensors' feedback
  - Monitor viscosity changes and decide when to start heating
  - Identify minimum viscosity and decide about pressure
  - Detect unexpected events and follow alternative routes
  - Improve simulation accuracy and design intelligent strategies
  - Real-time cure cycle decisions based on Tg and degree of cure rather than time
  - Real-time quality control for Composites 4.0 and scaled-up composites production
  - Real-time data capture for digital twins

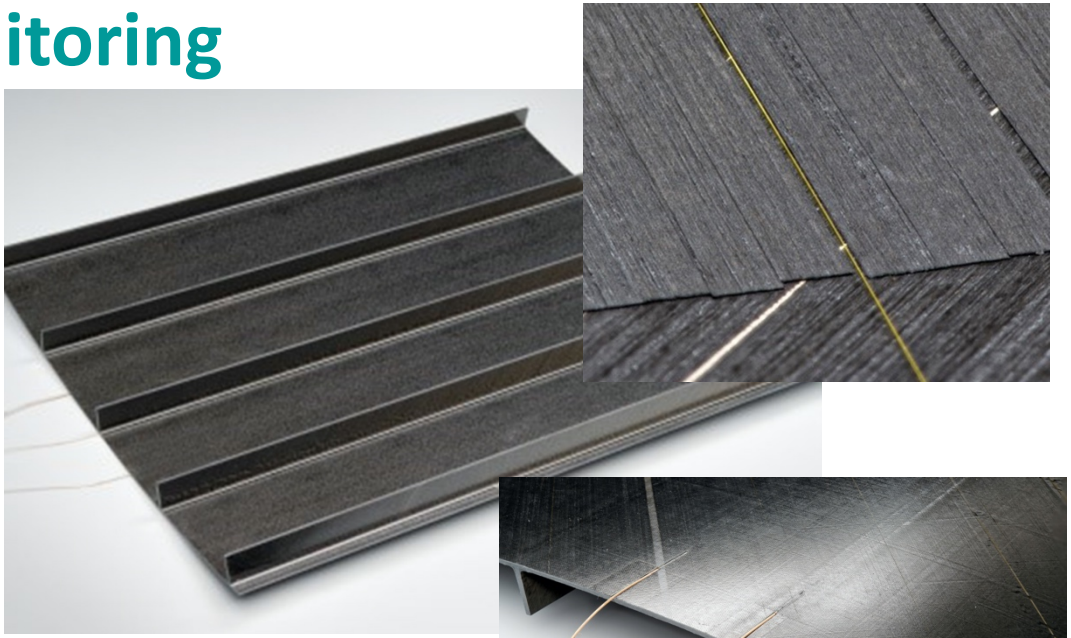


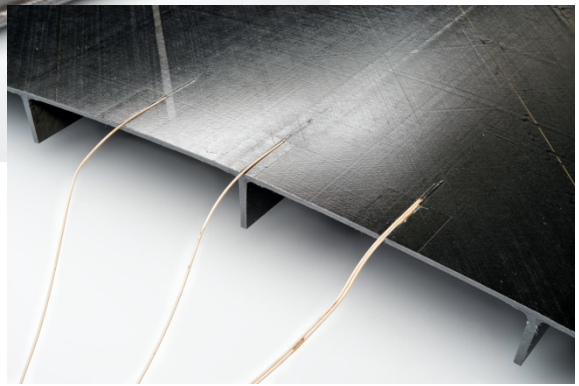


Sensors for process monitoring

- Technobis
  - Fiber Bragg Grating (FBG) measures reflected light translates to strain or temperature
  - Polyimide coated fiber can withstand 300°C (up to 400°C for short periods)
  - Laid via one of 8 feeds in AFP head
  - Cure monitoring: strain transfer into the FBG sensors during the cure process captured by the interrogator
  - PEEK tubes protect optical fiber at ingress/egress
  - Fibers connected to Technobis SwitchedGator interrogation system outside autoclave
  - Demo successful – further tests for structural health monitoring of the composite panels, i.e. thermo-mechanical load monitoring, and damage and impact detection.

Optical fiber placed with AFP





Risk mitigation structure with integrated stiffeners made using AFP and hot forming with embedded optical fibers with FBG sensors.

SOURCE | SuCoHS_Newsletter #3 – Work progress and SuCoHS_Newsletter #3 – Interviews, July 2020

Reversible Resins

Thermoplastic epoxy

- Dow patent filed U.S. patent 3,317,471 in 1959
- Union Carbide patent
- L&L Products – L-F610 reformable epoxy adhesive
- Cecence K_Series

Deils-Alder

- Evonik "thermoreversible crosslinkable thermoplast-thermoset hybrid"
- Epoxy below 100°C, Thermoplastic above 170°C
- Loss of crosslinks upon reheating

Vitrimers

- CIDETEC 3R
- Mallinda

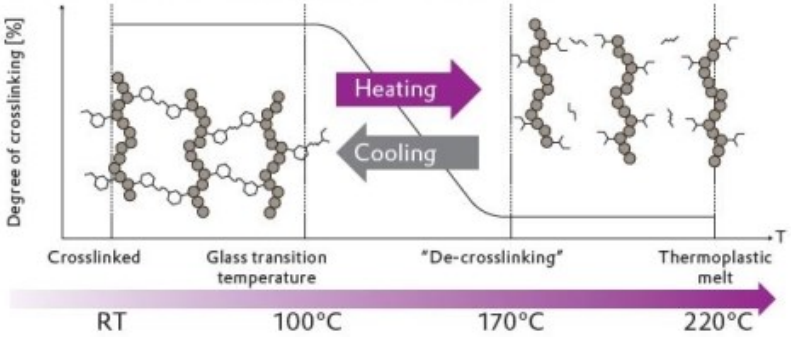
ECOxy AIRPOXY HARVEST MALLINDA VITRIMER MATRIX COMPOSITES FOR THE CIRCULAR ECONOMY

3,317,471
Patented May 2, 1967

The new composition is the first linear epoxy resin known to the industry. The prior known "cured" epoxy resins were all cross-linked thermoset resins which could not be worked after "curing." The advantages of the new linear resins over the older thermosetting resins are obvious. Thus, for example, the new resins can be repeatedly molded, extruded or drawn whereas the thermosetting resins must be cured in shape and are usually subject to degradation before any softening is apparent.

Switchable material behavior without a catalyst

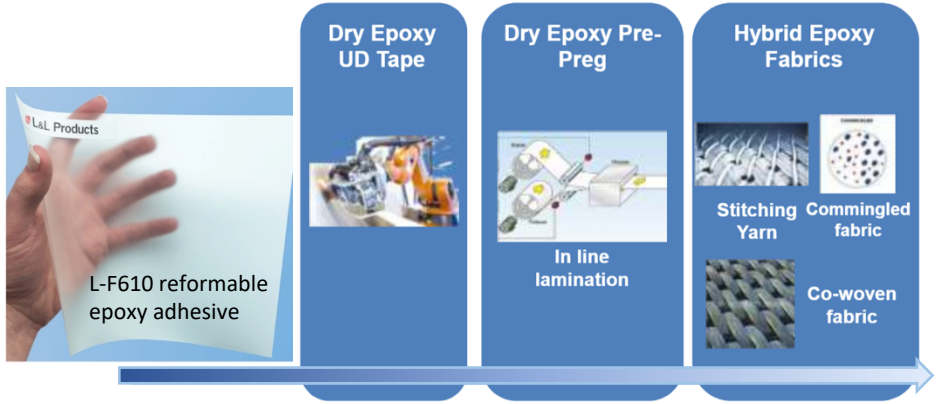
When heated, the polymer network dissolves and the system can be reshaped. When cooled, the network reforms to yield a stable form.



SOURCE | "Hybrid Polymers", pp. 15-16, *Elements #54*, published by Evonik, cited in ***CW*** blog Dec 2016

Reversible Resins

- L&L thermoplastic epoxy resins (TPER)
  - Polymerization of linear polymer chains based on epoxy resins
  - Amorphous TP with high strength, stiffness
  - Yield stress = 8400 psi/ 58 Mpa
  - Strain-to-failure up to 40%
  - Tg = 80-90°C, processing at 175-200°C
  - Short cycle times (<15 min)
  - RT stable, 2-yr shelf life



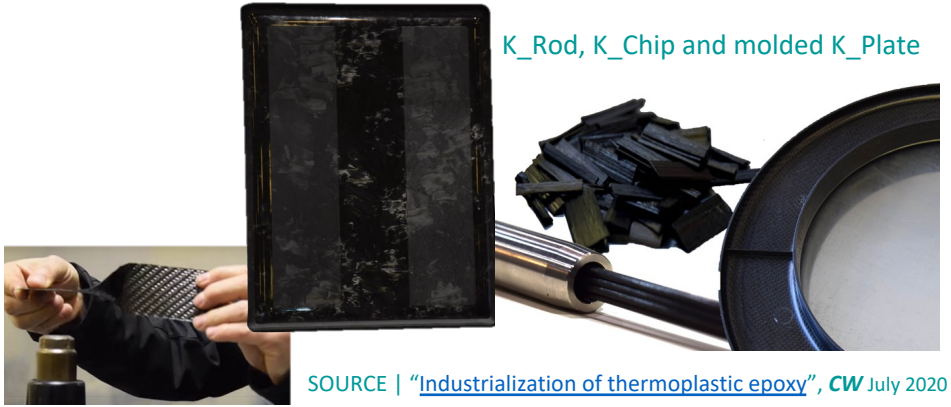
SOURCE | L&L commercial presentation 2015

SOURCE | Chmielewshki, Kaffenberger, "… composites based on a novel thermoplastic epoxy resin matrix", SPE Automotive 2008 and L-F610 data sheet

https://www.youtube.com/watch?v=yetG-AzZVIE

Reversible Resins

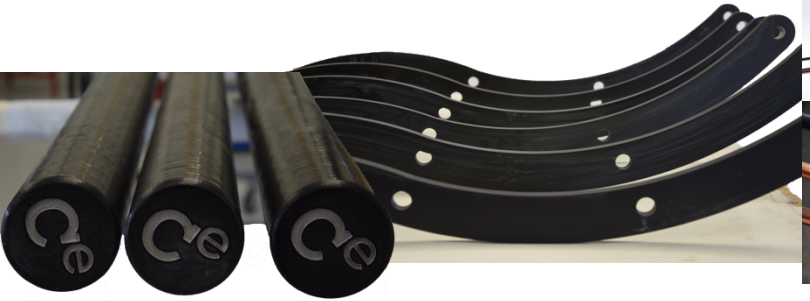
K_Rod, K_Chip and molded K_Plate

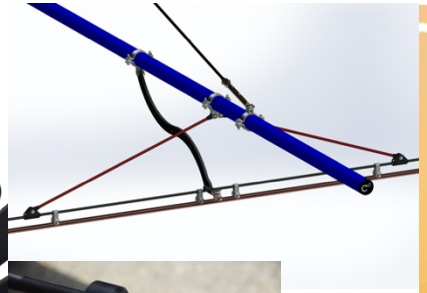


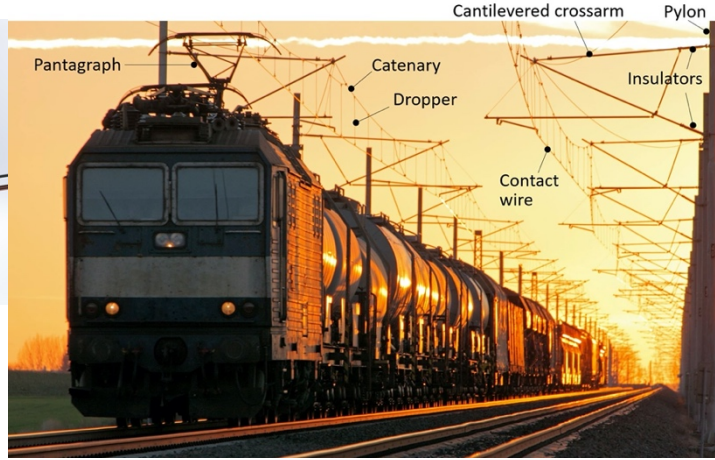
SOURCE | "Industrialization of thermoplastic epoxy", *CW* July 2020

Cecence K_Series

- Thermoplastic w/ epoxy components at end of polymer chains
- Low viscosity (80 cP) at 100°C
  Easily prepregged, 60% fiber by weight
- Fast compression molding:
  RocTool auto hood in 2 min 40 sec
- Reformable: K_Plate at 150-220°C, K_Chip at 240°C
- Epoxy-like bondability, paintability







Reversible Resins

Self-healing and thermoreversible rubber from supramolecular assembly

Philippe Cordier, François Tournilhac, Corinne Soulié-Ziakovic & Ludwik Leibler

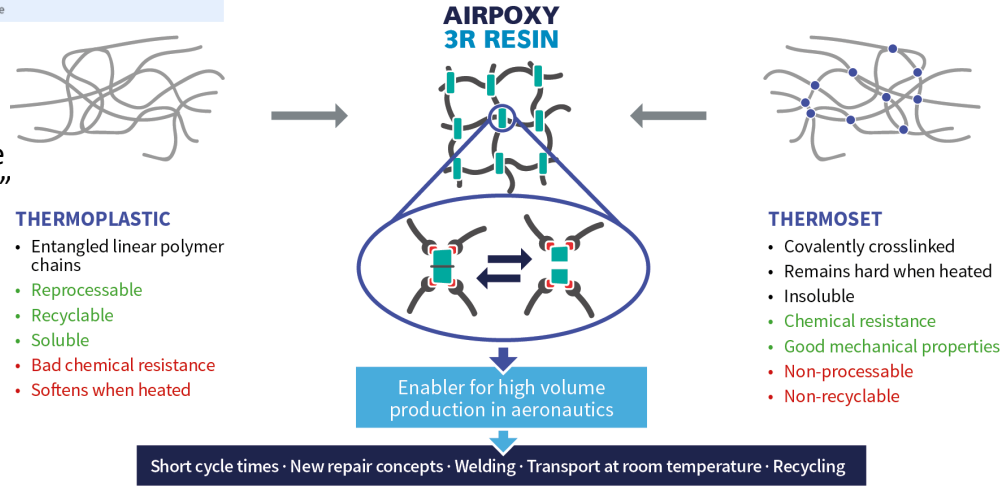
Nature **451**, 977–980(2008) | Cite this article

Vitrimers

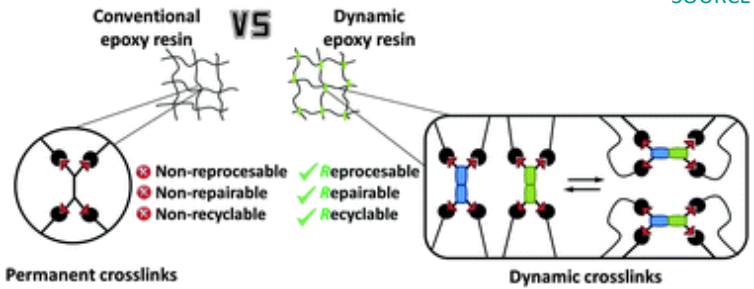
- "Leibler patent US2013/0300020 epoxy thermoset composite which could be [reprocessed/remolded], repaired or recycled" — CIDETEC patent EP 2 949 679 A1 filed 2014
- Catalyst (e.g., Zn salt) essential for reversibility
- Dynamic crosslinks / dynamic exchange reactions
- Permanently cross-linked polymer networks undergo temperature-induced bond shuffling through an associative mechanism allows reshaping and welding

CIDETEC Surface Engineering "3R"

- Reprocessable, Repairable and Recyclable
- WO2015181054A1 "Thermomechanically reprocessable epoxy composites and processes for their manufacturing"
- Eliminates need for catalyst
- Working with Airpoxy, Ecoxy and Harvest



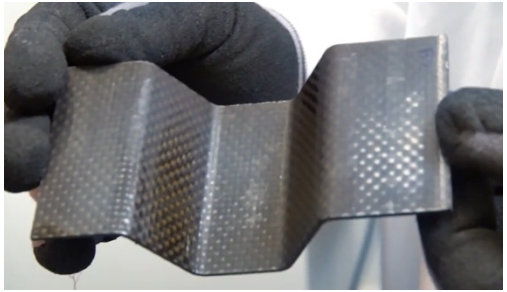
SOURCE | https://www.airpoxy.eu/

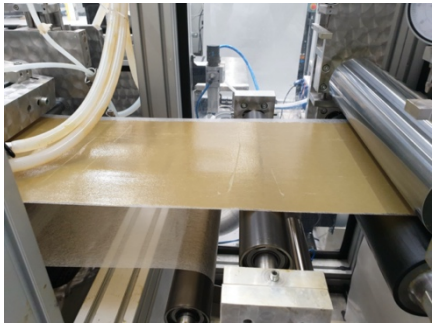


Javier Rodríguez, Ibon Odriozola (CIDETEC), "Epoxy resin with exchangeable disulfide crosslinks …" May 2016

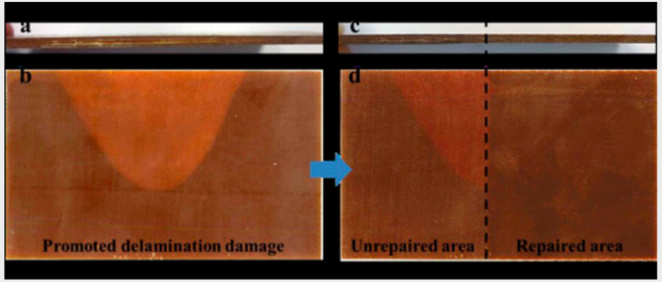
Vitrimers

- Airpoxy
  - 11 partners, 6 countries, 42 months – started Sep 2018
  - New family of 3R thermoset resins via commercially available dynamic hardeners
  - TRL 3 to TRL 5 via 2 aircraft panel demonstrators
  - Thermoforming at 80°C
  - Enable recyclability
  - Transient mechanochromism – material changes color with damage, reversible within in a few hours
  - Self-repair





First 3R adhesive. SOURCE | airpoxy.eu/

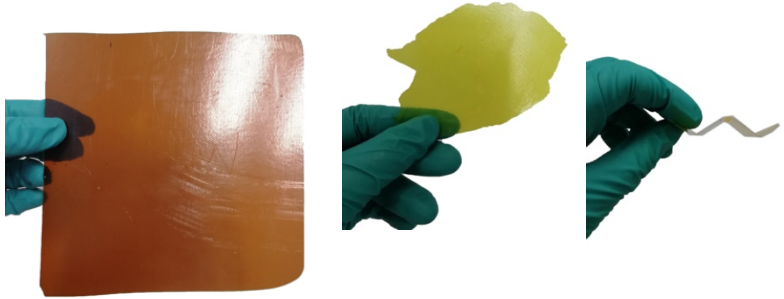


Delamination in 3R laminate (left) repaired by applying heat and pressure (right).

SOURCE | https://www.cidetec.es/en/top-achievements/3r-leading-technology

Vitrimers

- Ecoxy
  - Bio-based 3R composites – 13 partners, 8 countries
  - Improved-property biofibers, novel FR + 3R bioresin
  - Pultrusion, wet compression molding and/or RTM
  - Mechanical & chemical recycling demonstrated
  - Auto seat back and construction window profile demo parts



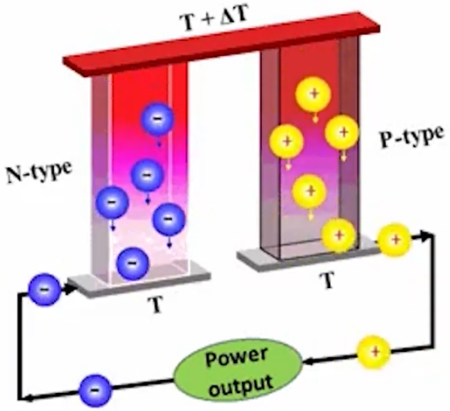
Lab-scale demonstrators. SOURCE | https://ecoxy.eu/

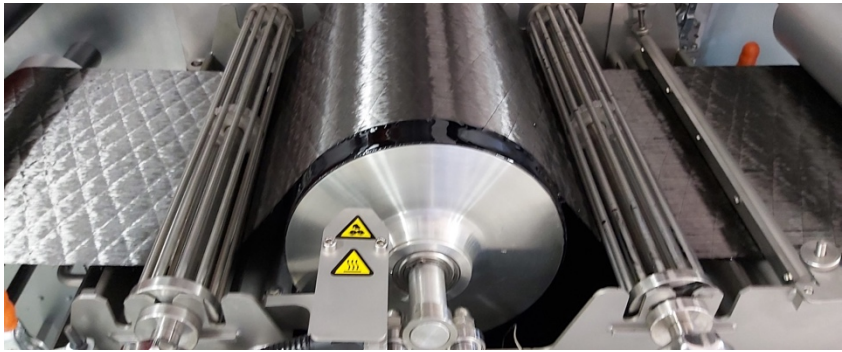
Vitrimers

Harvest

- 11 partners, 6 countries - 36-month project started Sep 2018
- Develop multifunctional, thermo-electric energy generating (TEG) structural composites for aviation
- Capable of SHM, energy harvesting and self-repairing
- Bio-inspired hierarchical carbon fiber reinforcements (micron-scale CF with nanoparticles)
- Nano-modified 3R matrix (Repair-Recycle-Reprocess)
- Printed ink and roll-to-roll mfg of TEG-enabled prepregs

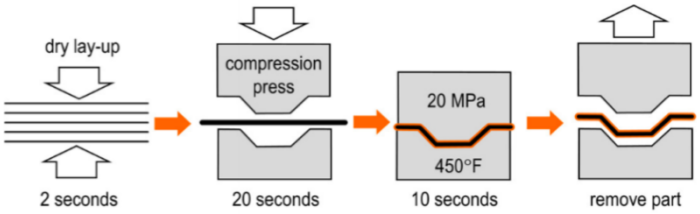
First nanomodified 3R resin tubular demonstrator (June 2020).
SOURCE |https://www.harvest-project.eu/first-nanomodified-3r-resin-prepregs/





First nanomodified 3R prepreg (May 2020).
SOURCE |https://www.harvest-project.eu/first-nanomodified-3r-resin-prepregs/

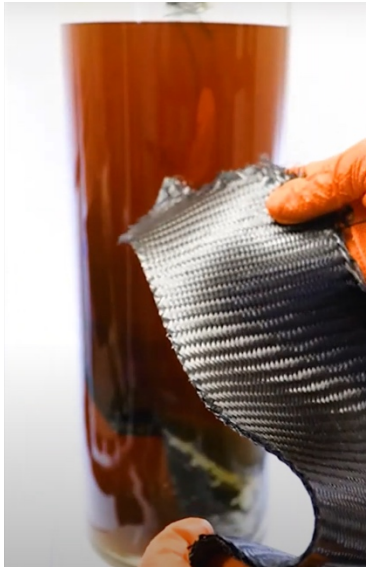
Vitrimers

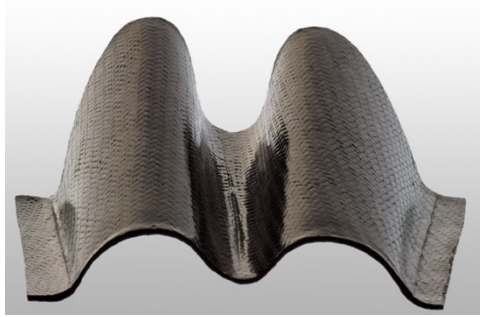


Fast consolidation and compression molding.
SOURCE | Kissounko, Taynton, Kaffer, "New Material: Vitrimers Promise to Impact Composites"

Mallinda

- Vitrimers = new class of polymers based on dynamically exchangeable imine-linked polymer networks without catalysts
- When heated above Tg, fully cured polymer undergoes rapid dynamic covalent bond exchange: TP above Tg - TS below Tg
- Chemistry is highly tunable – Mallinda formulated polymers with Tg from 20°C to 240°C and elastomeric to crystalline
- Liquid resin must be cured/polymerization into solid;
  low viscosity facilitates prepregging;
  then rapid (< 1 min) compression molding
- Closed-loop system for recycling/recovery of polymer and fiber;
  30% recycled resin into prepreg without mech. property loss
- Predicting prepreg cost $11-16/lb;
  elimination of preforming – direct prepreg thermoforming
  estimated CFRP cost savings 25-30%





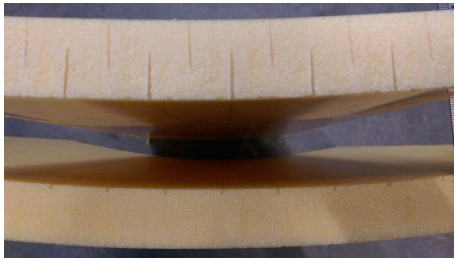
SOURCE | IACMI member spotlight Mallinda

Recovery of fiber and resin.
SOURCE | mallinda.com/the-technology

Pin-based Tooling

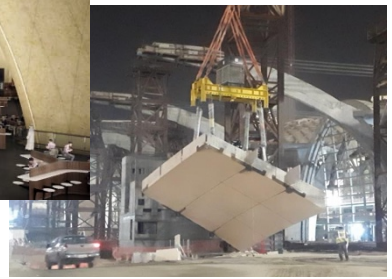
Adapa

- Surface shape from 3D design files - actuates < 5 min
- Bed of linear actuators powered by stepper motors
- Multilayer molding surface attached by magnets
- 3D laser projector aids layup
- Systems customized for panel material, single- or double-curvature and size (1m x 1m to 10m x 20m)
- Options: oven integration, snaps for panel edge precision and vacuum systems for resin infusion



Thermoformed foam takes up less resin.

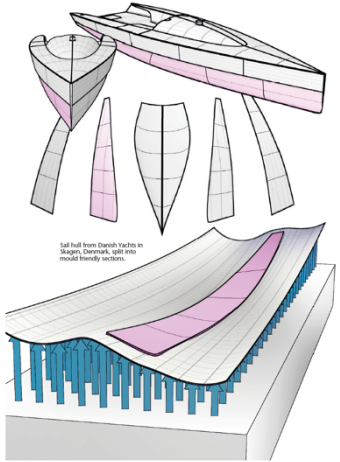
SOURCE | Curve Works



Adapa supplied 85 adaptive molds for production of 40,000 precast concrete panels for Kuwait airport.

Beirut's 5-story North Souk building used Adapa's system vs. disposal of 5,530 molds.

Adapa

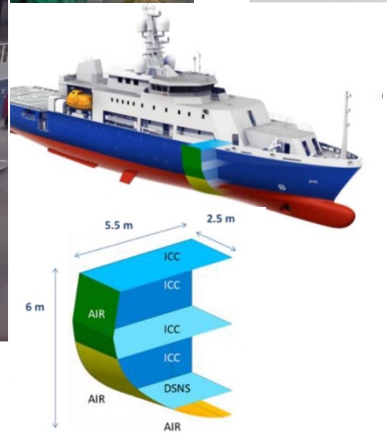


Curved composite sandwich cladding for FiberCore Europe's 21m bridge – 120m² weighs < 1000kg.

SOURCE | Curve Works

Infused 6m hull section.

SOURCE | RAMSSES and FIBRESHIP

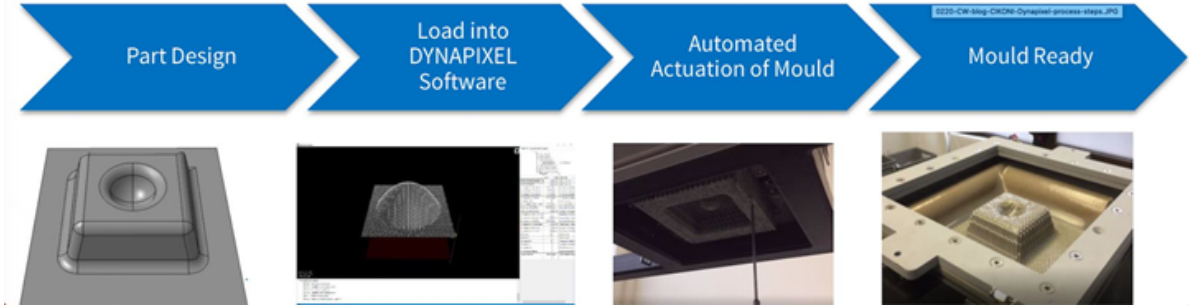


Solutions for organic façade elements

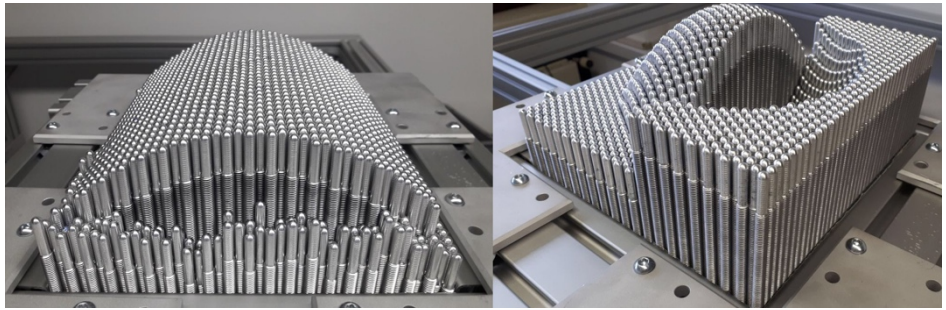
Curve Works

Curve Works FR Tempera panels (rPET core, GF, water-based resin).

Pin-based tooling



- DYNAPIXEL by CIKONI
  - Compared to ADAPA uses smaller-sized actuators
  - Can produce sharp corners and more complex geometries
  - Surface interpolated using silicone membrane
    - molding processes up to 180°C
    - 0.5, 1.0 and 3.0 mm thick
  - Uses:
    - R&D tooling
    - Preforming
    - Flexible automotive jigs for bonding/adhesive joining
    - Tailored, individualized helmets, protective structures, orthotics



SOURCE | "DYNAPIXEL: automated, reconfigurable molds", CW Feb 2020

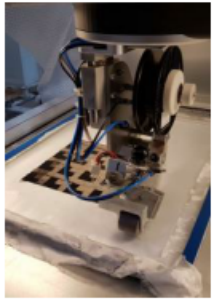
Pin-based tooling

- DYNAPIXEL by CIKONI
  - Joint research project with University of Stuttgart
  - Bring together tailored tow placement processes and automated preforming with DYNAPIXEL.
  - Target: to manufacture any geometry at any volume

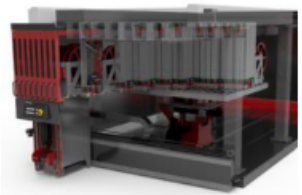
Integration of flexible and reconfigurable preforming systems into the composite production environment

Product Design and Optimization → **Preforming systems** → Impregnation systems → Part finishing

Automated 2D Layup systems

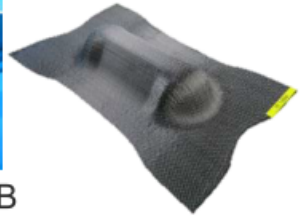


Fixed tow placement by M&A Dieterle/IFB



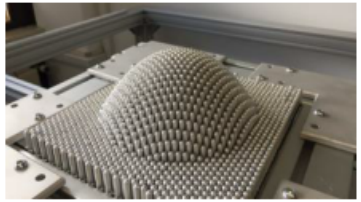
FILL Multilayer

Automatically configured draping systems



Flexible draping cell at IFB

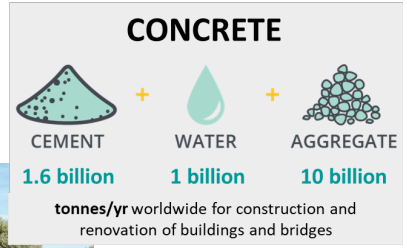
Dynapixel tool by CIKONI



„any geometry, any volume“

CF-reinforced Concrete

- Reduce concrete amount by 50-80%, Reduce CO_2 by 50-70%
- Dr. Manfred Curbach, TU Dresden



Higher performance in precast concrete with CFRP

C-GRID precast panels
15-25% faster construction

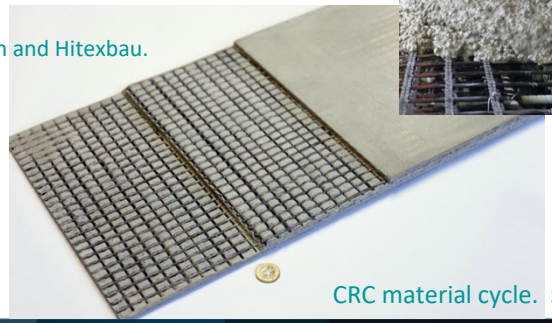
SOURCE | ***CW*** Nov 2017

Two-story, 220-m² CUBE building at TU Dresden and Hitexbau CF grid.

SOURCE | © Iurii Vakaliuk, HENN, TU Dresden and Hitexbau.

C3 carbon concrete composite

- Largest research project in German construction industry
- >150 partners, 300 projects completed since 2006
- Increasing regulations/standards, applications, products
- Cement production = 6.5% of global CO_2 emissions



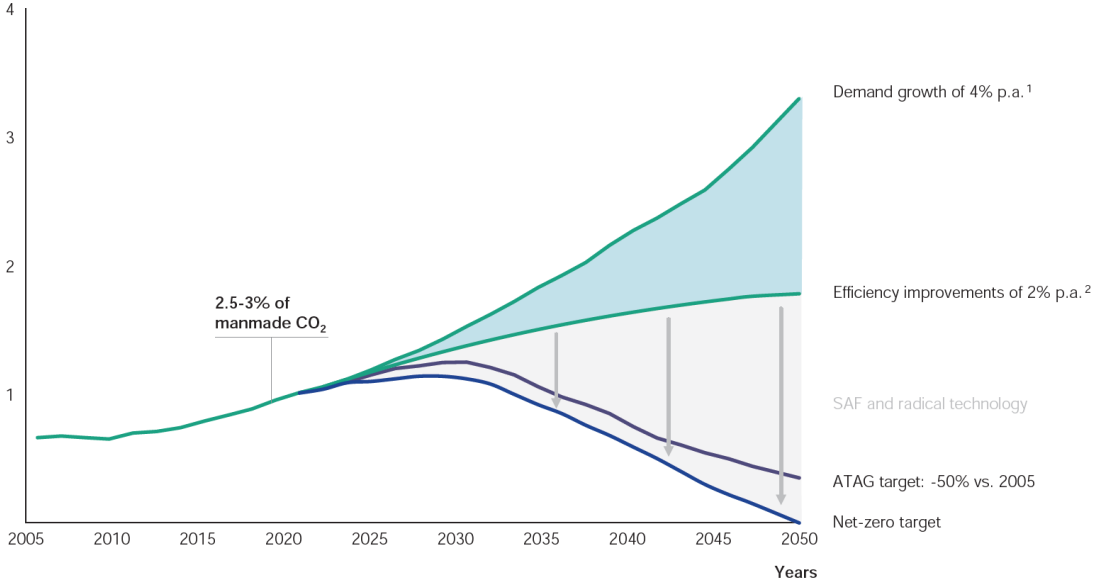
CRC material cycle. SOURCE | C3

Hydrogen in Aviation

- Reduce climate impact
  - 50-75% via H_2 combustion
  - 75-90% via H_2 fuel-cell propulsion
- Best-suited for commuter, regional, short- and medium-range aircraft
- H_2-powered aircraft could reach 40% by 2050 (synfuel, biofuels 60%)
  - Aviation would abate 1.8 gigatons CO2
  - Meet EU and ATAG* goals
- Targeting RJ and short-range aircraft by 2035

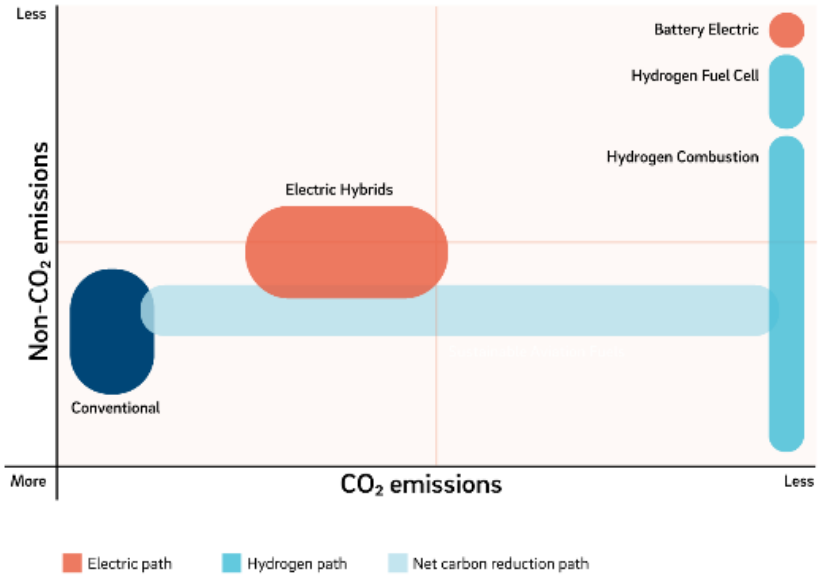
* ATAG = Air Transport Action Group

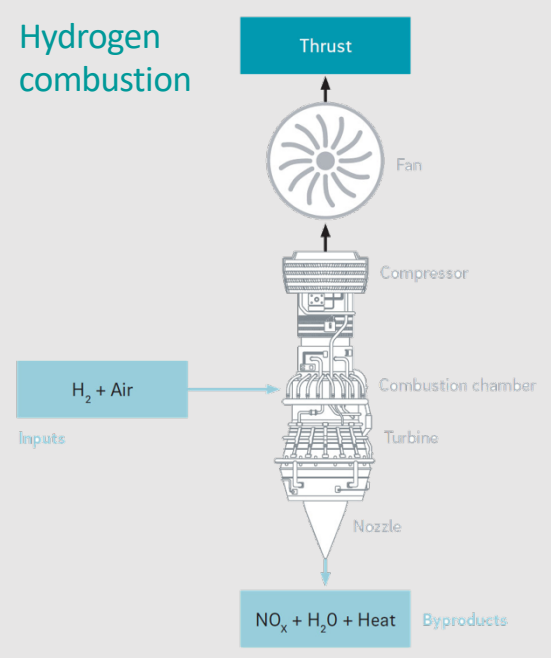
Projection of CO2 emissions from aviation (gigatons)

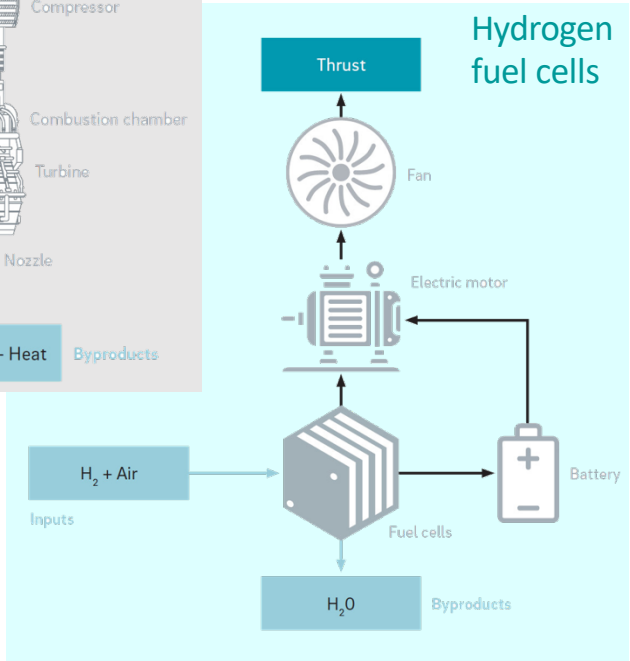


SOURCE | Exhibit 1, "Hydrogen powered aviation", Clean Sky 2 (May 2020)

Hydrogen in Aviation







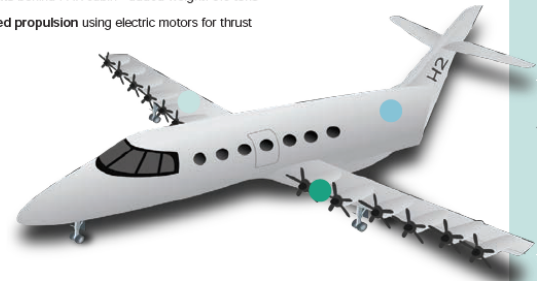
SOURCE | "Hydrogen: A future fuel for Aviation?" Roland Berger (March 2020)

Commuter aircraft powered by fuel cells

Revolutionary aircraft

Design mission: 19 PAX, 500 km range, cruise speed 500 km/h

- **Highly efficient** wing
- **2 LH_2 tanks** behind PAX cabin - added weight: 0.5 tons
- **Distributed propulsion** using electric motors for thrust



Cost	+0-5%
EIS	<15 yrs
MTOW	+15%

Regional aircraft powered by fuel cells

Revolutionary aircraft

Design mission: 80 PAX, 1,000 km range, cruise speed Mach 0.44

- **Highly efficient** wing
- **2 LH_2 tanks** behind PAX cabin - added weight: 2 tons
- **Distributed propulsion** using electric motors for thrust

Cost	+5-15%
EIS	10-15 yrs
MTOW	+10%

Short-range aircraft powered by hybrid H_2 propulsion

Revolutionary aircraft

Design mission: 165 PAX, 2,000 km range, cruise speed Mach 0.72

- **2 LH_2 tanks** behind PAX cabin -added weight: 4 tons
- **Fuel cell system (11 MW)** powering electric motors
- **Electric motor** driving main turbine fan shaft during cruise, while H_2 turbine is turned off

Cost	+20-30%
EIS	15 yrs
MTOW	+14%

SOURCE | Exhibit 1, "Hydrogen powered aviation", Clean Sky 2 (May 2020)

Medium-range aircraft powered by H_2 turbines

Evolutionary aircraft

Design mission: 250 PAX, 7,000 km range, cruise speed Mach 0.82

- **2 LH_2 tanks** in front and back of PAX cabin - added weight: 29 tons
- **H_2 turbines** generating propulsion power

Cost	+30-40%
EIS	20 yrs
MTOW	+12%

Long-range aircraft powered by H_2 turbines

Evolutionary aircraft

Design mission: 325 PAX, 10,000 km range, cruise speed Mach 0.85

- **2 LH_2 tanks** in front and back of PAX cabin - added weight: 52 tons
- **H_2 turbines** generating propulsion power

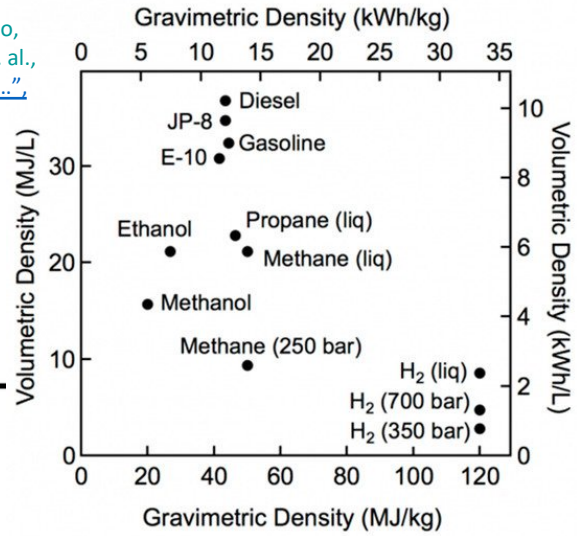
Cost	+40-50%
EIS	20-25 yrs
MTOW	+23%

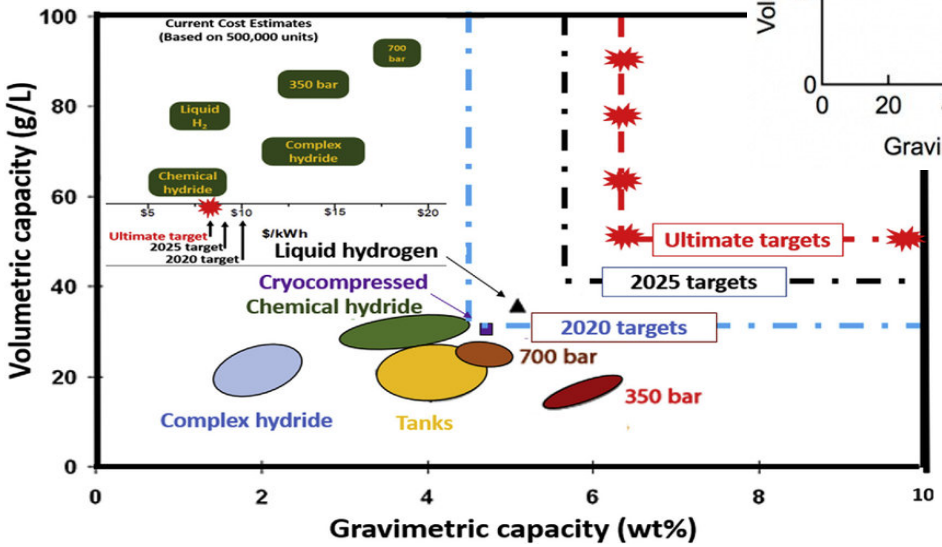
SOURCE | Exhibit 1, "Hydrogen powered aviation", Clean Sky 2 (May 2020)

Hydrogen in Aviation

- Targeting liquid H2 due to higher volumetric density
  - ISSUE - cryogenic requirements vs. alternative gaseous H_2 and carriers such as dimethyl ether (DME)

SOURCE | "Rivarolo, Riveros-Godoy, et. al., "Clean hydrogen ...", Nov 2019.

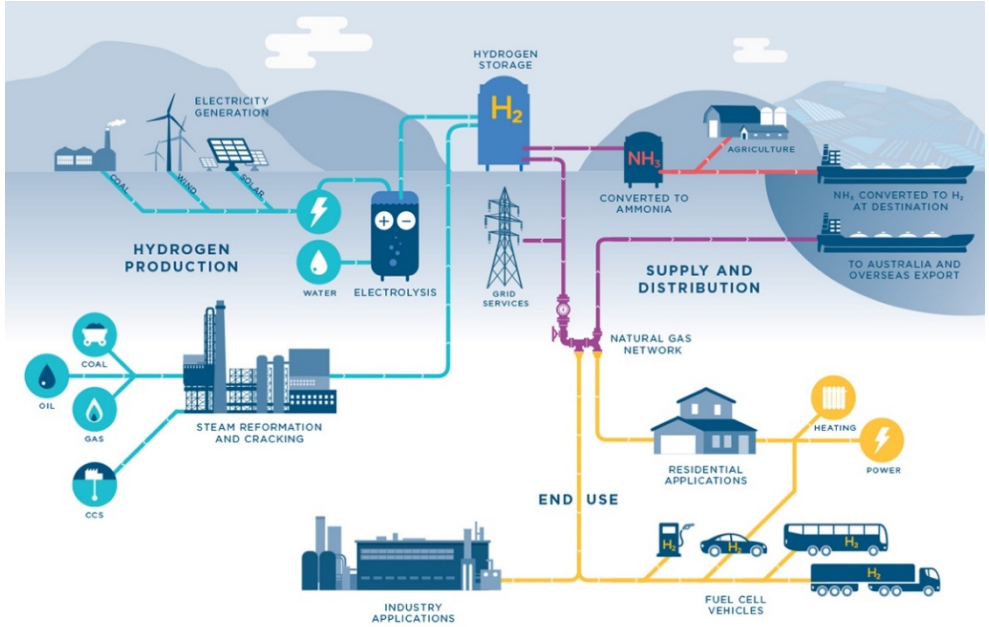


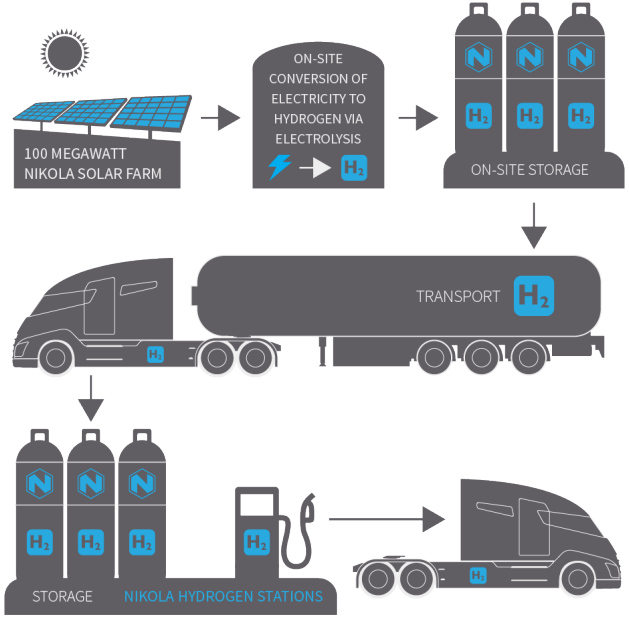


SOURCE | "Boateng, Chen, "Recent advances in nanomaterial-based solid-state hydrogen storage", June 2020.

Hydrogen in Aviation

- Developable infrastructure

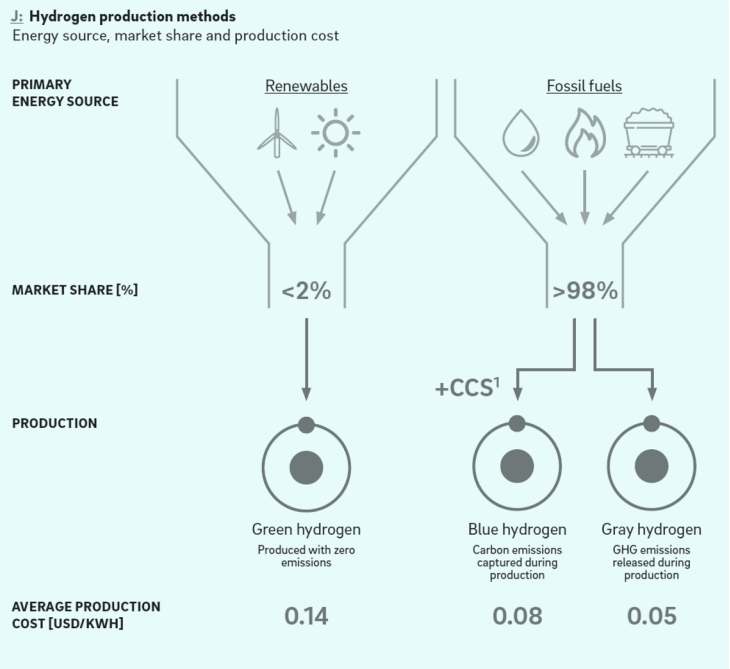




SOURCE | "Australia national hydrogen strategy" Coventuslaw.com (Sep 2019)

Hydrogen in Aviation

SOURCE | "Hydrogen powered aviation", Clean Sky 2 (May 2020)



SOURCE | "Hydrogen: A future fuel for Aviation?" Roland Berger (March 2020)

Exhibit 18

Comparison of hydrogen technology and synfuel

Major advantages
Major challenges

	H_2 fuel cell	H_2 turbine	Synfuel
Climate impact	75-90% reduction	50-75% reduction	30-60% reduction[1]
Aircraft design	Only feasible for commuter to short-range segment	Feasible for all segments except for flights >10,000km	Only minor changes
Aircraft operations	1-2x longer refueling times for up to short-range	2-3x longer refueling times for medium- and long-range	Same turnaround times
Airport infrastructure	LH_2 distribution and storage required		Existing infrastructure can be used
Fuel supply chain	1.7x energy[2] required for fuel production		4.6x energy[3] required for fuel production
Cost comparison between H_2 and synfuel	Lower for commuter to short-range aircraft	Lower for medium-, higher for short-range aircraft	Higher than H_2 aircraft for commuter - medium-range

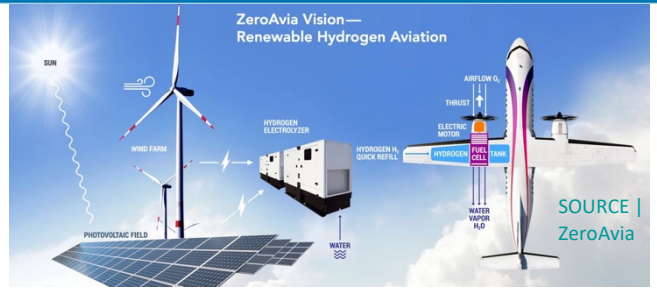
1. CO_2 from direct air capture assumed
2. Assuming PEM electrolysis, compression, pipeline transport, liquefication, storage and distribution
3. Assuming PEM electrolysis, CO_2 direct air capture, synthesis, pipeline transport, and distribution

H: Current hydrogen aircraft developments

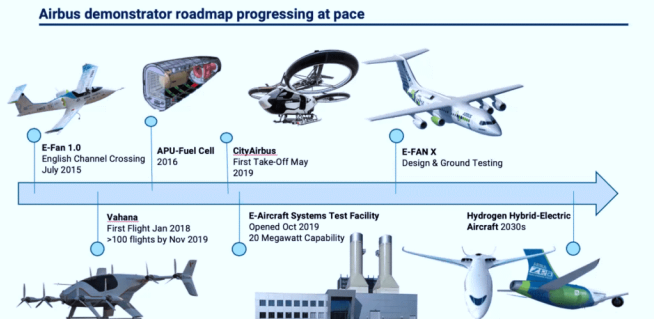
Details and status of hydrogen aircraft projects

	YEAR ANNOUNCED	POWER	DESCRIPTION	STORAGE SYSTEM	RANGE [KM]	STATUS
HY4	2015	Hydrogen fuel cells and electric batteries	Four seat fixed wing aircraft, single propeller, twin fuselage	Gas	1,000	Flown
HES Element One	2018	Hydrogen fuel cells	Four seat, fixed wing aircraft, 14 propellers	Gas/liquid	500-5,000	Under development
Alaka'i Skai	2019	Hydrogen fuel cells	Five seat futuristic "air-taxi" rotorcraft, six rotors	Liquid	640	
Apus i-2	2019	Hydrogen fuel cells	Four seat fixed wing aircraft, two propellers	Gas	1,000	
NASA CHEETA	2019	Hydrogen fuel cells	Blended wing-body large commercial aircraft	Liquid	n/a	
Pipistrel E-STOL	2019	Hydrogen fuel cells	19 seat, fixed wing aircraft	n/a	n/a	
ZeroAvia[1]	2019	Hydrogen fuel cells	10-20 seat fixed wing aircraft, two propellers	Gas	800	
Airbus Cryoplane	2003	Hydrogen combustion	Large commercial aircraft	Liquid	n/a	Feasibility study
NASA Concept B	2004	Hydrogen fuel cells	Blended wing-body large commercial aircraft	Liquid	6,500	

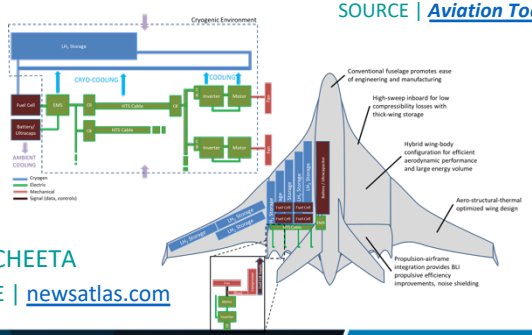
SOURCE | "Hydrogen: A future fuel for Aviation?" Roland Berger (March 2020)



SOURCE | ZeroAvia



SOURCE | *Aviation Today*



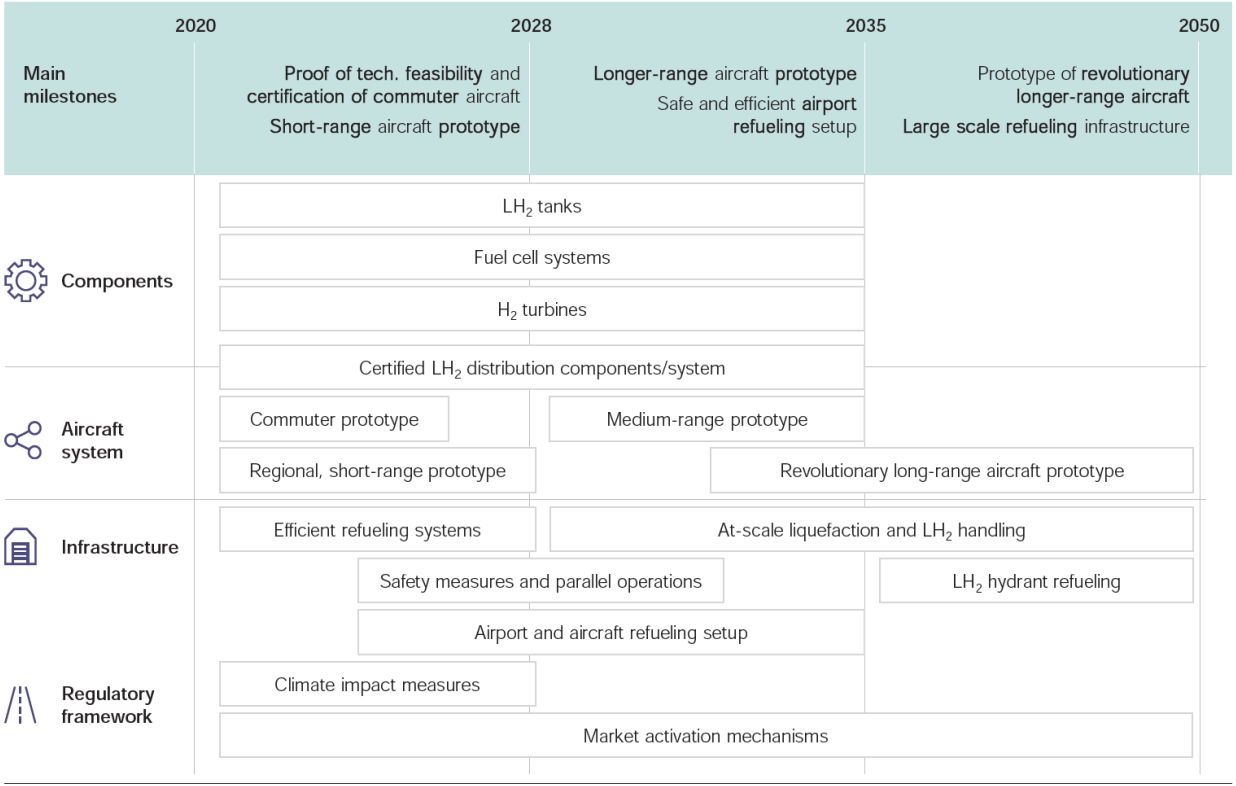
NASA CHEETA

SOURCE | newsatlas.com

Hydrogen in Aviation

Exhibit 24

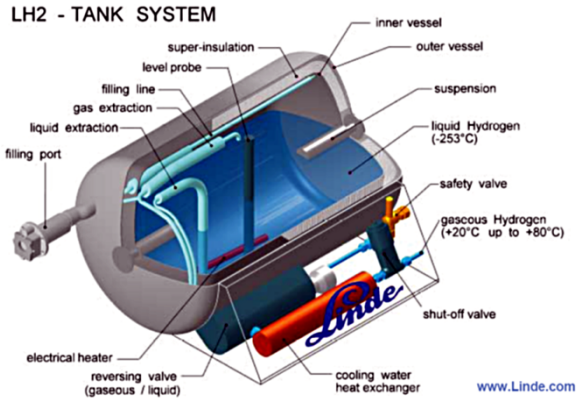
Research & Innovation roadmap – 4 main research areas



SOURCE | "Hydrogen powered aviation", Clean Sky 2 (May 2020)

Hydrogen in Aviation

- Lightweight and safe LH_2 tanks



SOURCE | Krishna, "Hydrogen storage…", Sep 2012

Objective: Decrease weight of LH_2 tanks to enable more efficient H_2-powered aircraft and better economics – potentially enabling competitive economics for long-range aircraft

Target: 35% gravimetric index for short-range (5 tons of LH_2 stored), 38%+ for long-range aircraft (more than 30 tons of LH_2)
Cost target in 2050: <550 US $/kg LH_2

Where we are today: 15-20% gravimetric index (for tank with less than one ton of LH_2)

Research timeline: For short-range in the next 5 years, longer-range aircraft in next 10 years to ensure on time development of first aircraft prototypes

SOURCE | p. 63, "Hydrogen powered aviation", Clean Sky 2 (May 2020)

CompositesWorld.com

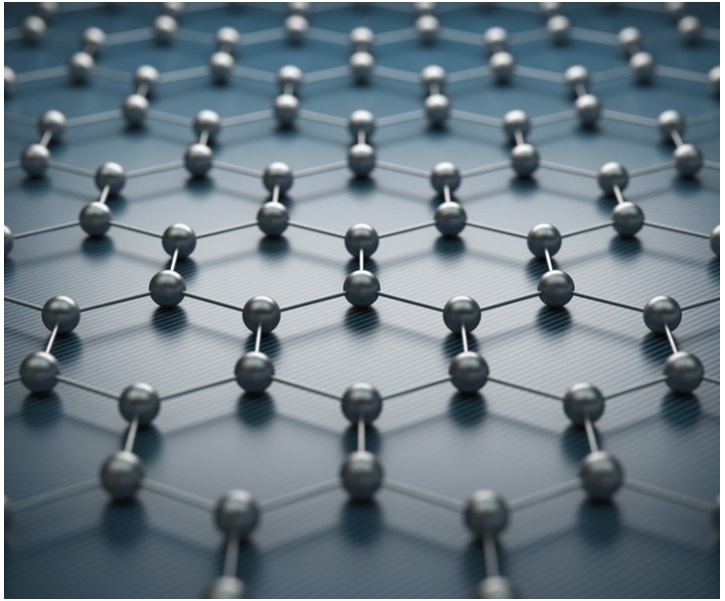
CompositesWorld

Next-Generation Composite Materials and Processes

Hannah Mason
Associate Editor
CompositesWorld

hmason@compositesworld.com

Graphene-enhanced composites



Source | Oxford Advanced Surfaces

What graphene is:

- Two-dimensional, planar sheet of bonded carbon atoms
- First isolated in 2004 by researchers at University of Manchester
- Awarded a Nobel Prize in 2010
- Exfoliated from graphite, or deposited from gaseous feedstock

Reasons to use it:

- Strength
- Stiffness
- Low weight
- Electrical conductivity
- Thermal conductivity
- Durability
- Flexibility
- UV resistance
- Fire resistance
- Tendency to reduce interlaminar shear failure
- Impact resistance
- Sustainability
- And more

Graphene-enhanced composites

Suppliers:

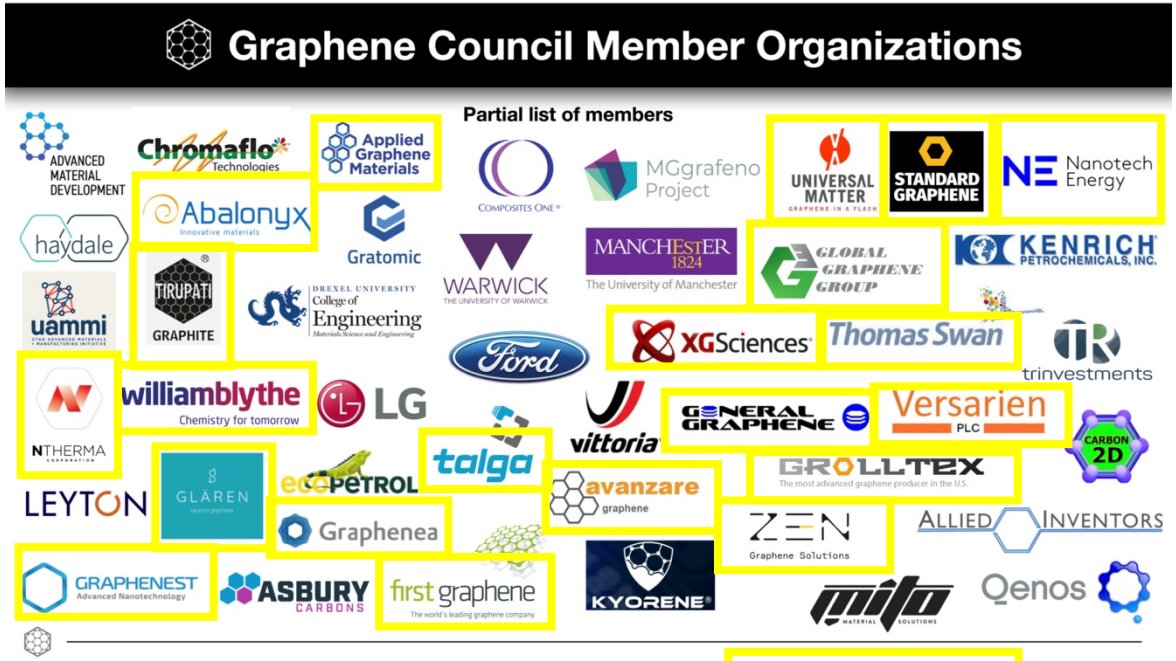
- More than 200 graphene suppliers, about 30 or so at the industrial scale

Forms of graphene:

- 1-2 atomic carbon layers, or up to 10+
- Commercial formats include graphene oxide, reduced graphene oxide, powder, solution, paste, nanoplatelets, or functionalized graphene
- Most common in composites: multi-layer graphene

Cost:

- The smaller the number of carbon layers, the higher the cost



Source | [The Graphene Council]

Graphene suppliers

Graphene-enhanced composites

Composite applications:

- Sporting goods
- Automotive
- Commercial aerospace
- Space
- Tooling
- 3D printing

Future opportunities?

- Full commercialization
- Larger-scale applications
- Additional markets

Source | XG Sciences (left), Graphene Flagship (top right), ICT Composites Technologies (bottom right)

Learn more

- Other CW webinars:
  - Thermoplastic Composites in Automotive (2019)
  - Thermoplastic Composites in Aerospace (2019)
  - Click links above or email Jeff Sloan for copy of presentations: jeff@compositesworld.com

- National Composites Week
  - August 24-28
  - Second annual celebration
  - Highlight your and your company's work, employees, projects, technologies
  - Share images/videos via social media
  - Virtual plant tours
  - #NationalCompositesWorld #CompositesAreEssential
  - More information, guides: www.nationalcompositesweek.com

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Q&A

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