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CENTRE DES COMPOSITES CONCORDIA

Automated composites manufacturing: Recent advances, challenges and opportunities

CONCOM

Suong Van Hoa, Professor, Mechanical-Industrial-and Aerospace Engineering Department

Pre-symposium for ACM5- Bristol University-April 2021

Université Concordia University

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Outline

Focus of the presentation

Thermoset matrix composites

1. Speed of deposition – Efficiency of machine use
2. Inspection
3. Fiber steering
4. Dry fibers

Thermoplastic matrix composites

1. Heating
2. Interlaminar shear strength
3. Distortion for structures with free edges

Future outlook

Conclusion

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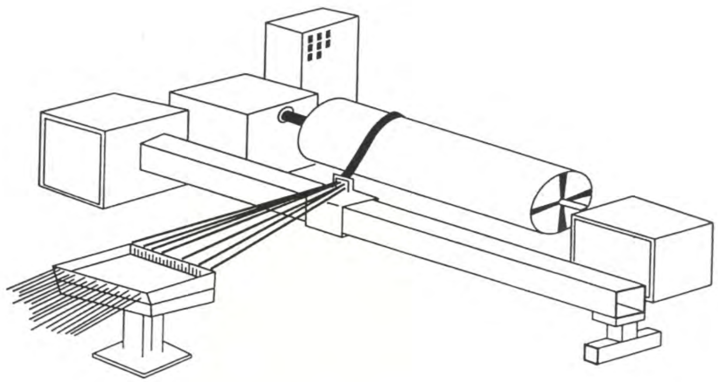
Automated composites manufacturing

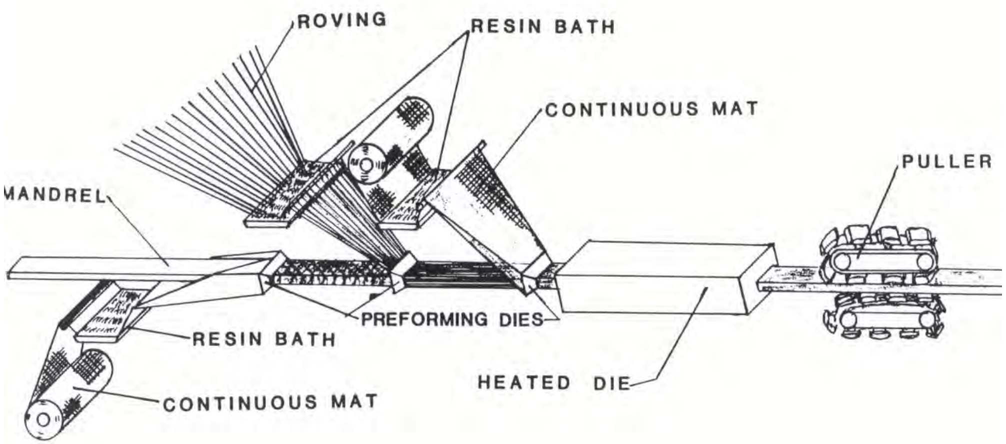
Any manufacturing process of composites that utilizes machines with some degree of automation

Items not discussed

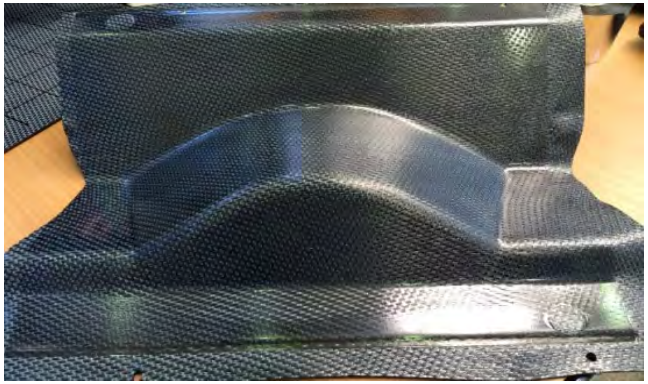
Filament winding



Pultrusion



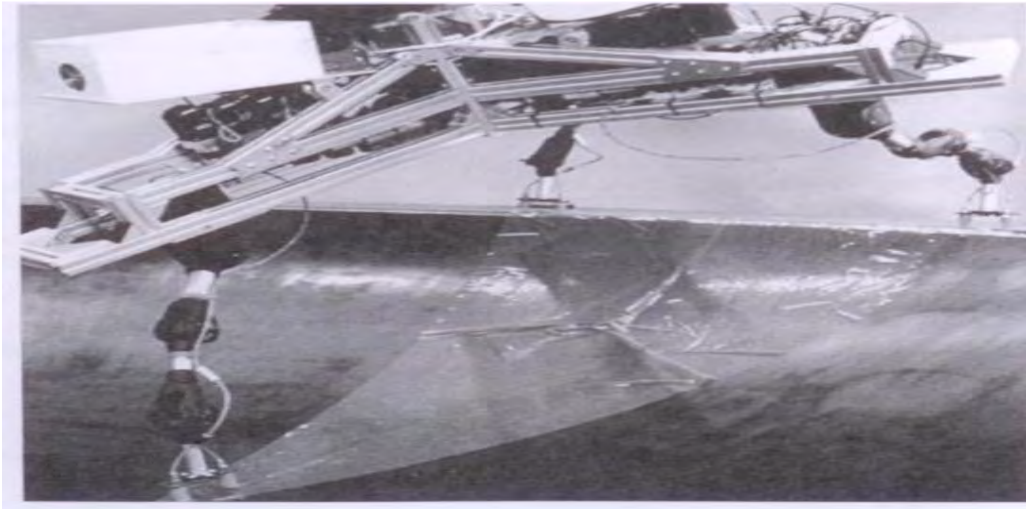
Thermo-stamping



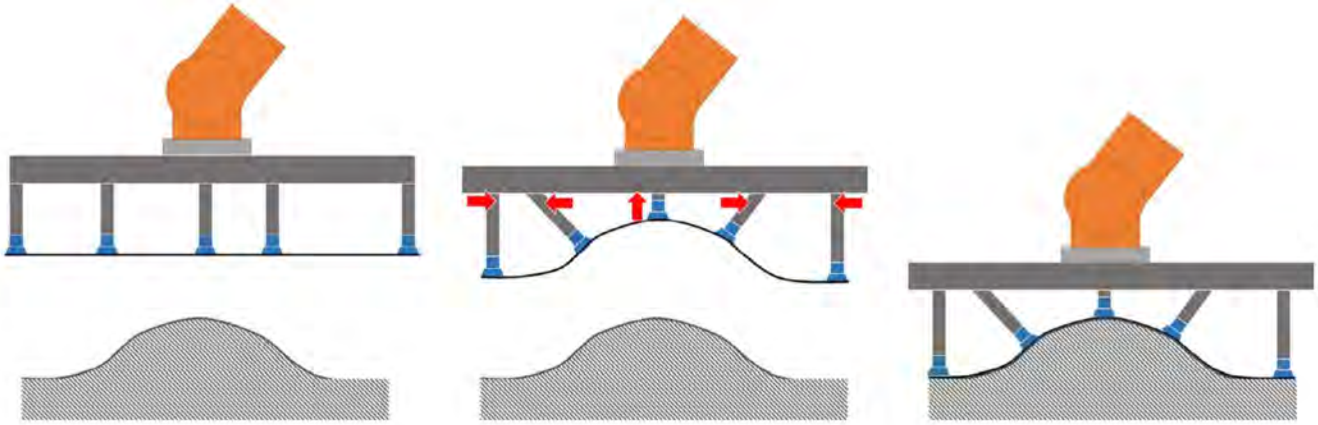
Items not discussed

Material Handling-Pick and Place

- **Prepregs**
- **Dry fibers**
- **Auxiliary materials-bagging materials**



A. Bjorsson, M. Jonsson, K. Johansen, "Automated material handling in composite manufacturing using pick-and-place systems. A review", Robotics and computer integrating manufacturing, 51, 2018, 222-229



Focus on Automated Tape Layup (ATL) and Automated Tape (Fibre) Placement (AFP)

- Thermoset matrix composites: Information obtained from the literature
- Thermoplastic composites: Work done at Concordia

Aircraft Factory of the Future Concept

Current aerospace composite part manufacture

Composites Clean Room

Current automobiles manufacture

Large, simple structures

How to deposit materials at high speed, with good accuracy and few defects

- Large parts
- Limited geometrical complexity

Thermoset composites more suitable than thermoplastic composites

Photo from Composites World magazine

Outline

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Thermoset matrix composites (40°C- 60°C)

1. Speed of deposition – Efficiency of machine use
2. Inspection
3. Fiber steering – Tow shearing
4. Dry fibers

Thermoplastic matrix composites

1. Heating
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Applications of AFP made thermoset matrix composites

Boeing 787 Dreamliner

Airbus 350 XWB

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A lab size machine

THANK YOU

Time analysis of a production AFP machine

1. Loading tows onto the depositing head

2. Different modes of material deposition

- Mid course pay out: Lay up length large enough for machine to go for maximum speed
- Adds and cuts
- Minimum pieces and gaps
- Off part motion

3. Reliability recovery

- Splicing tow ends
- Breaking tows
- Twisted tows
- Tow sticking to roller

4. Inspect and review

- Manual or automatic
- Defects treatment

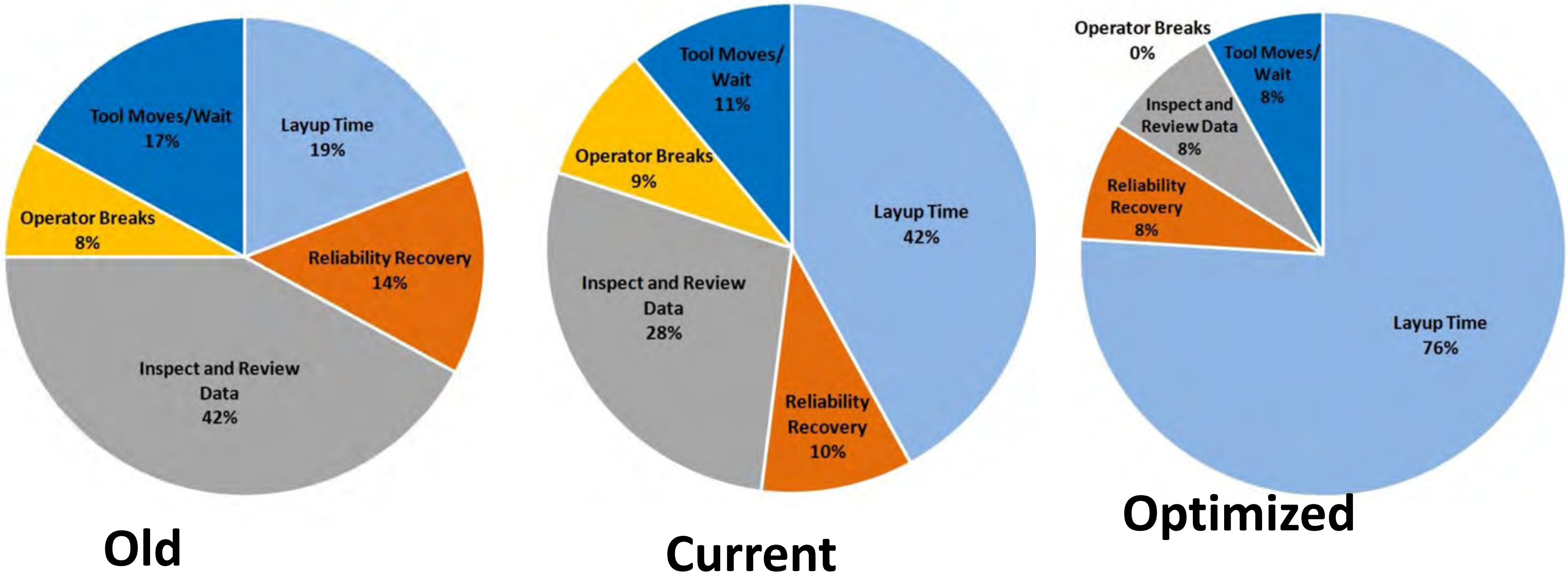
5. Tool move and wait

- Head exchanger

Challenges

T. Rudberg, J. Cemenska, and E. Sherrard, “A process for delivering extreme AFP reliability), SAE paper 2019-01-1349

- **AFP machines in aerospace manufacturing spend much of their existence doing nothing.**
- **Challenges for next generation AFP cells is to increase lay up as percentage of cell time.**



Lay up analysis- Electroimpact

Gillespie C., "Integrating 20 tow, 1.5 inch AFP head on large part for high deposition rate application", SAE technical paper 2017-01-2049.

- **20 tows, 1.5 inch wide, AFP for high speed deposition rate. The OH20.**
- **For the manufacturing of large surface area and low contour parts (wing skins).**
- **4 heads with quick change automatic tool changer.**

- **Mid course pay out speed 4,000 inch/minute (IPM) (6 km/hr). Corresponds to 3050 lbs/hour (PPH).**
- **Add and cut speeds: 1,200 in/minute (IPM)**
- **Minimum pieces and gaps:600 IPM**
- **Off part motion: 6,000 IPM**

Courtesy of Electroimpact

- **> 900 pounds per hour (PPH) lay up rate during production part program execution.**

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Defect detection

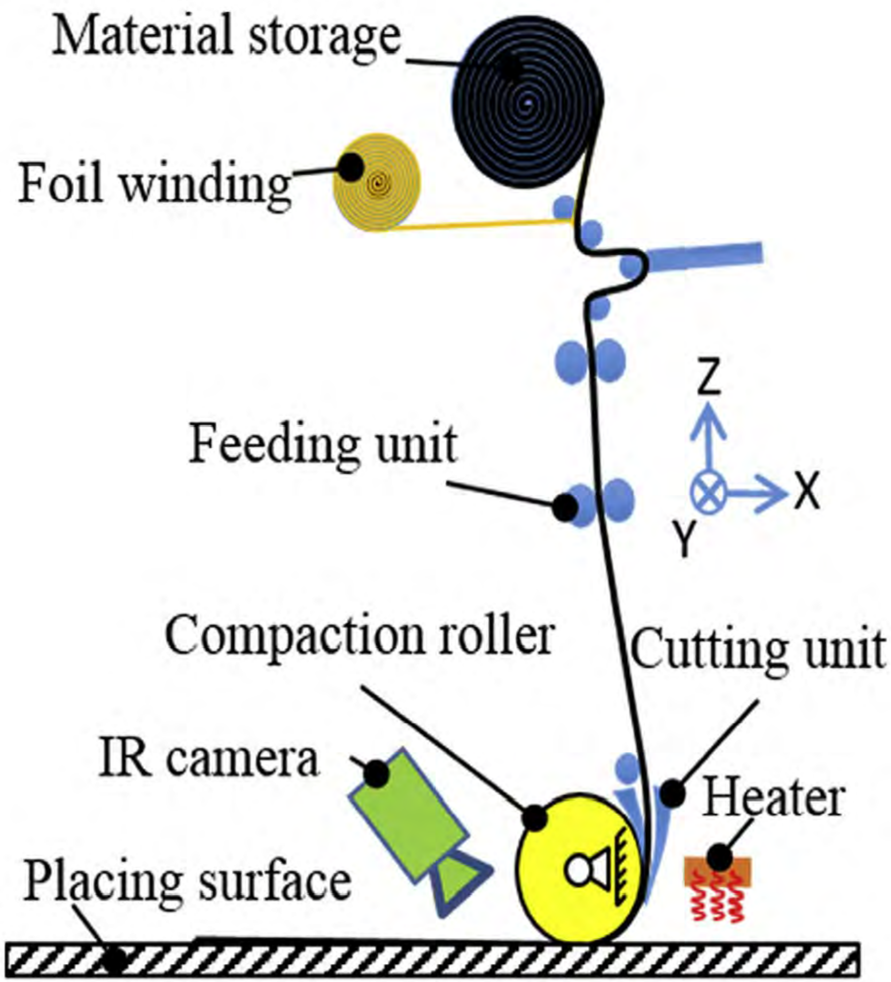
- In AFP, manually inspection of parts consumes a large portion of production time, and is susceptible to missing defects.
- Manual inspection can consume more than 25% of total production time, and many defects escape detection.

Many organizations have projects to address this issue:
Universities
Companies

Thermographic system

Denkena B., Schmidt C., Voltzer K., Hocke T. "Thermographic on line monitoring system for automated fiber placement processes", Composites Part B. Eng., 2016, 97, 239-243.

Can detect tow locations, gaps, laps, foreign bodies



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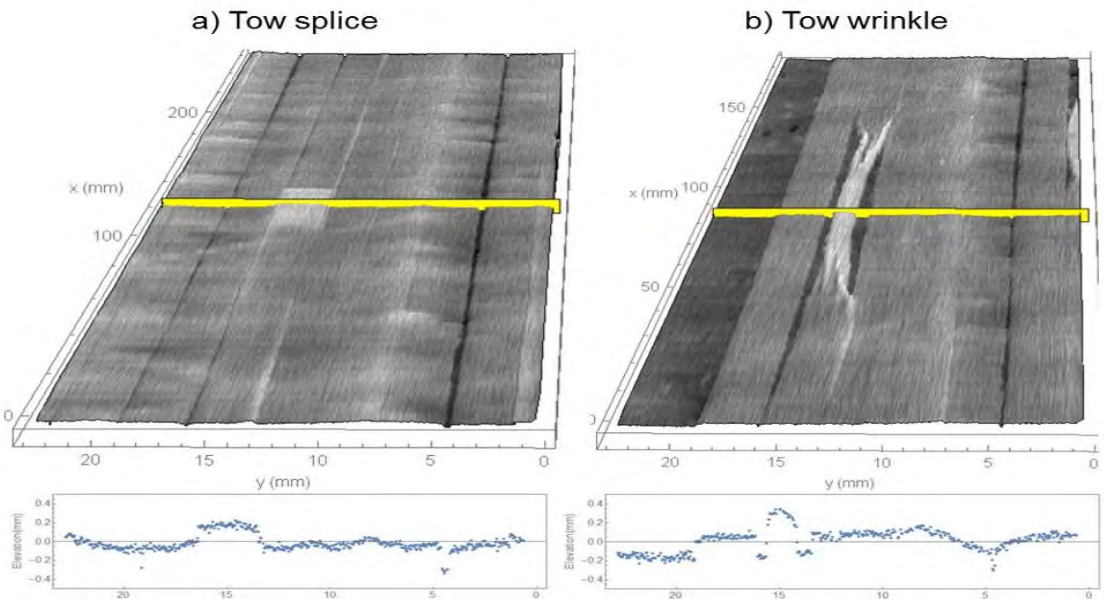
Defect detection

Marc Palardy-Sim et al, "Next generation inspection solution for automated fibre placement", Proc. ACM4, Automated Composites Manufacturing, ed. S.V.Hoa, Destech 2019.

Optical coherence tomography (OCT)-National Research Council of Canada, Fives Machining system

- **Similar to ultrasound imaging.**
- **OCT imaging probes a material with light and detects reflection to map the position of the material interfaces.**
- **Interferometer with two optical paths. Sample arm emits and collects the light from the same point, like the end of an optical fiber.**

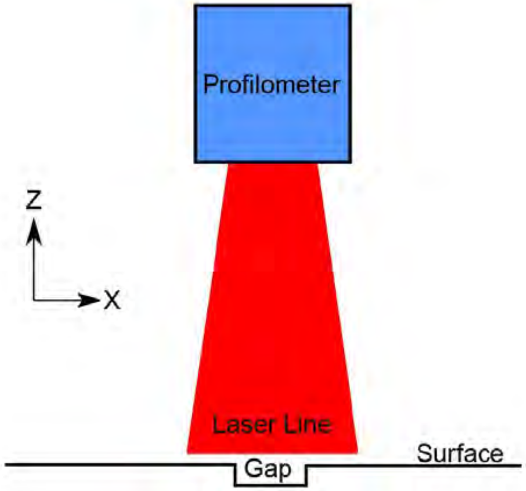


Defect detection

J. Cemenska, T. Rudberg, M. Henscheid, A. Lauletta, B. Dvis, “AFP automated Inspection system performance and expectations”, SAE technical paper **2018-**01-2150.

Electroimpact system

- **Cameras, laser projectors, laser profilometers, & user interface.**



- **On large parts with >1,000 tow ends, a few minutes to inspect.**
- **Ply boundary inspection - Identify and measure 92% of tow ends in standard ply.**
- **Gap measurement has a mean error < 0.003” and a standard deviation of 0.005”.**
- **Overlap measurement data has a mean error < 0.010” and standard deviation of 0.013”**

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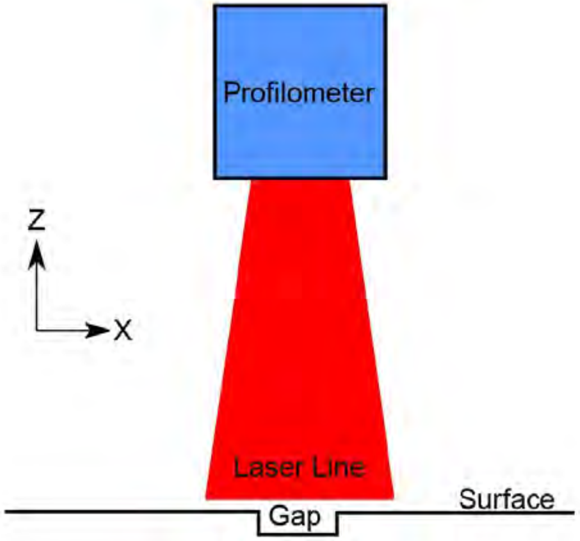
Electroimpact system

- Suite of software programs processes the data.
- Data is stored in a data base which acts as the interface between different software programs for interaction and data sharing.
- Extensive interface ties all the data together and displays the results.



- Inspection data consumes a large amount of hard drive space. Data can approach 1 TB/ part for complex parts.

Data value and utility

- Reduces inspection time.
- Reduces human errors.
- Statistical process control can eliminate unnecessary fixes. Instead of reworking every out-of-tolerance error, operators can rework only conditions that make the population out-of-tolerance.

Resource burden

- System cost: $1,000,000.
- Manufacturers need to make decisions about how to use the inspection data.

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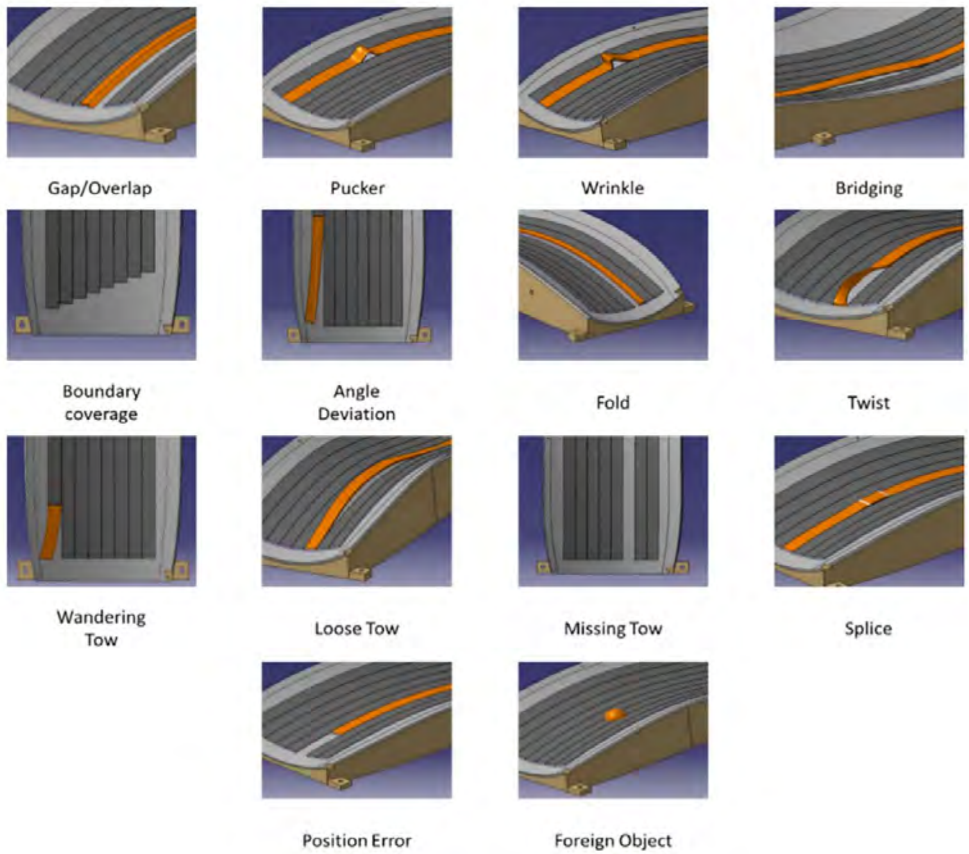
Defects

Chevalier P.L., Kassapoglou C., Gurdal Z., “Fatigue behavior of composite laminates with automated fiber placement induced defects- a review”, Int. J. Fatigue, 2020, 140, 105775.

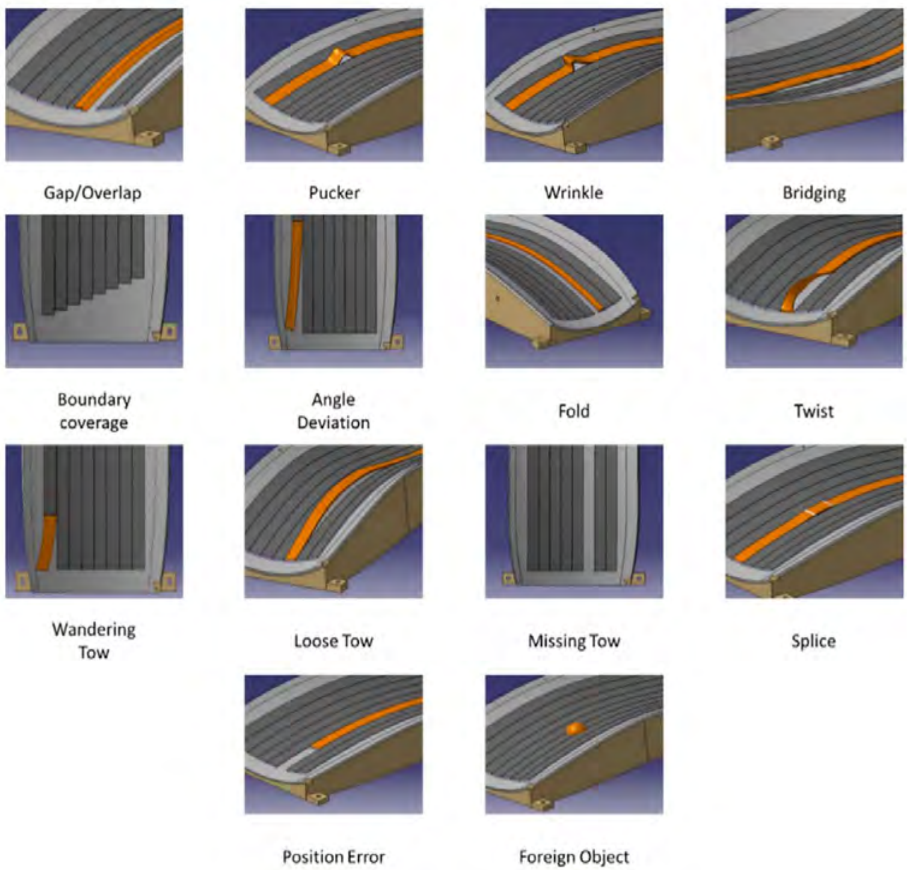


Five perspectives:

- **Anticipation: Predicting occurrence**
- **Existence: Inspection**
- **Significance: Effect on performance**
- **Progression: Potential evolution**
- **Disposition: Defect treatment**

Effect of defects on performance

Chevalier P.L., Kassapoglou C., Gurdal Z., “Fatigue behavior of composite laminates with automated fiber placement induced defects- a review”, Int. J. Fatigue, 2020, 140, 105775.



- **Quasi-static loading in unnotched unidirectional laminates: Not significant effect.**
- **Fatigue loading: More influence**
- **More work required: Large variety of geometry configurations, large number of type of defects, loading conditions.**

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Thermoplastic matrix composites

1, Heating
2. Interlaminar shear strength
3. Distortion for structures with free edges.

Future outlook

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Fibre steering

Shown here is an Ingersoll Machine Tools AFP machine demonstrating a course of steered tows. While moderate steering is possible with infrared heating systems, smaller radii likely will require laser-based heating systems. Photo Credit: Ingersoll Machine Tools

Photos from Composites World magazine- Nov. 2020

- AFP well suited to tow steering
- Laser heating highly focused, well controlled.
- Requires:
  - Precise and focused heat
  - Good compaction

Fiber steering

Steering radius- Affecting factors:

- **Tow width,**
- **Tow thickness,**
- **Resin type,**
- **Resin tackiness,**
- **Fiber type,**
- **Fiber format,**
- **Substrate contour complexity,**
- **Substrate quality,**
- **Arc length and tolerance parameters.**

Fiber steering

Possibilities: (Electroimpact, Coriolis, Ingersoll machines)

- **0.125” tow R = 750 mm (19.5”)**
- **0.25” tow R = 280 mm (11”) to 1500 mm (59”)**
- **0.5” tow R = 150mm (6 “)**

- **Such steering sees limited use, given the fact that composite aerostructures operate in a certification environment that favors traditional quasi-isotropic ply schedules.**

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Advantages and disadvantages: DFP versus prepreg placement

Michael Assadi and Tyler Field, "AFP processing of dry carbon fiber materials (DFP) for improved rates and reliability", SAE Technical paper **2020**-01-0030

Advantages

- **No resin within dry fiber material, downtime events and repair times are reduced for DFP versus AFP processing. 15-30% increase in machine utilization.**
- **Better tension control. Higher DFP lay down speeds are also supported above 100 m/min (4000 in/min).**
- **The variable spot size laser (VSS) focuses heating on the active tows only.**

Disadvantages

- **Fuzz development for slit dry fiber can be excessive, resulting in some FOD creation.**
- **Requires higher temperature heating and finer tension control.**
- **Requires a class 4 laser, creating the appropriate safety measures.**
- **Laminates with lower tacking. This makes the part more fragile and produces challenges on thicker lay ups.**

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Dry fiber placment

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Ya-nan Liu, Chongxin Yuan, Chenxiao Liu, Jie Pan & Qinghai Dong, Scientific reports, May 2019

- **Method 1: DAFP and VARI-oven curing- Method 2: HLU and VARI-oven curing**

	Preform			Laminate		Thickness change rate (%)
	T-mm	ST(%)	W-g	T	SV(%)	
Manual	1.56	8.5	240	1.19	8.1	-23.3
ADFP	1.21	2.5	227	1.28	3.8	6.0

	Fiber volume fraction (%)	Void content (%)	Surface finish-bag side
Manual	47.8	2	
ADFP	56.3	0.6	better

	Infused resin weight (g)	Filling time (min)
Manual	440	35
ADFP	389	72.7

ADFP is better than HLU, except filling time

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Thermoplastic matrix composites (275ºC- 400ºC)

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Thermoplastic composites

(275C – 400 C)

The objectives in manufacturing of thermoplastic composites using AFP are

- Structures that have minimum amount of void
- Resins that have good degree of crystallinity
- No deconsolidation
- No distortion
- Good rate of production
- Good surface finish

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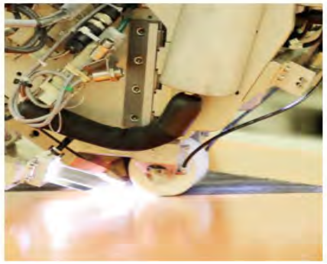
Heating sources(power & controllability)

1. Hot gas torch (nitrogen)
2. Direct/Open flame torch
3. Laser (Diode laser- 800-1000 nm, Nb-YAG laser). Laser spot 56.5 mm. 4 kW.
4. Heat lamp(Heraeus Noblelight, humm3)
5. Infrared



humm3® TECHNOLOGY

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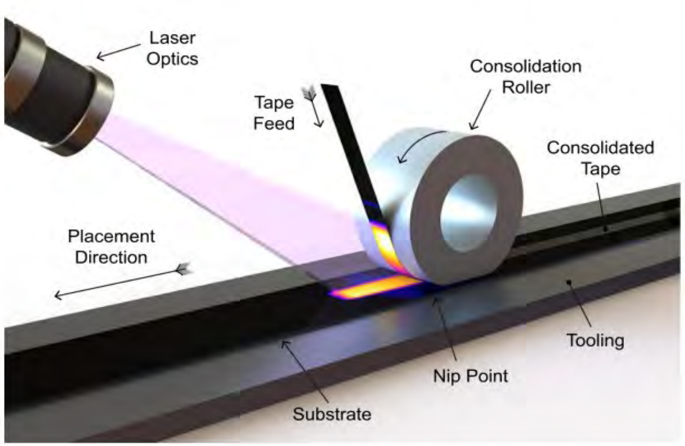


Stokes-Griffin C.M., Compston P., Composites part A, 2015,75, 104-115

Hot gas torch/ Direct flame

Hot gas torch:

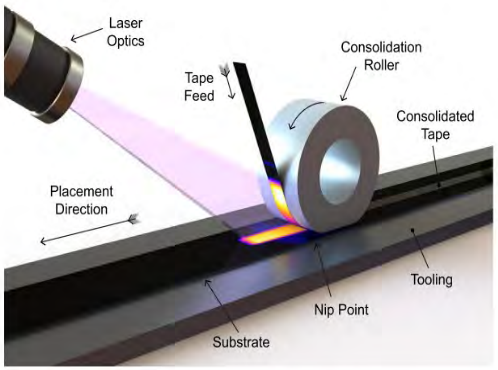
- Nitrogen gas is heated by an electric heater located before the tip of the nozzle.
- Nitrogen flow can be adjusted.
- Hot gas stream can not be pointed in multiple directions efficiently.
- Heat loss to environment.

Direct flame:

- A mixture of propane and air (oxygen) ignites a flame, which heats up the material through convection.
- Propane/air ratio can be adjusted.
- Flame can not be pointed in multiple directions efficiently
- Heat loss to environment.

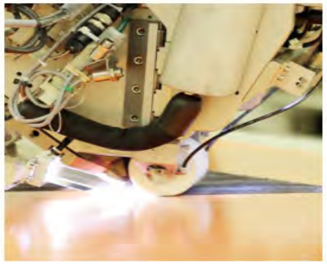
Lasers

- 3 kW diode laser, wavelength 1015 nm
- Lay down speed: 8 m/min to 12 m/min (5 inch/sec to 8 inch/sec)
- Target temperature 420 C.
- Roller material: Silicone
- Roller pressure: 1.2 Bar (17.6 psi)
- Cool down rate: 2 C/minute.
- Safety considerations



Heat lamp- Humm3

- High energy flashes via xenon lamp which heats the material through radiation
- Three adjustable parameters: Voltage, frequency, and Pulse duration.
- Asymetric prism with ~ 25% directed toward the incoming tape, 25% directed at the NIP point, and 50% power directed at the substrate.
- New



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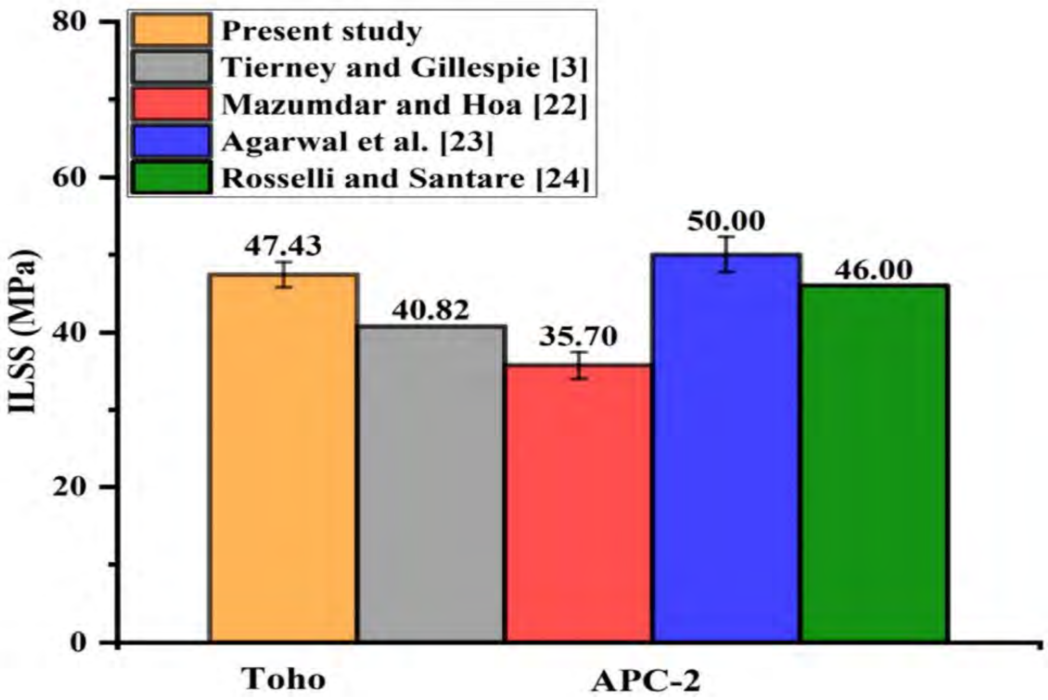
Interlaminar shear strength

A.K. Banderu et al, "Properties of a thermoplastic composite skin-stiffener interface in a stiffened structure manufactured by laser assisted tape placement with in situ consolidation", Composite structures, 2019, 214, 123-131

Autoclave = 80 MPa



Producing parts by ATP with mechanical properties comparable to autoclaved parts, at the rates demanded by industry, is extremely challenging.

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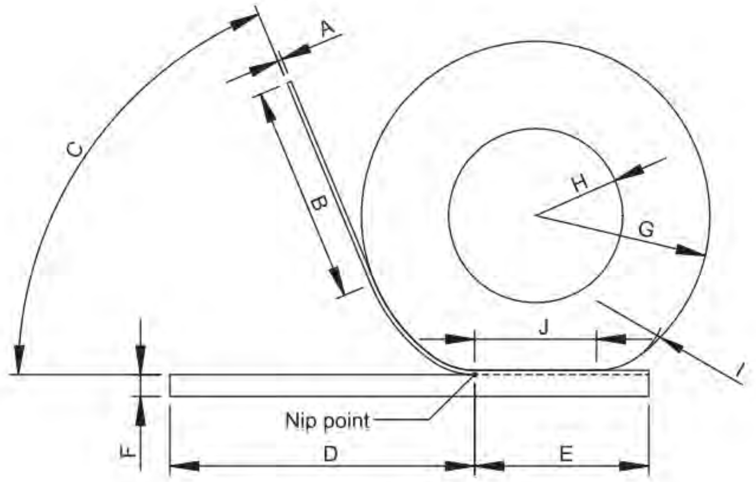
Reasons for poor interlaminar shear strength

1. Bond formation:

- Flattening surface asperities
- Intimate contact
- Reptation theory
- Dynamic shear effect



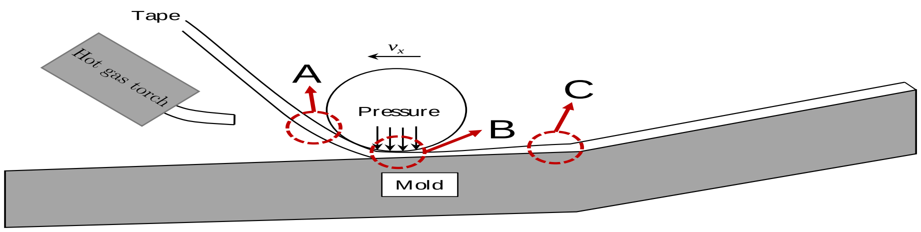
$$t_c = 22.9\eta$$ **Viscosity in MPa**

Viscosity 1 KPa.s, t_c **= 0.0229 sec.**

Process contact time: **t = E/V . V =4"/sec , E= 0.25", t = 0.0625 s, E = 0.125 " , t = 0.0313 s**

2. Deconsolidation after NIP point

Region between B and C-
Temperature above Tg- No pressure



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Issues in automated composites manufacturing for thermoplastic composites

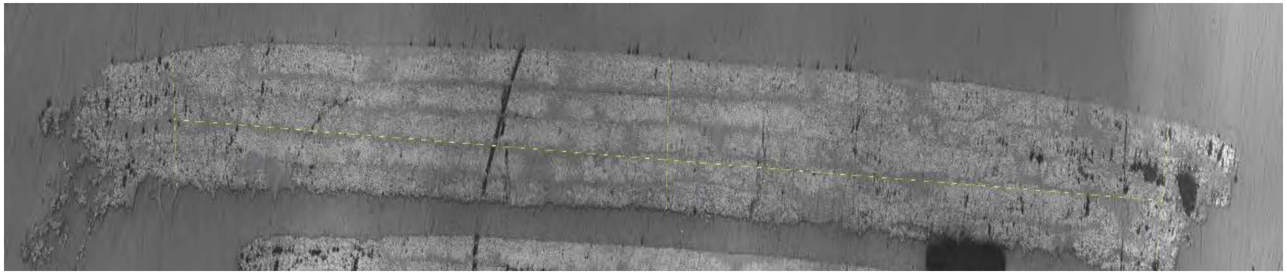
Structures with no free edges (tubes) can be made easily

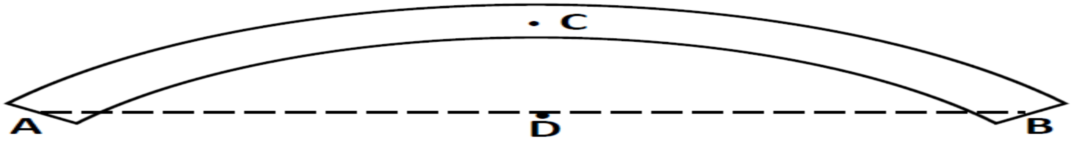
Structures with free edges (plates, shells, panels) can exhibit distortion- Cold mandrel

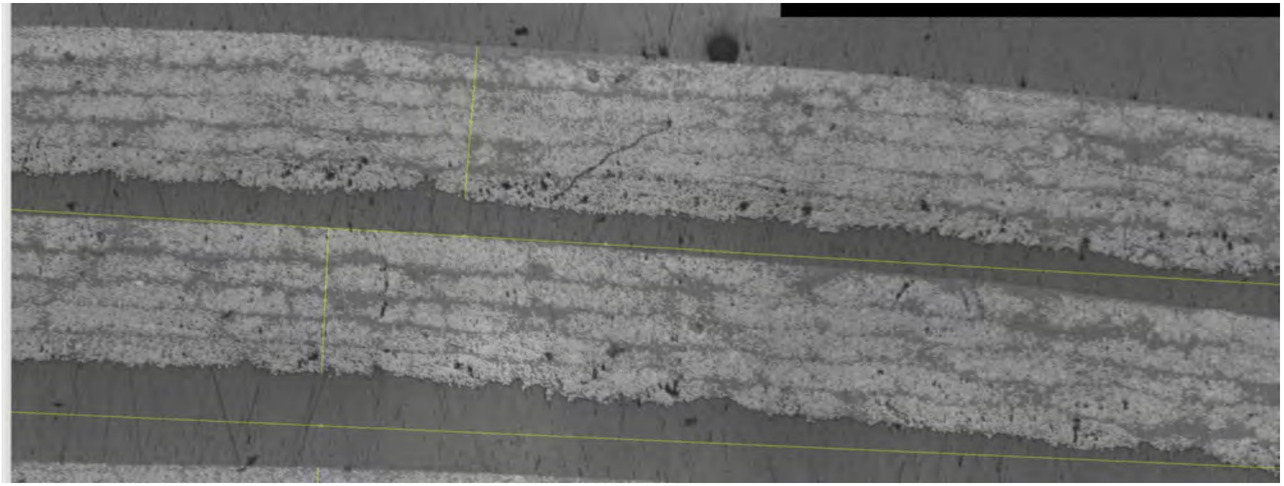
Reason: Thermal gradient in all directions: Developed during process

Example of thermal gradient
Bending along width direction

- Carbon/PEEK sample
- AFP- hot gas torch- 450 °C
- Width expansion
- Bending along width direction
- AB = width
- Offset distance CD







Work on thermoplastic composites made by AFP at Concordia Center for Composites

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Thermoplastic composites applications

BELL

BOMBARDIER
l'évolution de la mobilité

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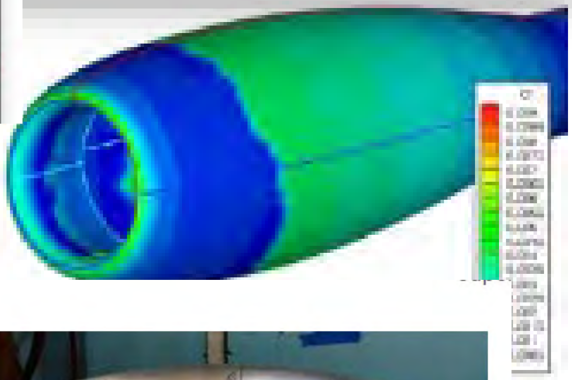
Cross tube for landing gear



Nacelle lip for laminar flow

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Thermoplastic composites applications

Replaces aluminum.
Stiff, strong.
Can absorb large amount of energy on failure.
Thermoplastic composites, with special lay up design.

Manufacturing of curved thermoplastic composite tube

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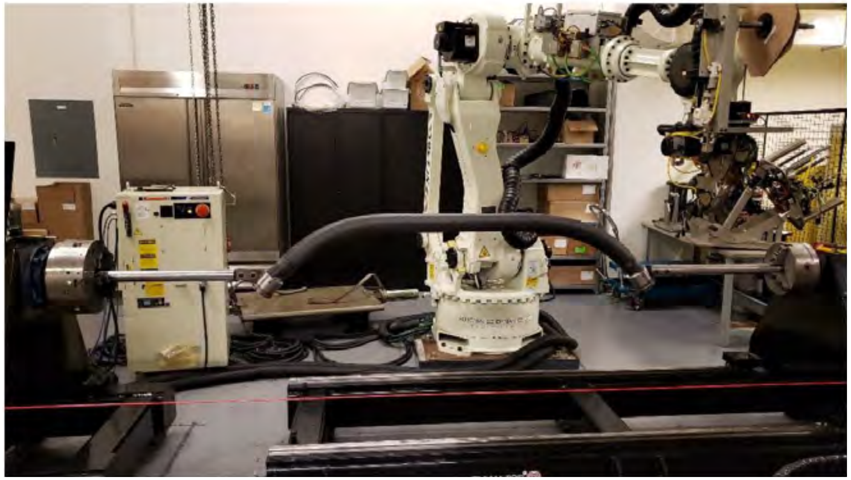
Thermoplastic composite tubes

110 layers



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Thermoplastic composites applications

ema

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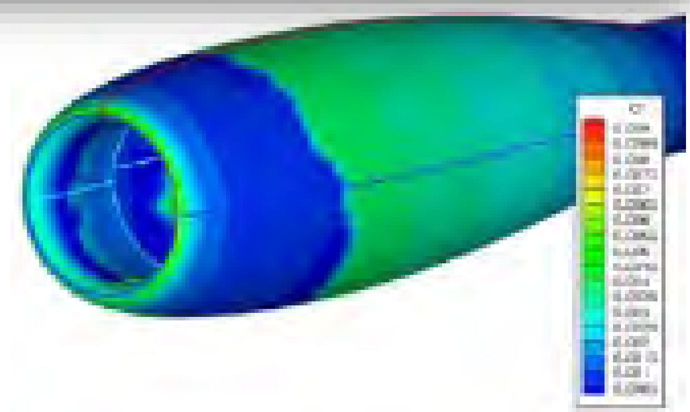
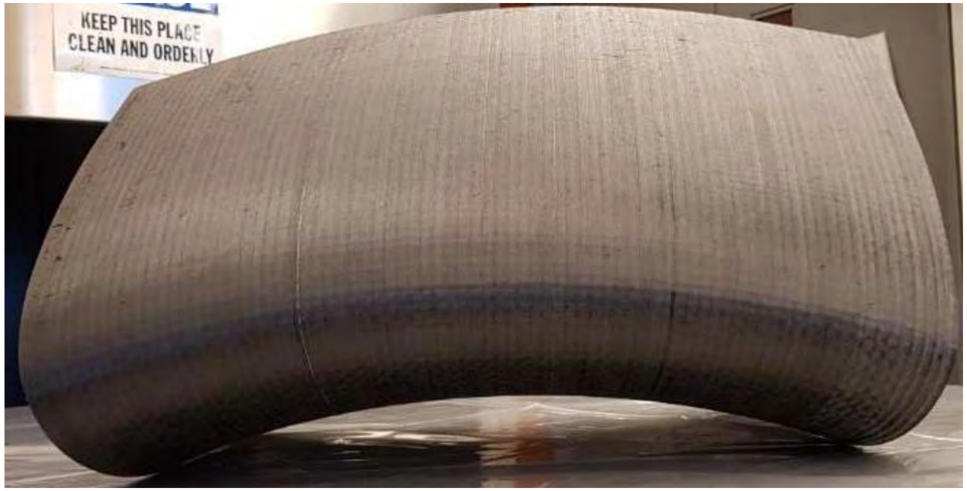
l'évolution de la mobilité

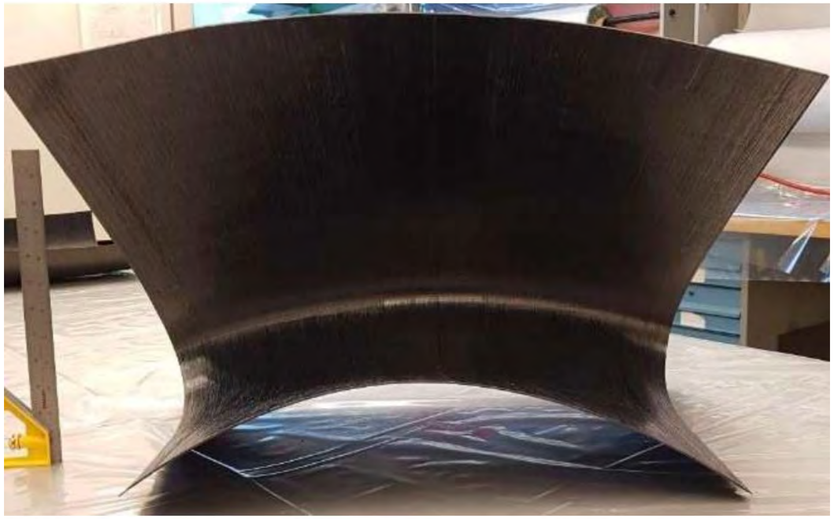


Nacelle lip for laminar flow

Requirement: Good surface finish for minimum resistance to air flow

Thermoplastic composite nacelle lip for laminar flow





Surface finish:
Repass
Distortion:
Anneal

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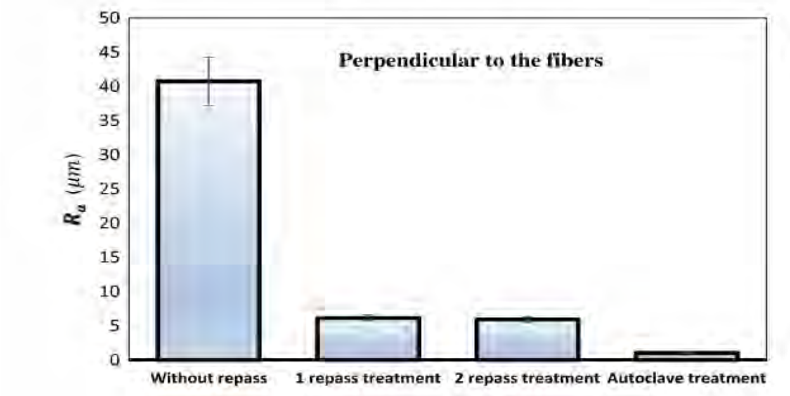
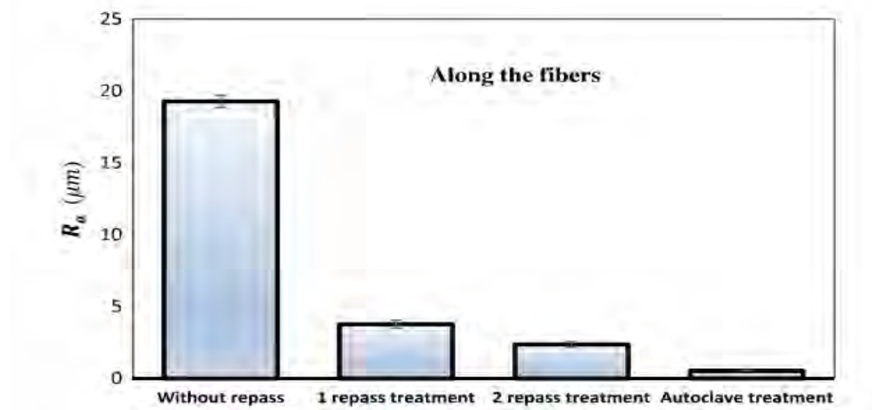
Effect of repass on surface finish



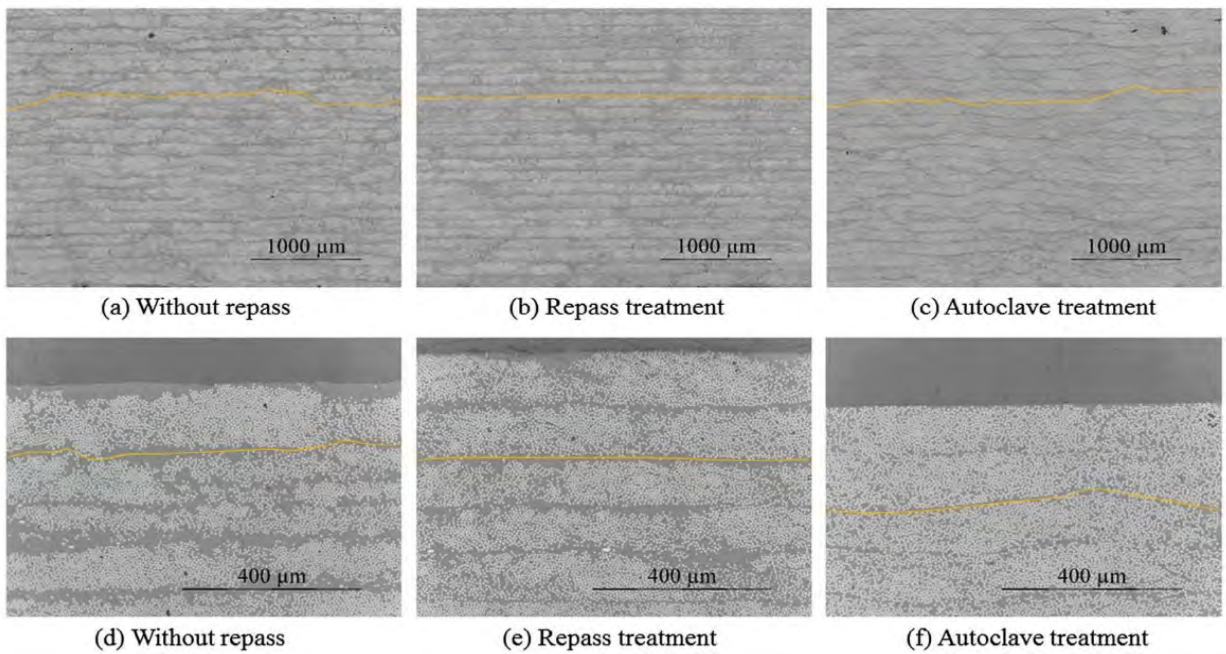


Repass:

Passing the torch and roller without material deposition

5X

20X



Université Concordia University

Outline

Thermoset matrix composites

1. Speed of deposition – Efficiency of machine use
2. Inspection
3. Fiber steering – Tow shearing
4. Dry fibers

Thermoplastic matrix composites

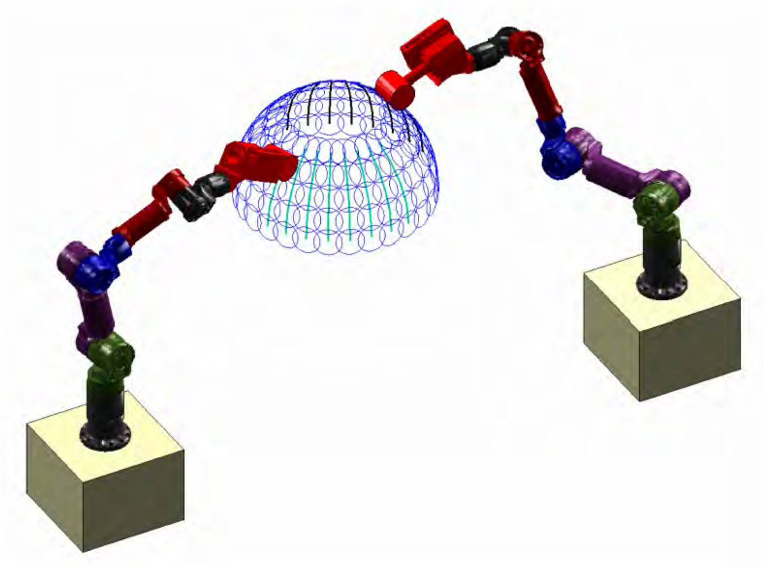
1. Heating
2. Interlaminar shear strength
3. Distortion for structures with free edges.

Future outlook

Conclusion

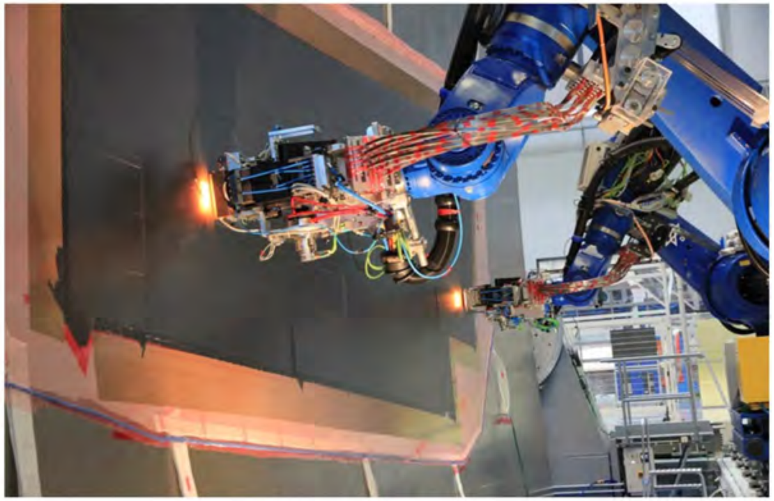
Hassan M., Liu D., and Xu D. "A two stage approach to collaborative fiber placement through coordinated of multiple autonomous industrial robots", J. Intell. Robot Syst, 2019, 95, 915-933.

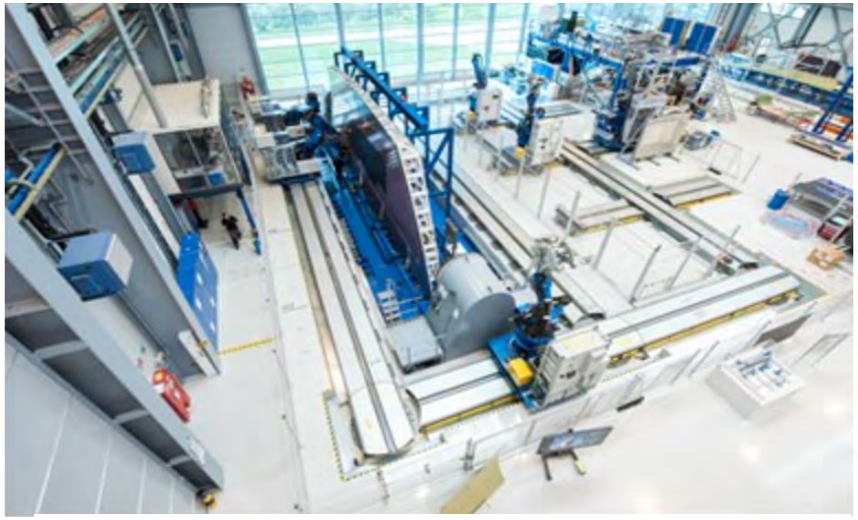
Collaborative fiber placement through coordination of multiple robots



GroFi from the German Aerospace Center (DLR)

Jeff Sloan, “Modular, mobile, multiple robotics poise to change the AFP/ATL paradigm, Composites World (CW) magazine, Oct. 31, 2019





- **Vertical mandrel surface**
- **Multiple robots, each does a specific task**
- **Cell of 8 robots, 4 active, 4 in reserve.**
- **Programming critical**

Limitations in applications of ATL & AFP

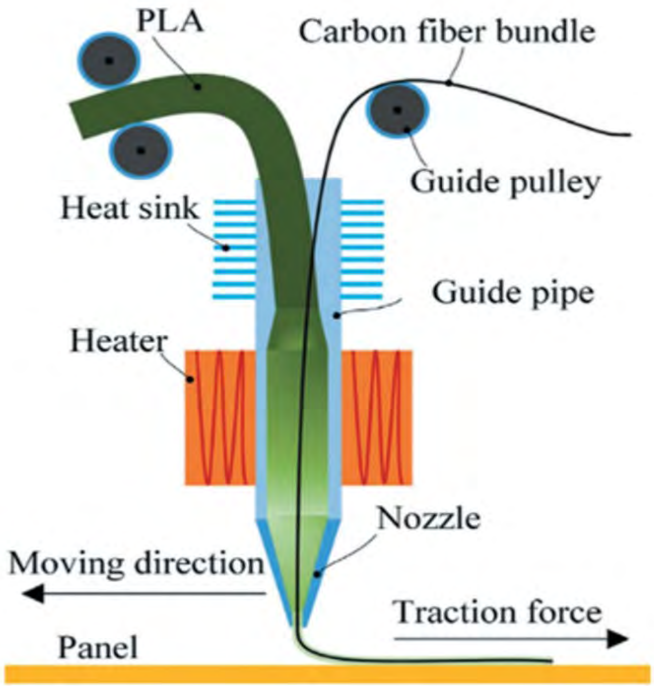
- **Small parts**: like ribs, spars, and brackets are too small to be efficiently manufactured using ATL or AFP.
- **Complex features** such as double curvature, tight corners, and steep ramps are challenging for ATL and AFP.

Capital costs are very high, preventing small and medium manufacturers to enter into the technology.

Future outlook- Additive Manufacturing- Smaller AFP

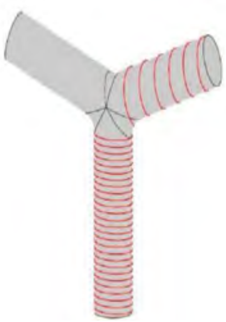
- To expand the technology, commercial applications.
- Materials produced by Additive Manufacturing with continuous fibres.
- Smaller AFP machines have been developed

Future outlook- 3D printer with continuous fibers



Carbon fiber
Natural fiber
Glass fiber

Two ends of the spectrum



Composite commercial product

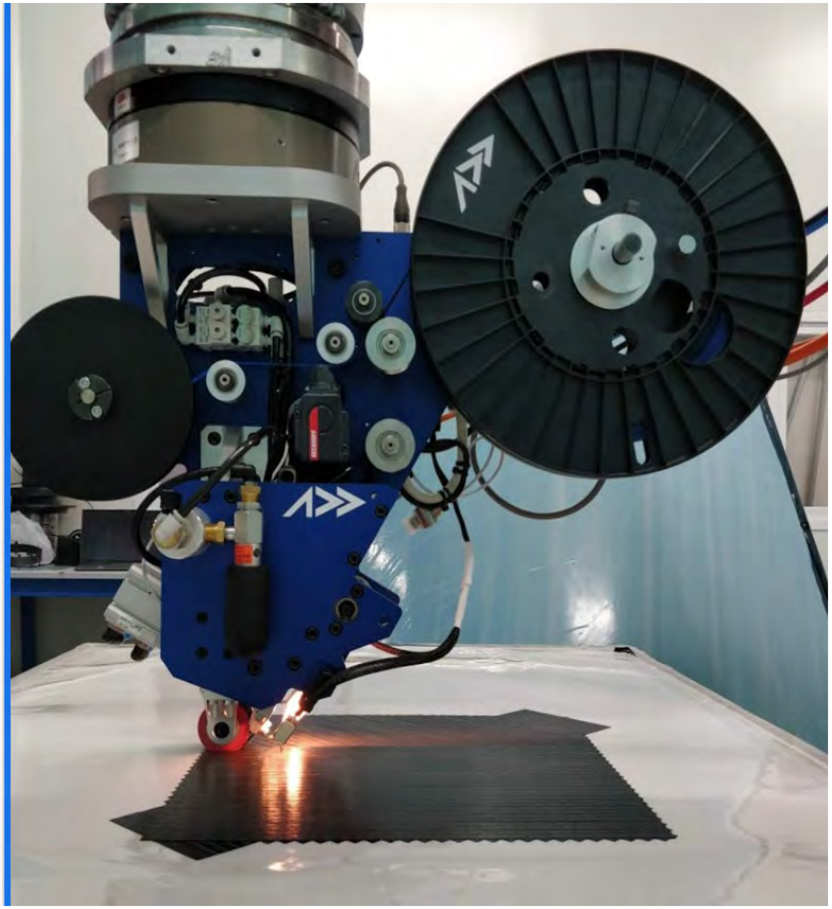
Large, simple structure- ATL-AFP
Airframe structure

Small, complex structure- 3D, 4D printing.
Composite flower

Future outlook- Smaller AFP

Add Composites machine:
2018, Espoo, Finland.

- **Weight =** 16.5 kg
- **Dimensions:** 595 mm x 255 mm x530 mm
- **Spool:** 76 mm ID, 320 mm OD.
- **Fibers:** Carbon, Natural, Glass
- **Matrices:** Dry, Thermoset, Thermoplastic
- **Tow widths:** ¼”, ½” , 1”
- **Aerial weights:** Dry 150-300 GSM, **Thermoset:** 200- 500 GSM, **Thermoplastic:** 100-350 GSM



CONCORDIA CENTRE FOR COMPOSITES
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Conclusion

Thermoset matrix composites:

- Have been successfully used in making aircraft structures.
- Improvements can be made on: Speed of deposition, Automated Inspection, Reduction in minimum radii in fibre steering, Understanding the performance of structures containing defects such as laps, gaps.

Thermoplastic composites:

- Improvements on heating sources.
- Obstacles to be overcome: Low interlaminar shear strength, Distortion of structures with free edges.

Future outlook:

- To expand, the technique needs to be adaptable to commercial products.
- Smaller AFP machines
- 3D printers with continuous fibers

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Natural Sciences and Engineering Research Council of Canada- Bell Flight Ltd., Bombardier, DEMA.

Daniel Rosca, Xiao Cai, Farjad Shadmehri, Heng Wang, Hoang Minh Duc, Jeffrey Simpson, Ashraf Fathy + many students

http://concom.encs.concordia.ca

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Thank you