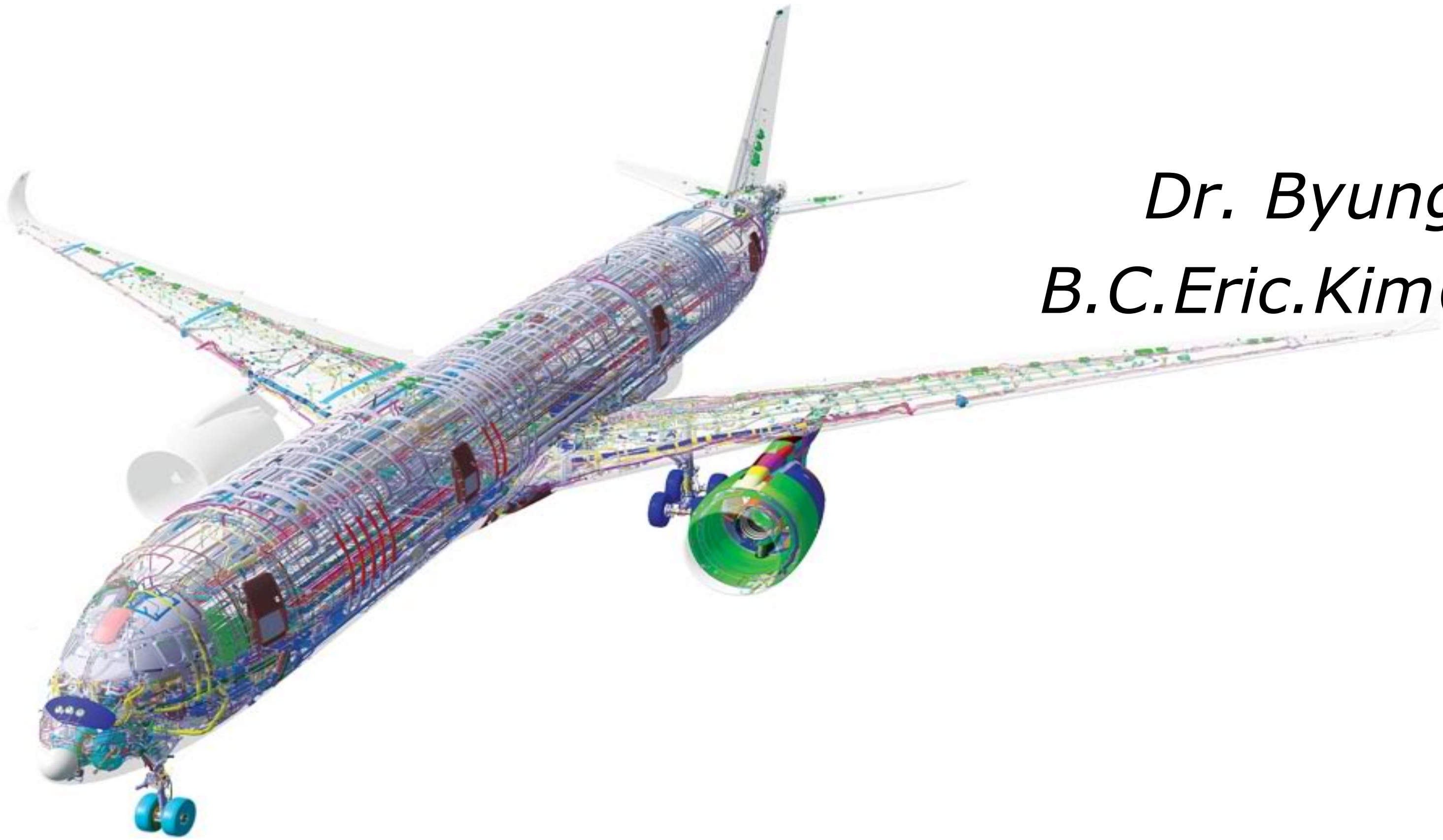
StM3. Aircraft manufacture

Part 2



Dr. ByungChul Eric Kim

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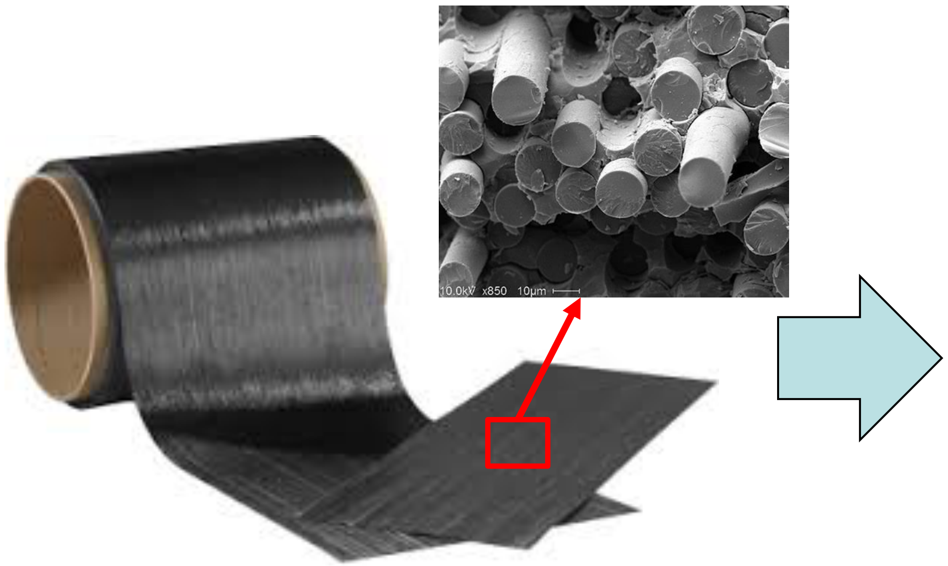
Case study – Aircraft wings

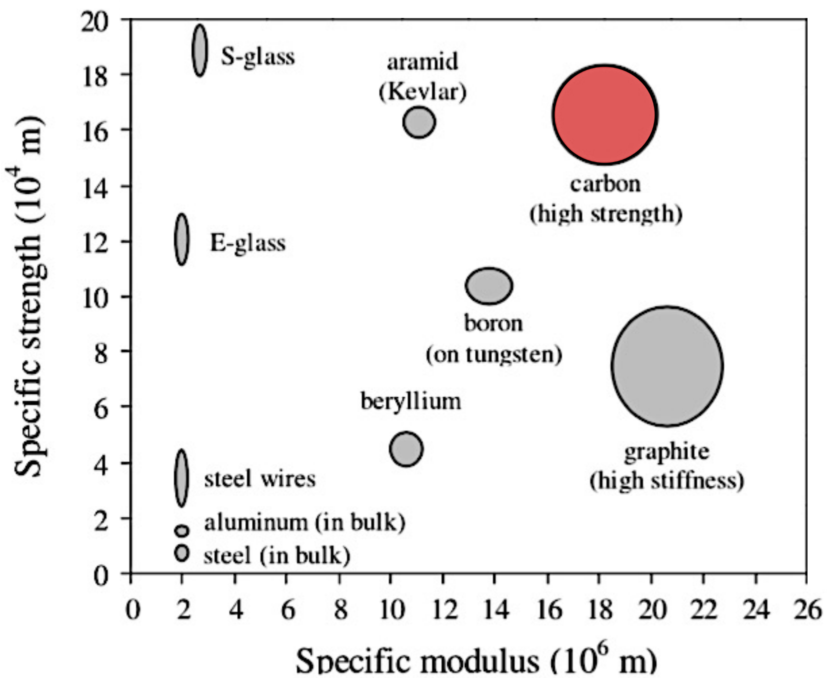
	Metallic ***A340, A380***	***Composite*** ***A350XWB, A400***
Main raw material	2000 and 7000 series Aluminium alloys	Carbon/epoxy composite
Raw material processing	Hot rolling	Prepreging
Key Manufacturing Processes	1. Metal cutting 2. Forming - Creep age forming - Die forging - Sheet metal forming	1. Automated Fibre Placement/Tape Laying 2. Drape forming 3. Autoclave curing 4. Composite machining
Assembly Process	Mechanical joining + Welding	Adhesive + Mechanical joining

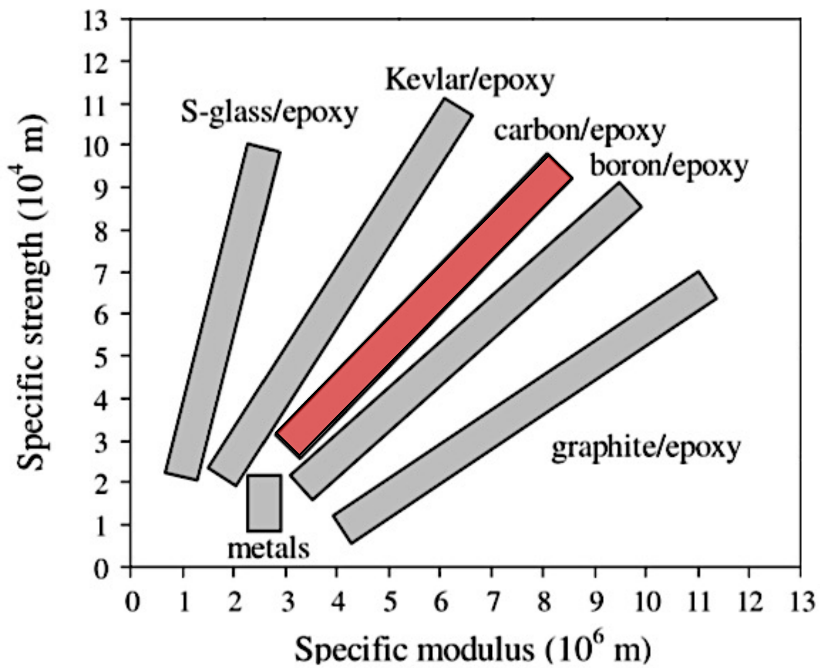
Composite wing



Why carbon/epoxy composites?

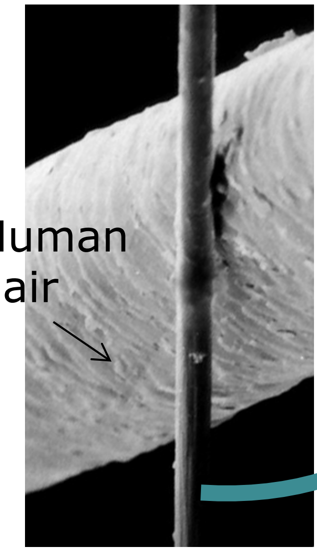
- Superior specific modulus and strength compared to metallic materials
- Customisable mechanical properties
- Low thermal expansion
- High corrosion resistance

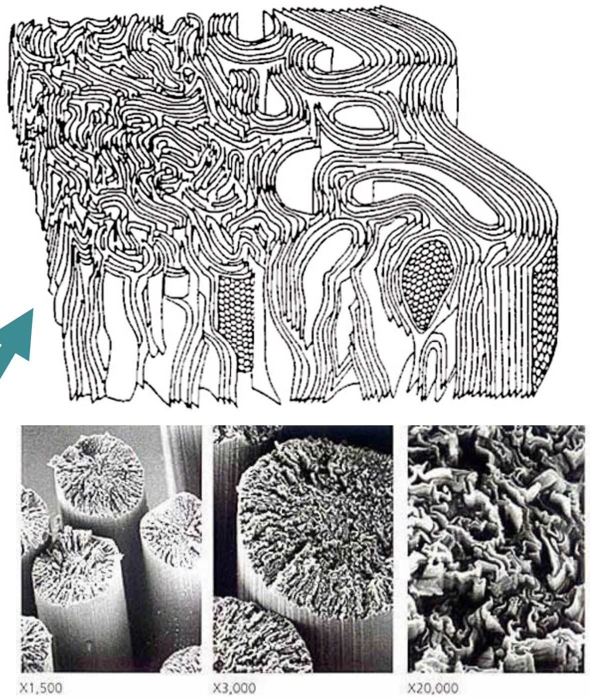


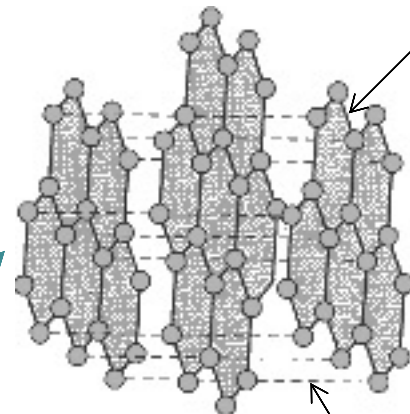


Carbon fibres

- Carbon atoms covalently bonded together to form a long hexagonal chain (high in-plane stiffness and strength)
- Carbonised from precursor materials
  - PAN (polyacrylonitrile)-based / Pitch-based / Rayon-based
  - 90% of carbon fibres is PAN based.

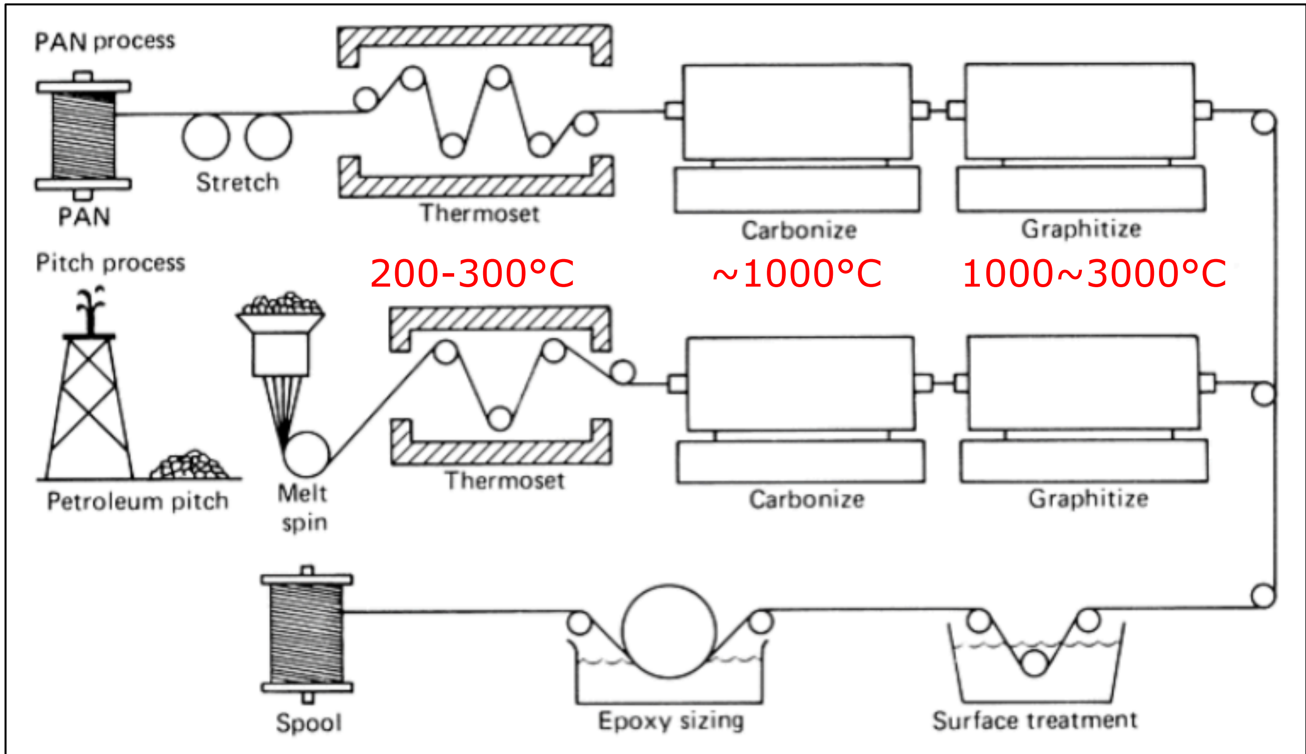






Carbon fibre production

Oxidisation stabilisation ➔ Carbonisation ➔ Graphitisation



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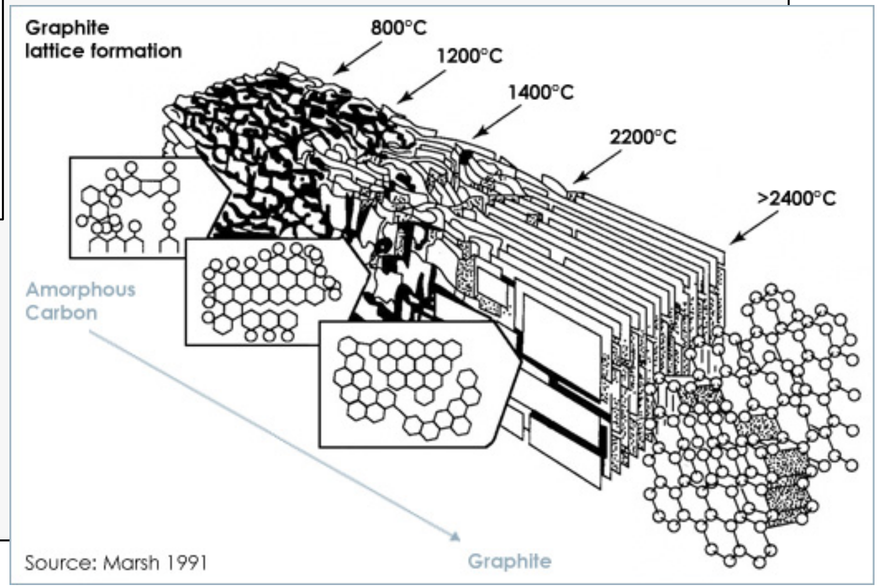


Carbon fibres

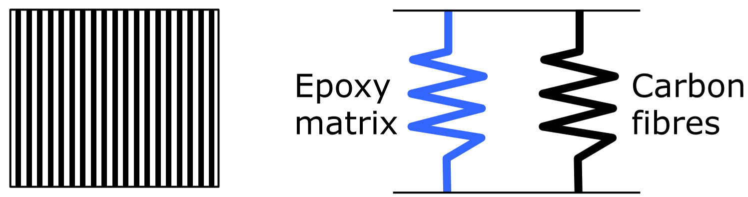
- Mechanical properties

Lower modulus, higher strength (PAN based carbon)

Higher modulus, lower strength (Brittle) (Pitch based carbon)

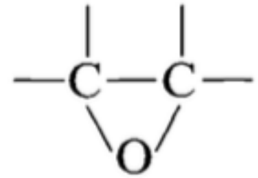
Fibre type	Tensile modulus (GPa)	Tensile strength (MPa)	Elongation at failure (%)	Density (g/cm^3)	Coefficient of Thermal expansion ($\times 10^{-6}$ /°C)	Fibre diameter (μm)
PAN based carbon Standard modulus Intermediate modulus High modulus	220-240 270-300 340-450	3400-4800 4100-6200 4100-5500	1.5-2.2 1.3-2.0 0.7-1.0	1.8 1.8 1.9	-0.4 -0.6 -0.75	6-8 5-6 5-8
Pitch based carbon High modulus Ultra high modulus	380-620 680-960	1800-2700 2400	0.5 0.3	2.0 2.2	-0.9 -1.6	10-11
Steel (SAE1010) Steel (AISI4340) Stainless (AISI440 H&T) Al 6061-T6 Al 7178-T6 Titanium alloy (Ti-6Al-4V)	207 207 196 69 69 110	365 1515 310 537 1790 950	20 22 4 8-10 10 14	7.8 7.8 7.8 2.7 2.7 4.5	12 12 10 24 24 9	

Bear in mind that the mechanical properties of a carbon/epoxy composite is dependent on its 'Fibre volume fraction, V_f'.



Epoxy matrix

- Epoxy resin
  - Polymeric resins containing a number of epoxide groups

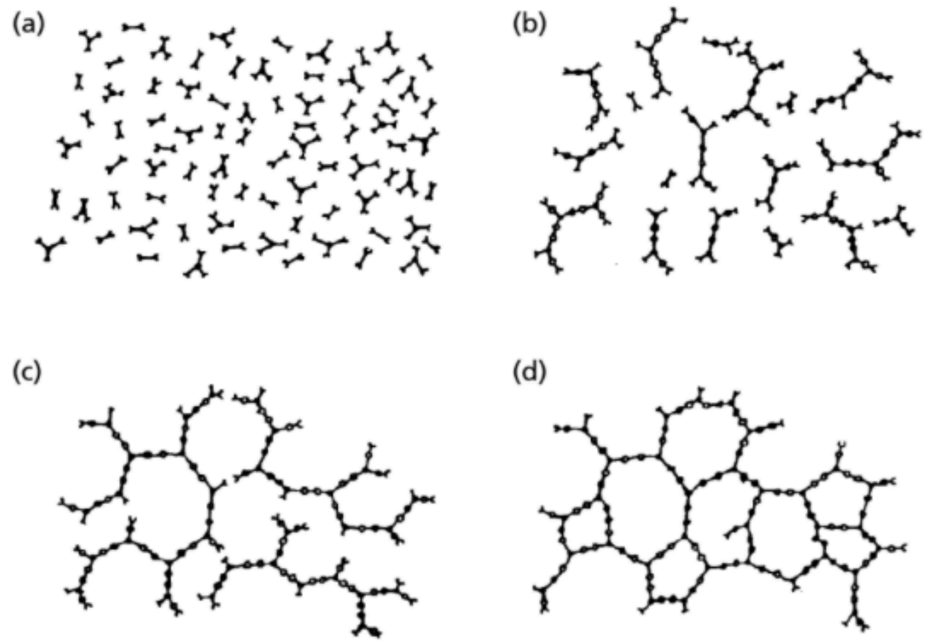


- Curing agent (hardener)
  - Aliphatic/aromatic amines, anhydrides/catalytic curing agents.

Advantages over other thermosets

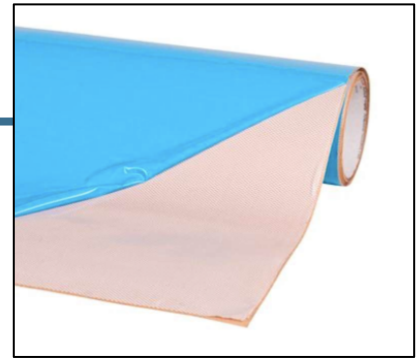
- A wide variety of properties
- Low shrinkage during curing
- Good chemical resistance
- Good adhesion to most fibres
- Good creep and fatigue resistance

B-staged epoxy resin:
Epoxy resin with a premixed low reactivity curing agent that can be active at high temperature.

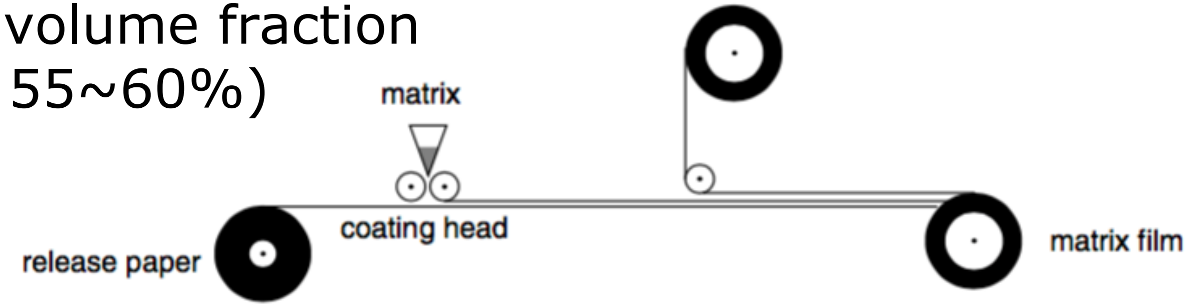


(a) Polymer and curing agent prior to reaction
(b) Curing initiated with size of molecules increasing
(c) Gelation with full network formed
(d) Full cured and crosslinked

Epoxy matrix



- B-staged epoxy resin film
  - Easy to handle
  - The areal weight is precisely controlled to guarantee a constant fibre volume fraction of the prepreg material (V_f 55~60%)



- Aerospace grade epoxy matrix
  - High temperature curing (170~180°C) ➔ High glass transition temp.

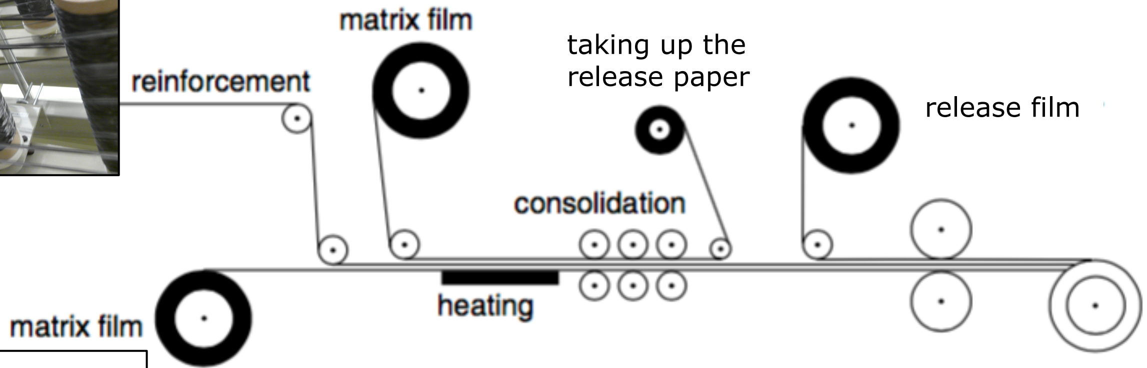
Tensile strength	MPa	60–80
Tension-E-modulus	MPa	3000–4000
Failure strain	%	2–8
Density	g/cm^3	1.1–1.3
Shrinkage	%	1–3

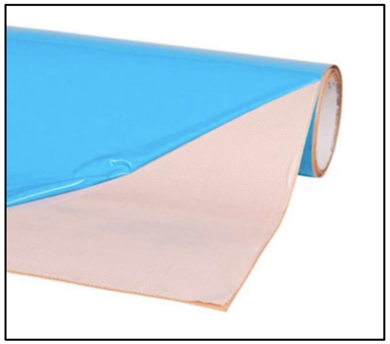
Prepregging ➔ Slitting

Pre-impregnated (semi-finished) material: ***Prepreg***

Carbon fibre tows

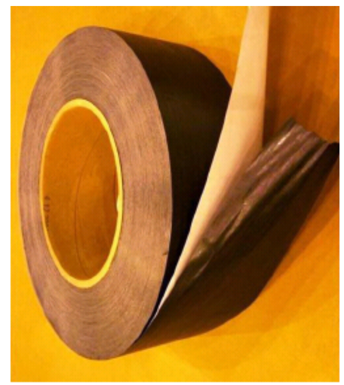
Hot-melt process (modern)

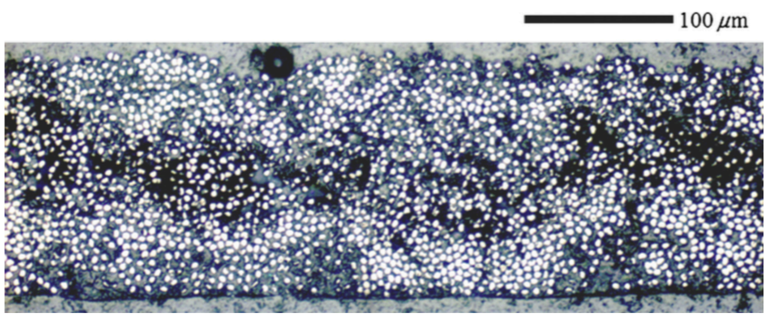




B-staged epoxy resin film

Slitting



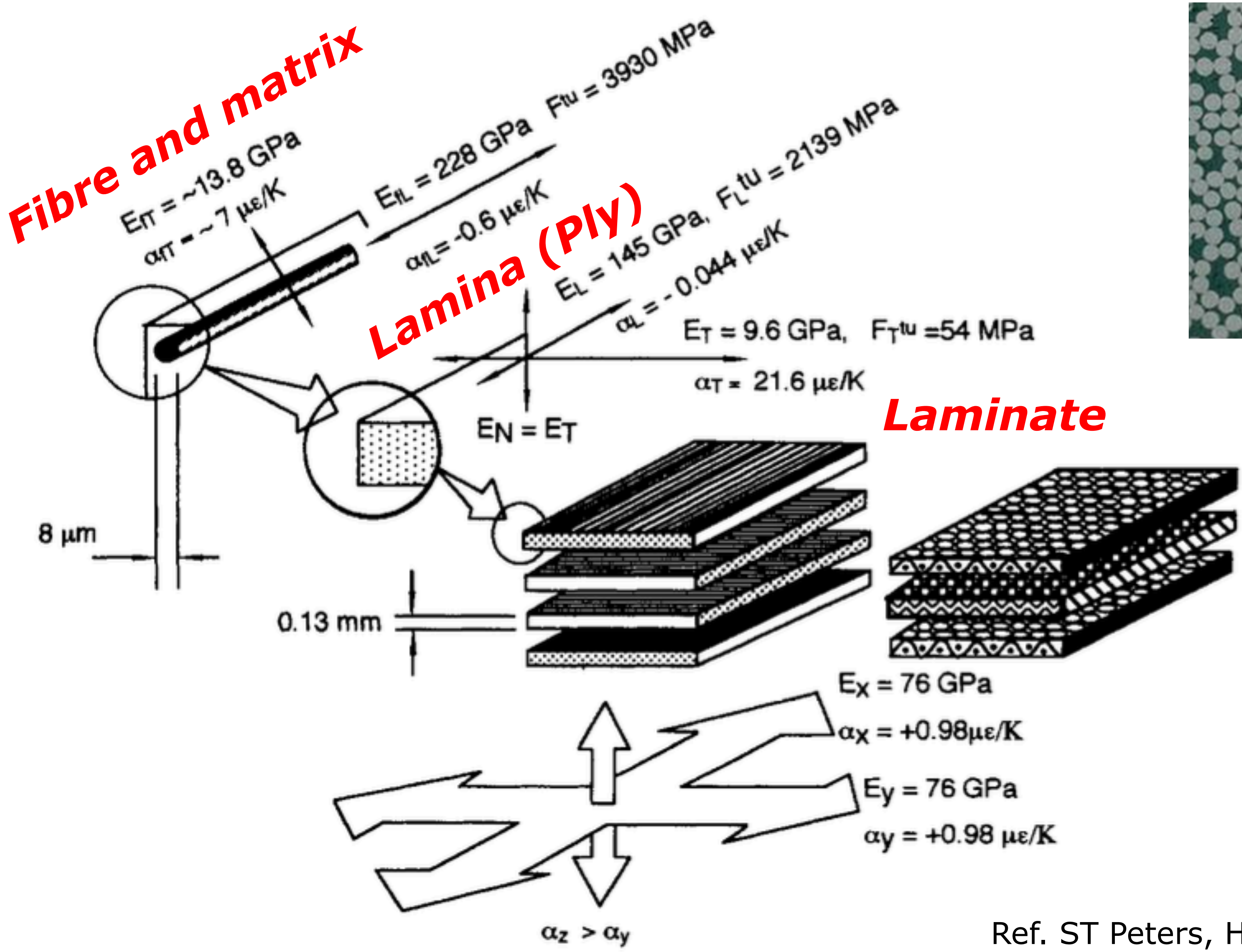


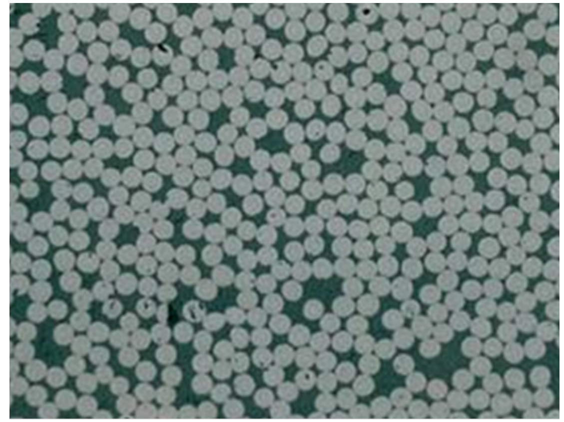
< Cross-section of a prepreg >

From PAN fibres to CF/epoxy prepreg

https://youtu.be/ki1aCdkMSeo

Anatomy of a composite laminate



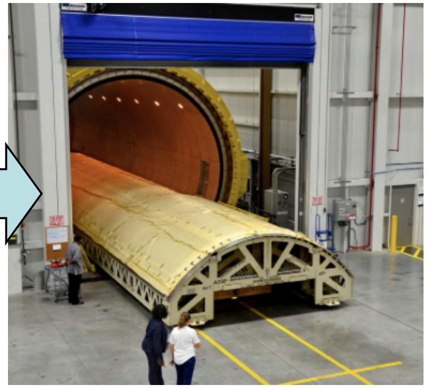


You can calculate the mechanical properties of the laminate using ***Classical Laminate Theory!***

Ref. ST Peters, Handbook of Composites

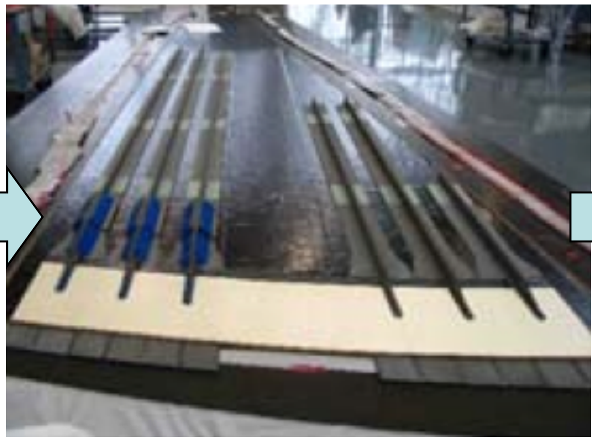
Composite wing panel

3D ATL (Automated Tape Laying) process

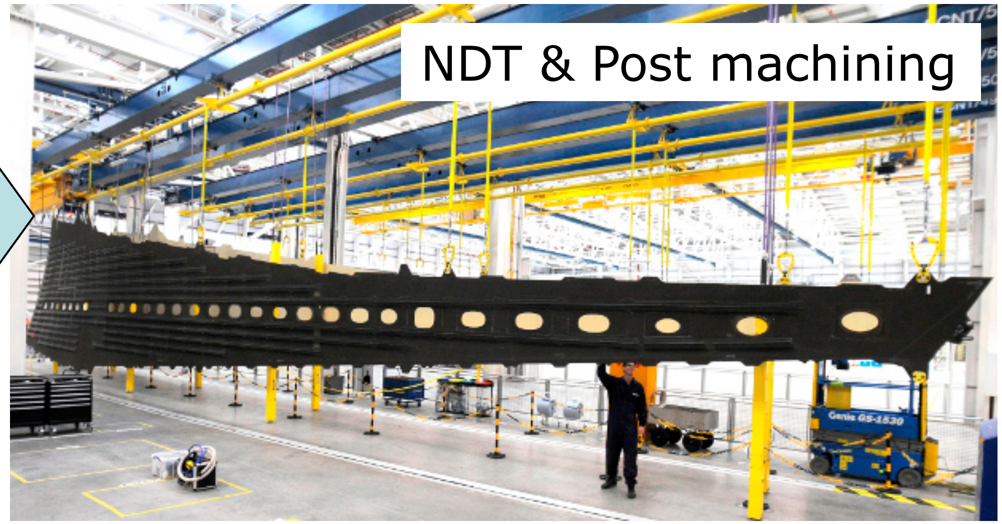

Autoclave curing of the wing skin


2D ATL for stringers


Hot drape forming of stringers


Stringer integration & Vacuum bagging

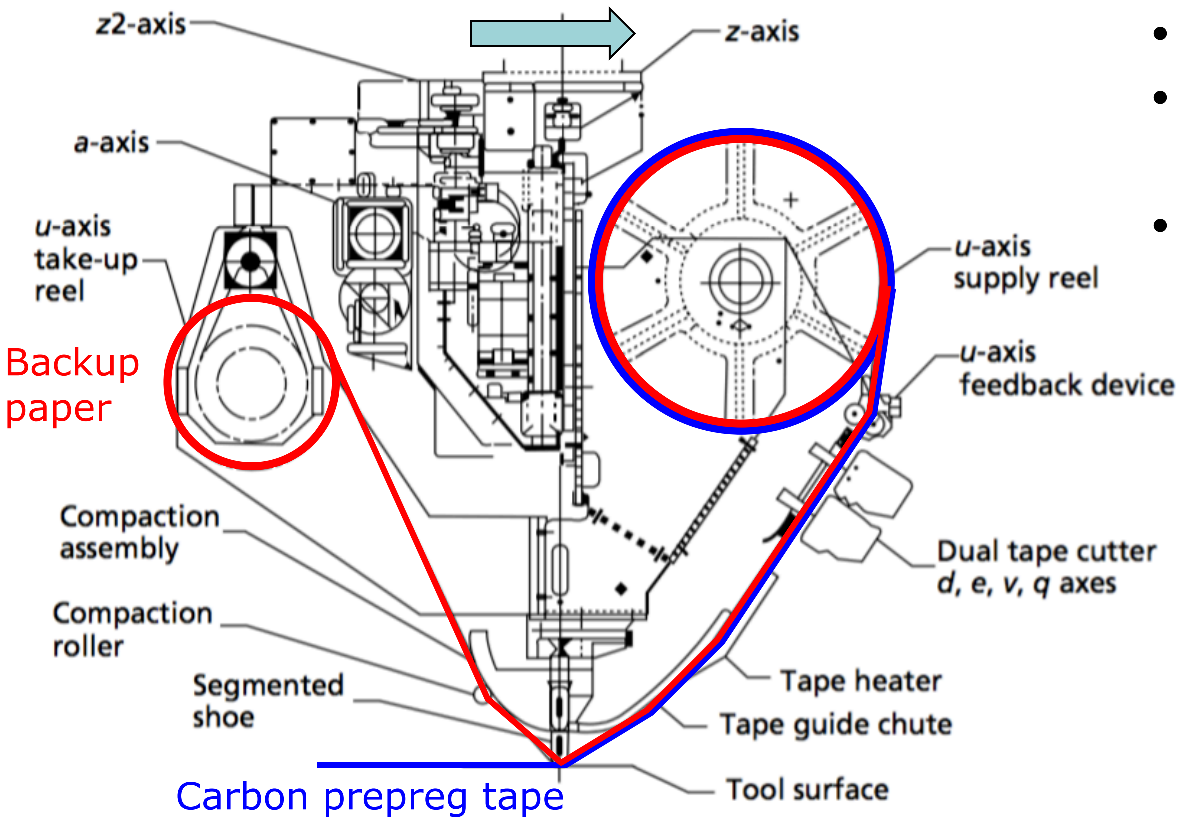

Autoclave curing



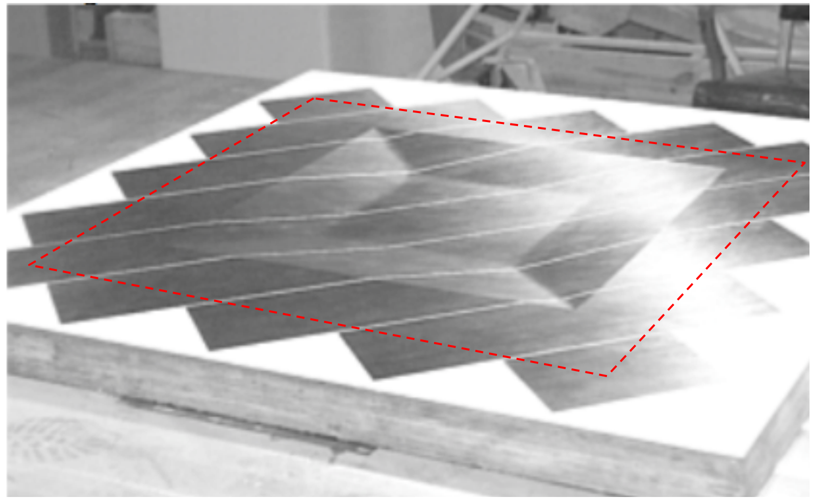
Automated Tape Laying (ATL)

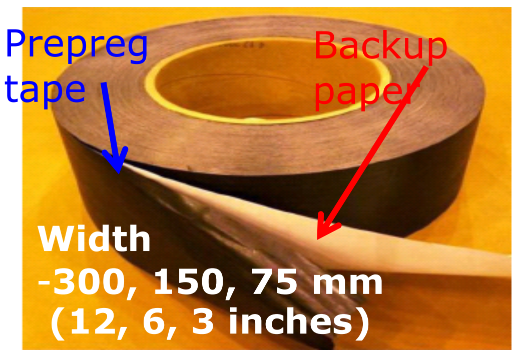
http://videos.airbus.com/video/84217417394s.html

Automated Tape Laying (ATL)



- First developed in 1980s
- Suitable for large and low curvature surfaces
- High scrap rate for small parts





Ref. Commercial Aircraft Composite Technology

	1970s	1980s	1990s	2010s
Aircraft	A300	A310/A320	A330	A350XWB
Process	Manual layup	9-axis ATL	11-axis ATL	11-axis ATL
Complexity	–	2D—limited 3D	moderate 3D	3D with steering
Size		7 m	12 m	33 m
Material type	Woven prepreg	UD prepreg	UD prepreg	UD prepreg
Material width		75 mm	150 mm	300 mm
Functional materials	Manual layup	Manual layup	Manual layup	Automatic

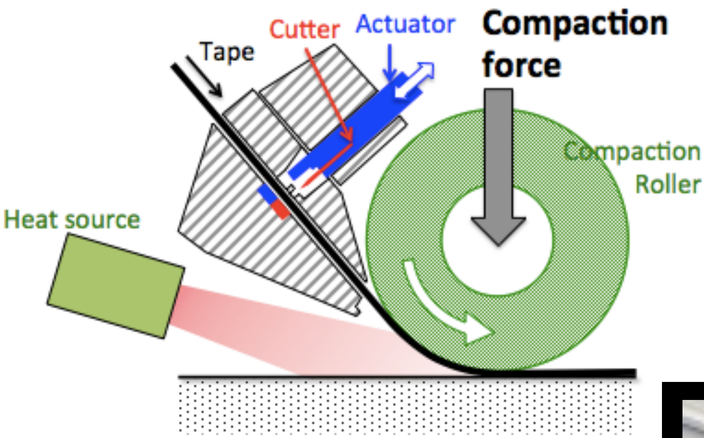
Automated Fibre Placement (AFP)

- Composite wing spars and fuselage panels

Width
–12.7, 6.4, 3.2 mm
(0.5, 0.25, 0.125 inches)

- Suitable for complex geometry
- Low scrap rate
- Higher layup speed, but low material deposition rate compared to ATL

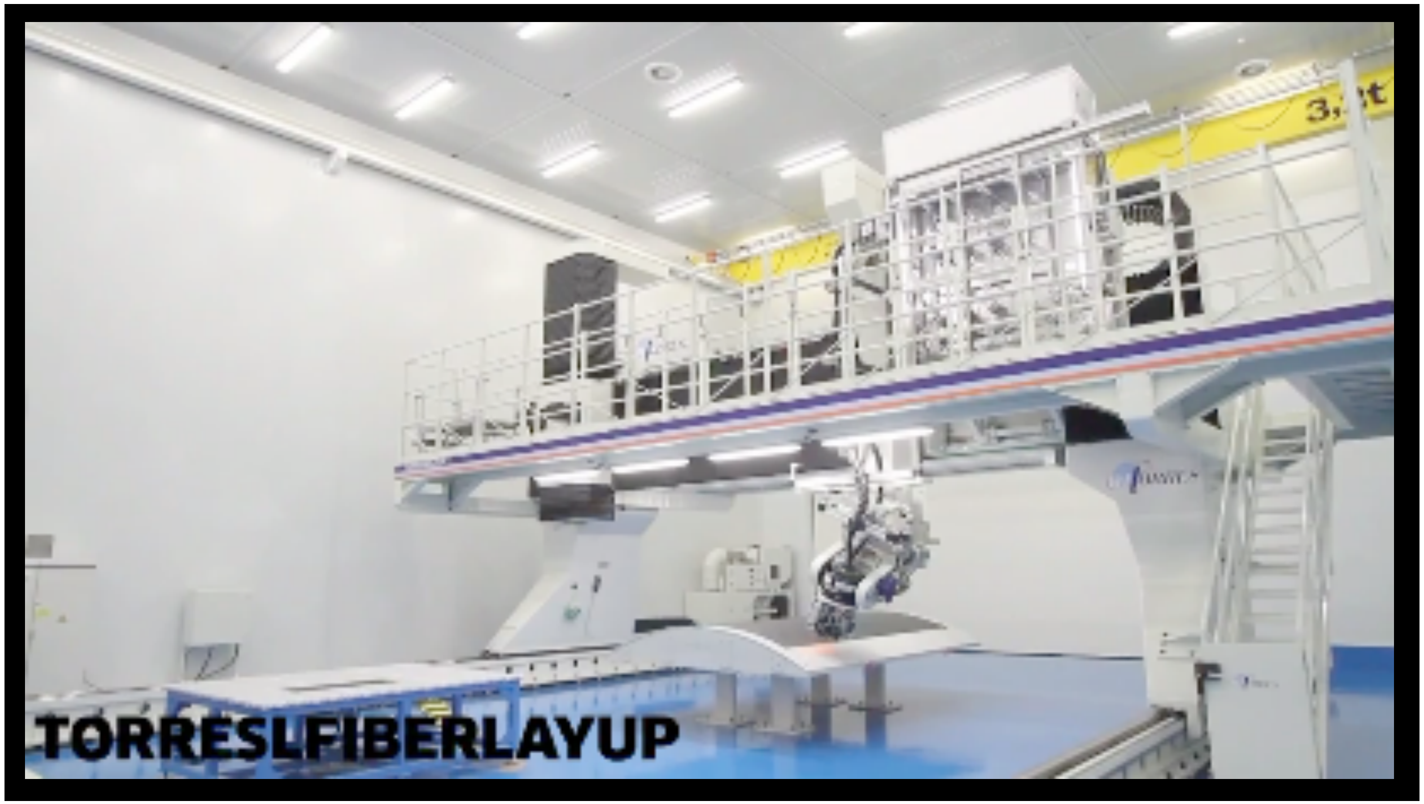
Automated Fibre Placement (AFP)



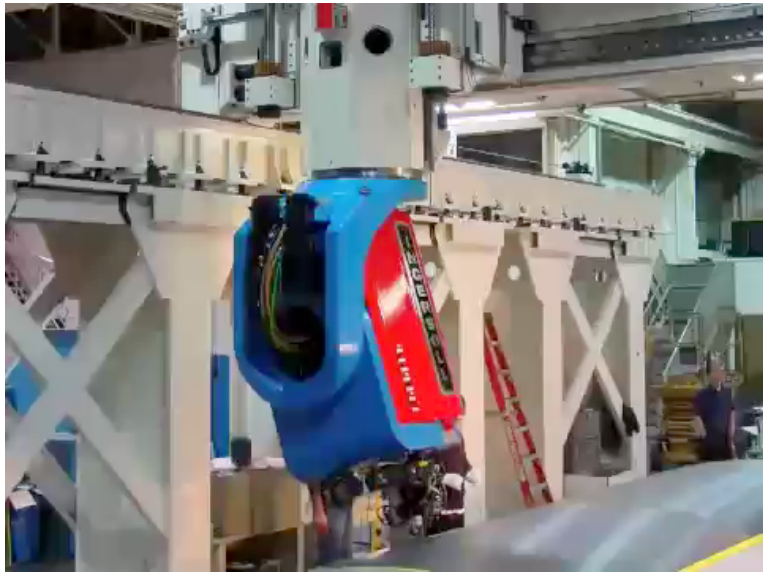
< Flow of the tape material >
Stored in the temperature controlled creel cabinet ➔ Tape redirection mechanism ➔ Heated by the heat source (increasing the surface tack of the tape) ➔ Compressed by the roller ➔ Naturally cooled

< Heat source >
- Infrared heater
- Laser
- Gas torch (for thermoplastic)

https://youtu.be/BZzfcJMYdLM



Automated Fibre Placement (AFP)



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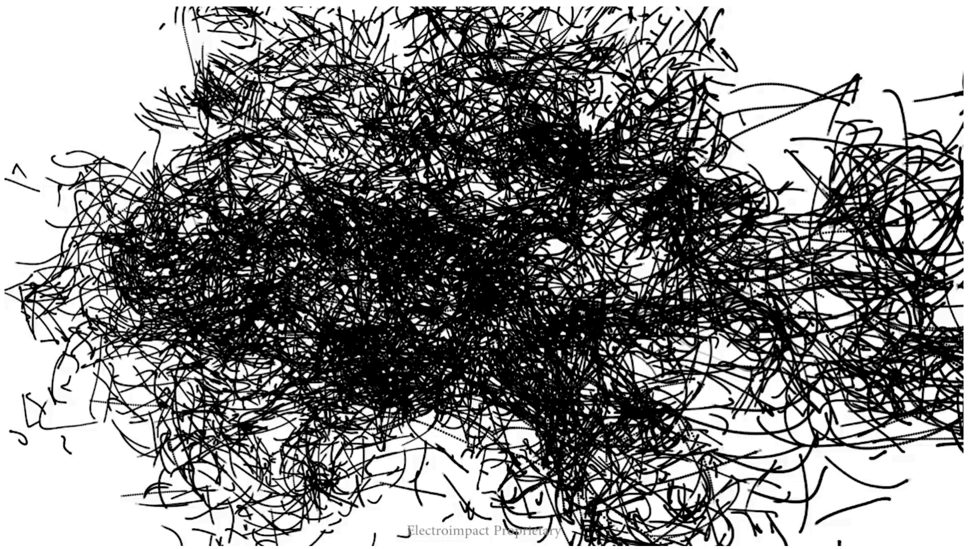
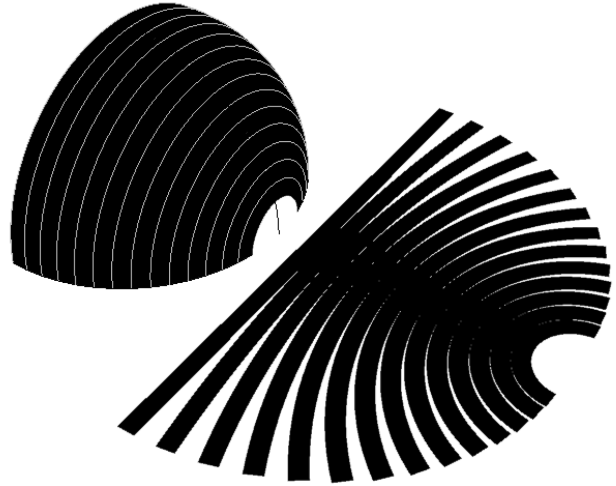


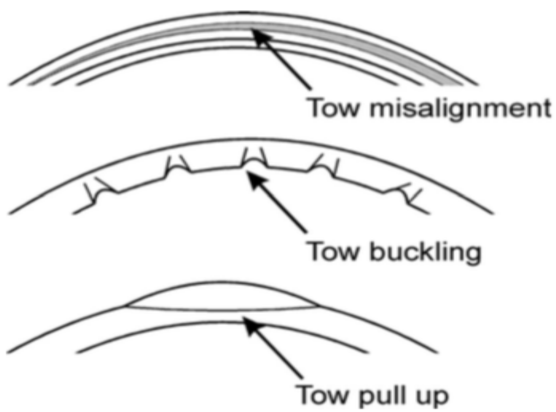
https://youtu.be/bLhmQsOiLoc

https://youtu.be/_GDqxnahwbk

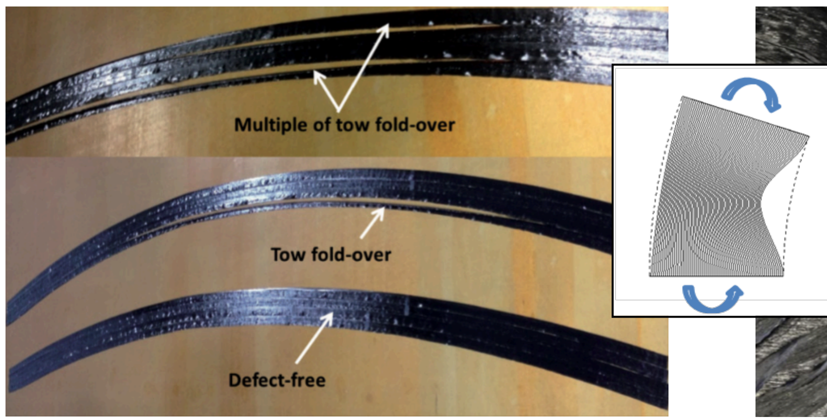
Manufacturing issues in AFP

- Fibre (Tow) steering
  - Capability of placing the carbon tapes along non-geodesic paths on a 3D surface (cf. filament winding)
  - Essential for manufacture of complex 3D components
  - All modern AFP machines utilise the in-plane bending deformation of the carbon tape ➔ Fibre straightening & buckling
  - Min. steering radius: Coupled with the tape width (e.g. 0.5-0.6 m for 6 mm wide tapes)

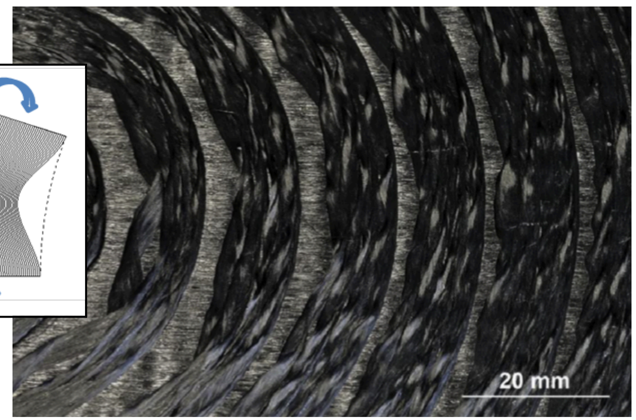




Ref. Dirk H.J.A Lukaszewicz
DOI: 10.1016/j.compositesb.2011.12.003

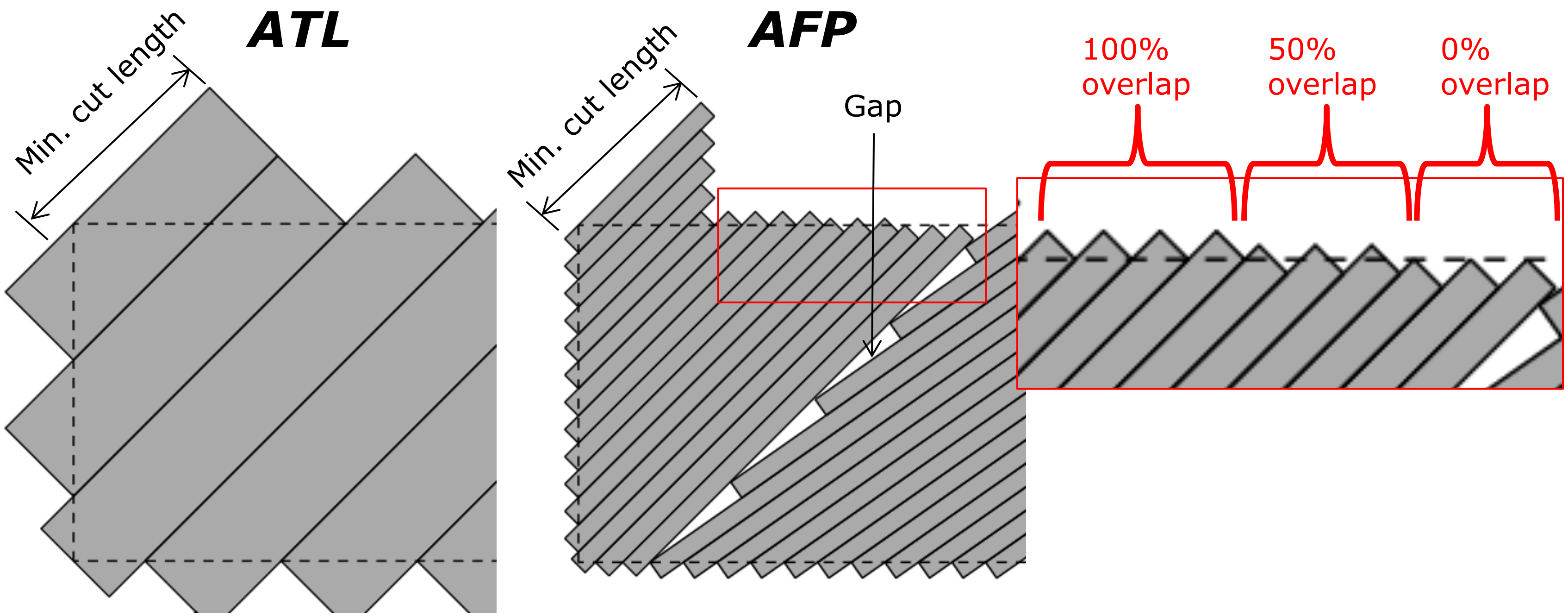


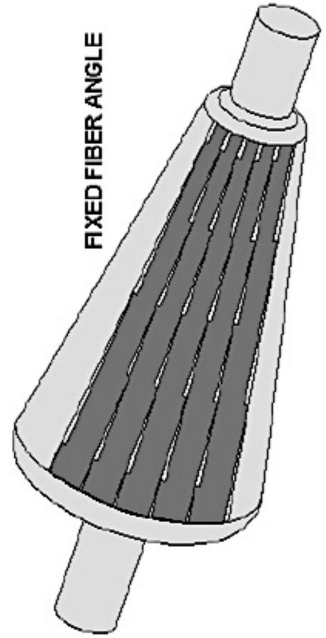
Ref. Smith RP et. al, AMRC (UK)
(DOI: 10.1177/0731684416659544)



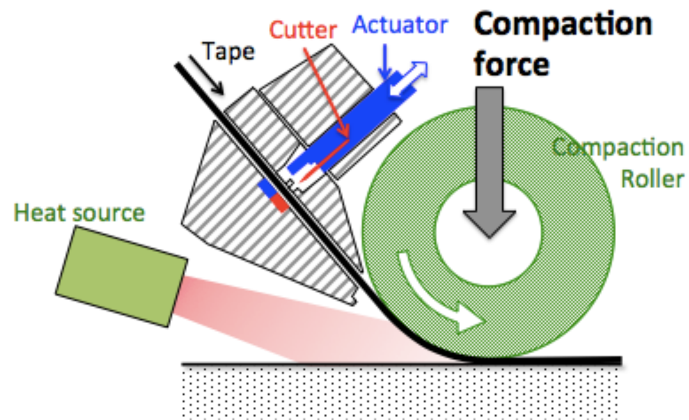
Nagelsmit MH, Gerrites W, National Aerospace Laboratory, Netherland

Manufacturing issues in ATL and AFP





- **Min. cut length**: distance from the tow cutters to the lay-down point (machine-dependent)
- **Gaps and overlaps**: Complex 3D surfaces may not be tessellated using the finite width tapes.
- **Downtime**: time when the machine is not laying tapes due to various causes (e.g. tape pull-out, tape twisting & folding, tape jam, spool change,…)

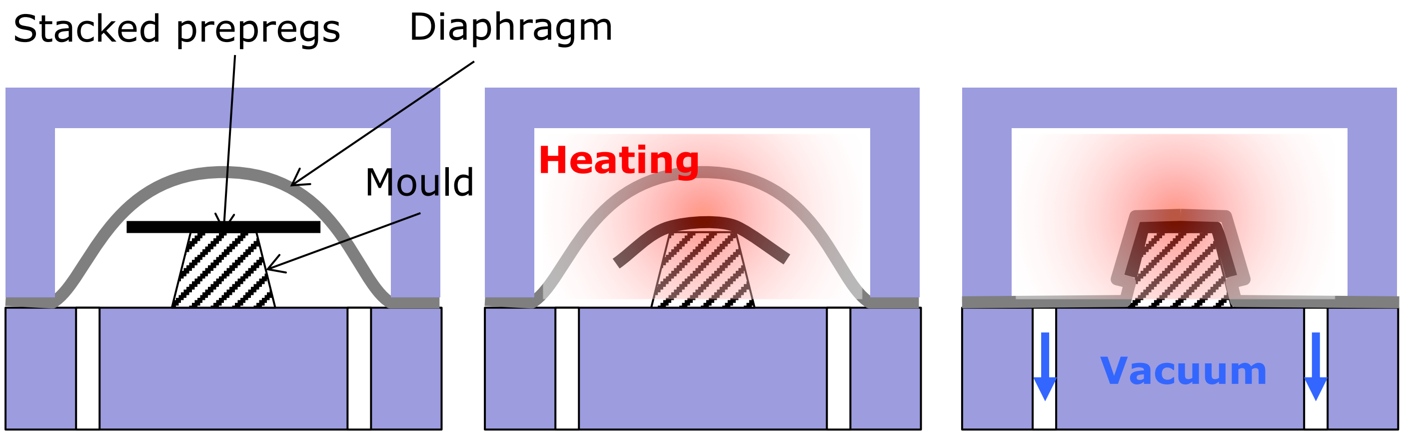


ATL vs. AFP

	ATL	AFP
Material	Wide tape (12″ wide thermoset prepreg)	Narrow tape (0.125″, 0.25″, 0.5″ wide)
Application	Simple and large components (e.g. Wing skins, …)	Complex components (e.g. Fuselage panels, curved spars and frames, engine covers …)
Pros	• Higher material deposition rate for simple geometry • Simple tape guiding system • No heating device required	• Available for both thermoset and thermoplastic prepreg tapes • Deposition of multiple tapes & Tension control of individual tapes ➔ Fibre steering • Tape cut and restart capability ➔ Low scrap rate, tape bandwidth adjustment
Cons	• Gaps and overlaps • Not suitable for complex geometry • No fibre steering available • Higher scrap rate for small parts • Additional forming process (e.g. HDF) may be required	• Gaps and overlaps • Lower material deposition rate • Complicated tape guiding system required

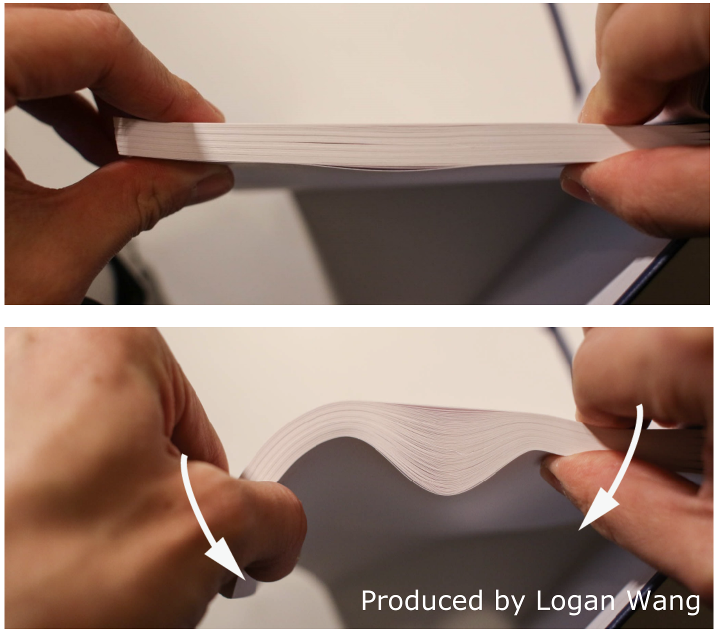
Hot Drape Forming (HDF)

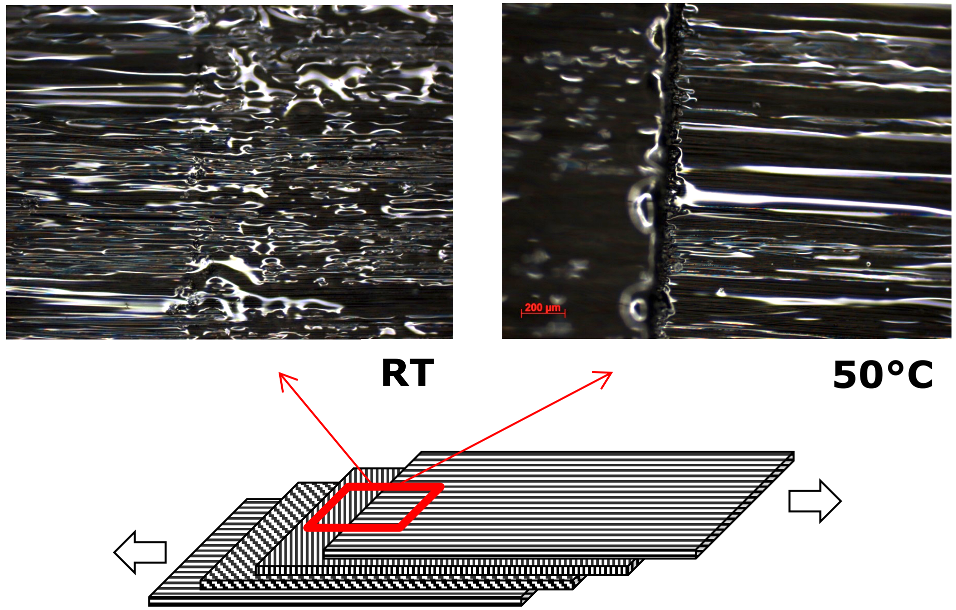
- In conjunction with ATL, for simple geometry (e.g. spars or stringers)



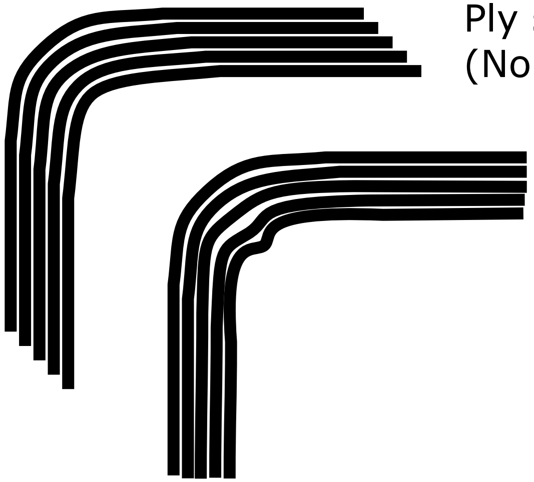
A350 spars: AFP ➔ Autoclave curing
A400 spars: ATL ➔ HDF ➔ Autoclave curing

Forming issues in HDF



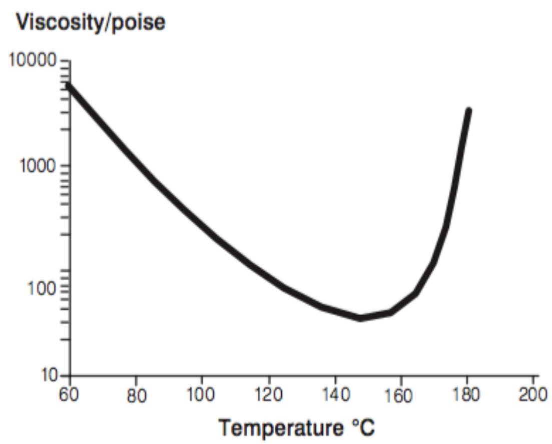


Interply slippage at the resin rich layers between plies



Ply slip
(No buckling)

No ply slip
(Buckling defect)



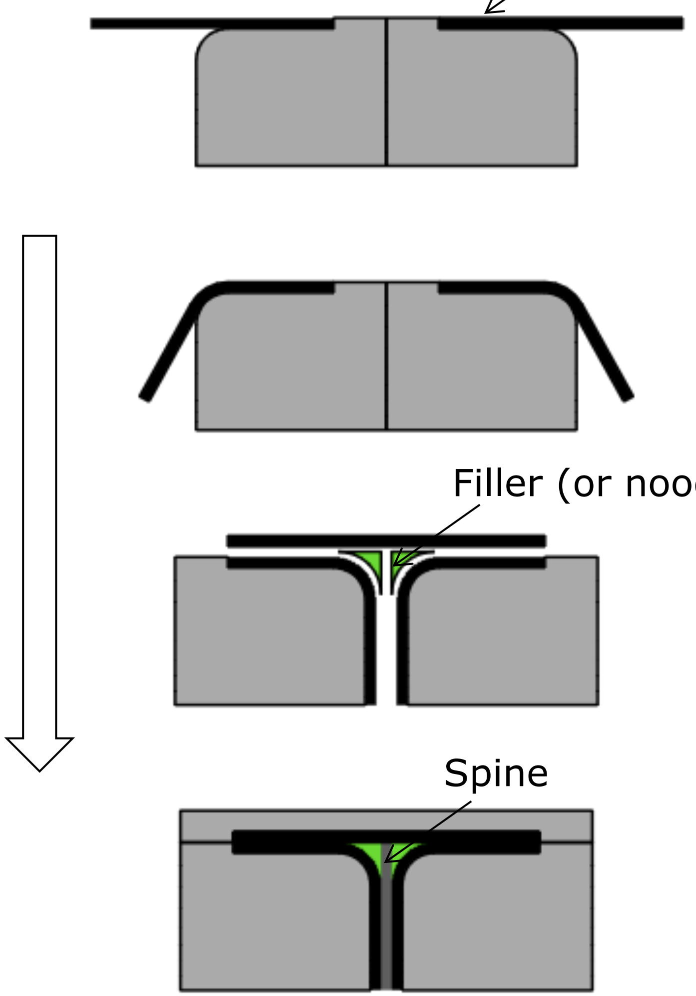
Forming quality improvement

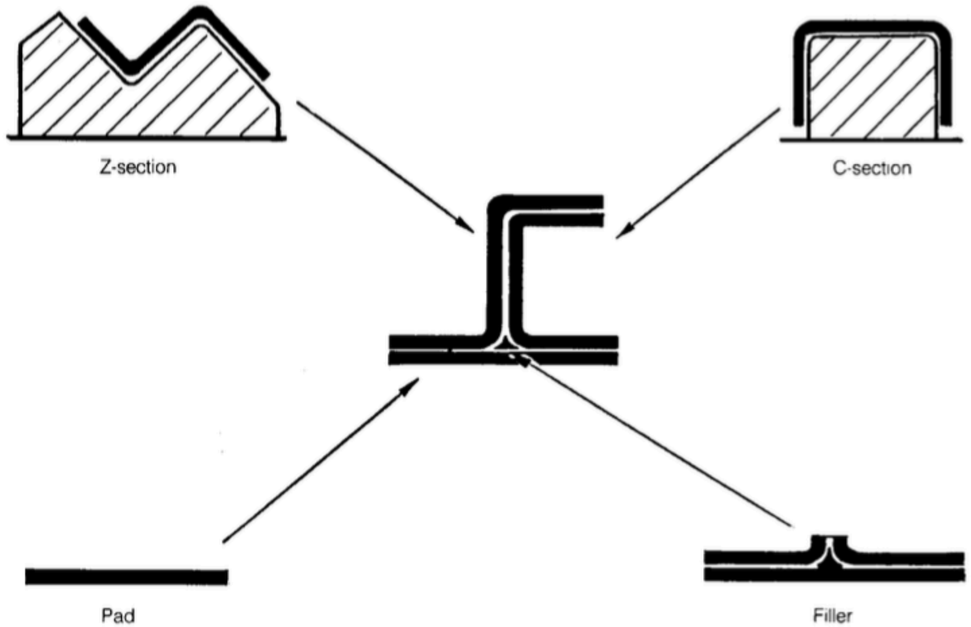
- Forming temp. ↑ → Resin viscosity ↓ → Interply friction ↓
- Productivity ↓, Energy consumption ↑

Difficult to optimise !

Discrete forming

- Stringers





Ref. Composite Airframe Structures

< Skin/stringer integration methods >

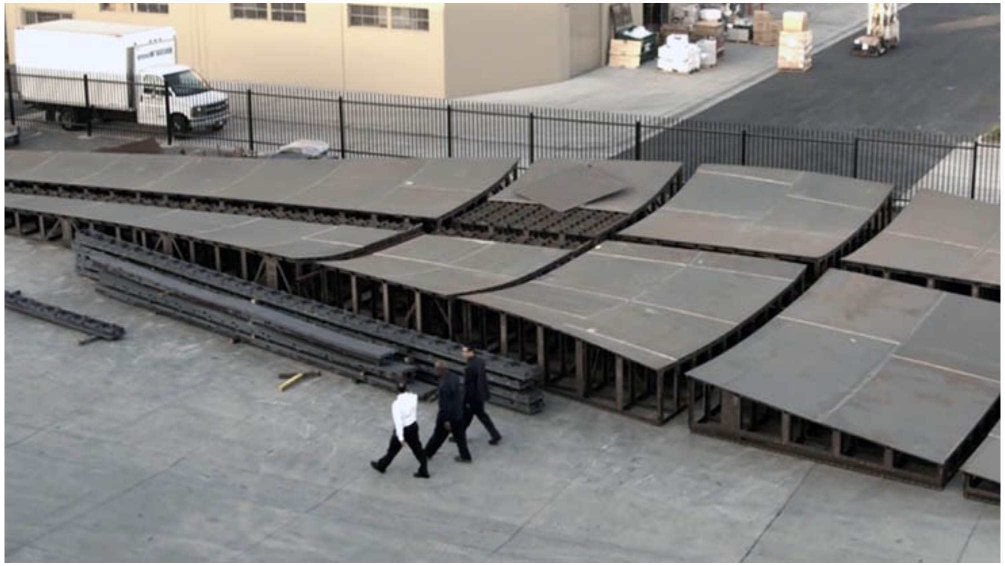
- Co-curing: Uncured + Uncured
- Co-bonding: Cured + Uncured
- Secondary bonding: Cured + Cured

Autoclave curing technology

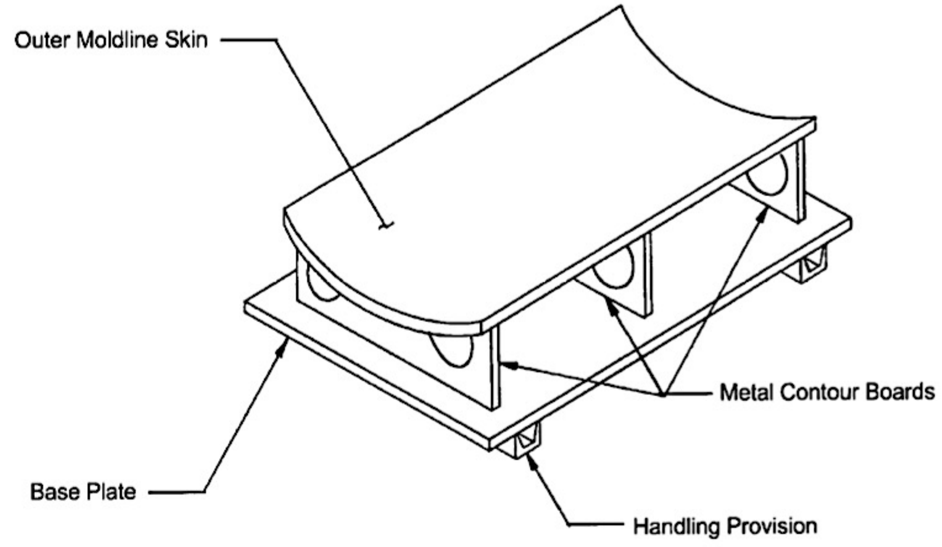
http://videos.airbus.com/video/84217417394s.html

Tooling for composite wing skins

- Invar mould

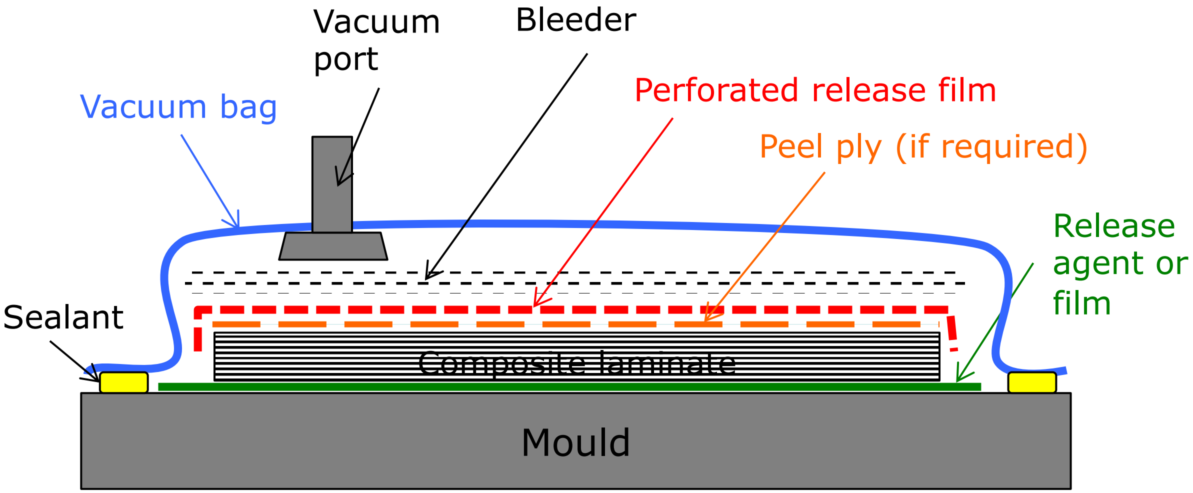


- Introduced in 1990s
- Low-expansion alloy
- CTE match with carbon/epoxy composites
- But, very expensive and difficult to work with, low thermal conductivity
- Premium tooling applications (wing skins)



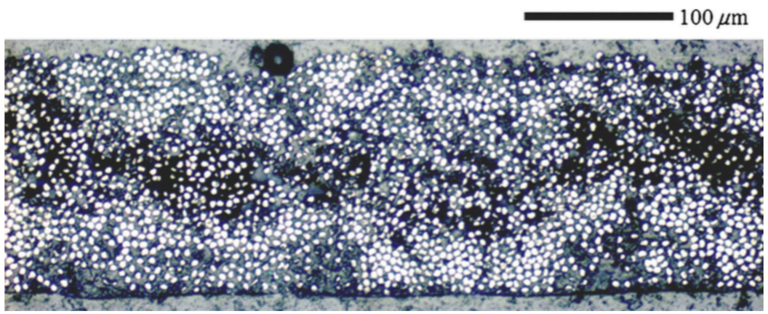
Material	Coefficient of thermal expansion, $\times 10^{-6}$/°C ($\times 10^{-6}$/°F)	Density, g/cm³ (lb/ft³)	Thermal conductivity, cal cm/s cm² °C (BTU in/h ft² °F)
Aluminum	23.7 (13.6)	2.7 (170)	0.48 (1400)
Electroformed nickel	13.3 (7.4)	8.6 (540)	0.19 (564)
Carbon/epoxy prepreg	4.5 (2.5)	1.4–1.5 (87–94)	16×10^{-4} (4.6)
Glass/epoxy	13.1 (7.2)	1.6–2.0 (100–125)	6×10^{-4} (1.7)
Invar 36	3.4 (1.9)	8.0 (504)	0.016 (48)
Invar 42	5.4 (3.0)	8.1 (507)	0.016 (48)
Monolithic graphite	2.16 (1.2)	1.76 (110)	0.28 (840)
High carbon cast steel	9.7 (5.4)	7.3 (456)	0.12 (360)
Steel	12–14 6.7–7.8	7.8 (490)	0.10 (300)

Autoclave curing technology



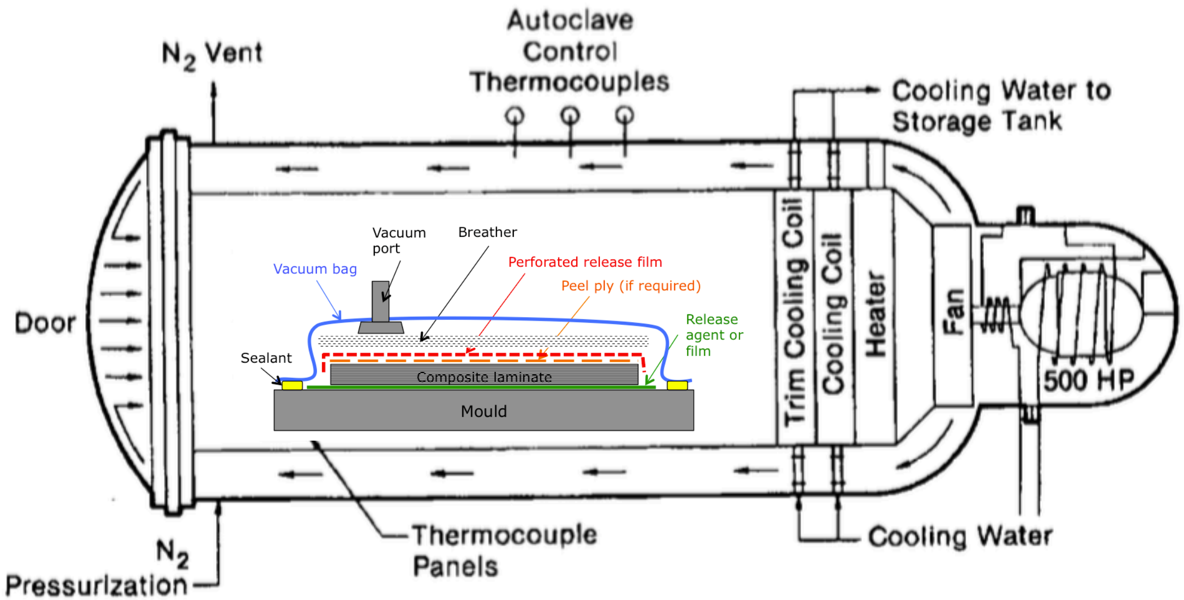
< Vacuum bag process >

https://youtu.be/X6addl525lc



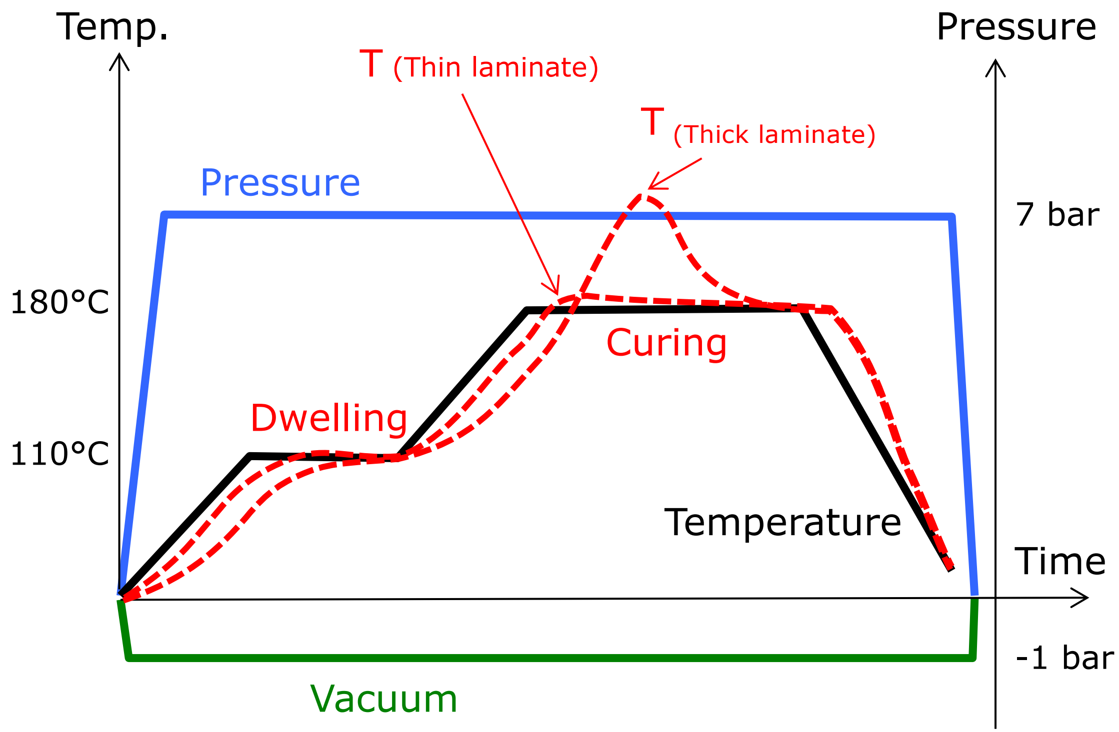
< Cross-section of a prepreg >

$$P_{void} > P_{hydrostatic} \Rightarrow void\ growth$$



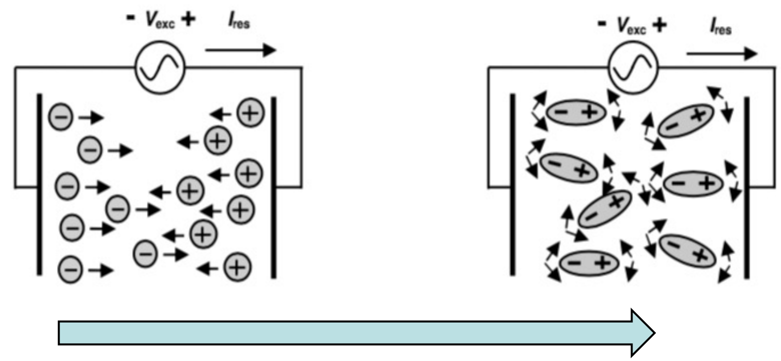
Autoclave curing technology

- Factors affecting the actual curing temp. control
  - Exothermic reaction of the epoxy resin
  - Airflow within the autoclave ➔ Temperature uniformity
  - Thermal conductivity of the mould



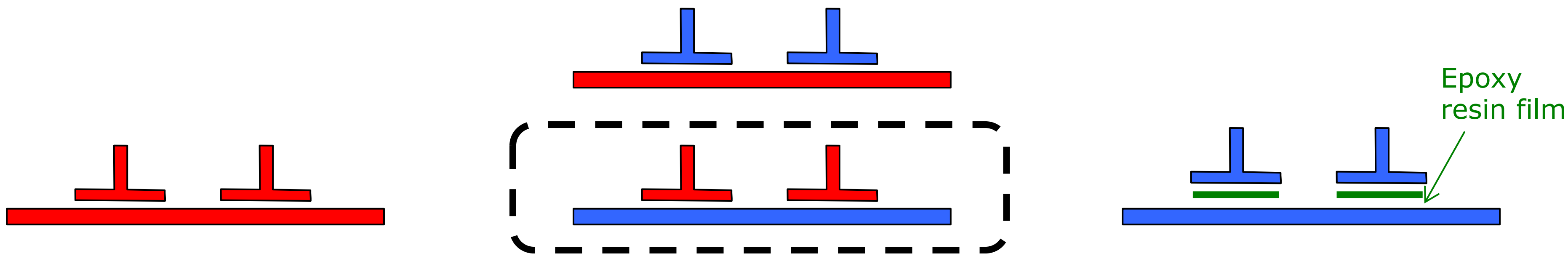
< Cure cycle >

- Cure monitoring
  - Dielectric property (conductance and capacitance) of the resin changes while it is solidified.



Autoclave curing technology

- Integration of composite stringers



Co-curing
Stringer (uncured) +
Skin (uncured)

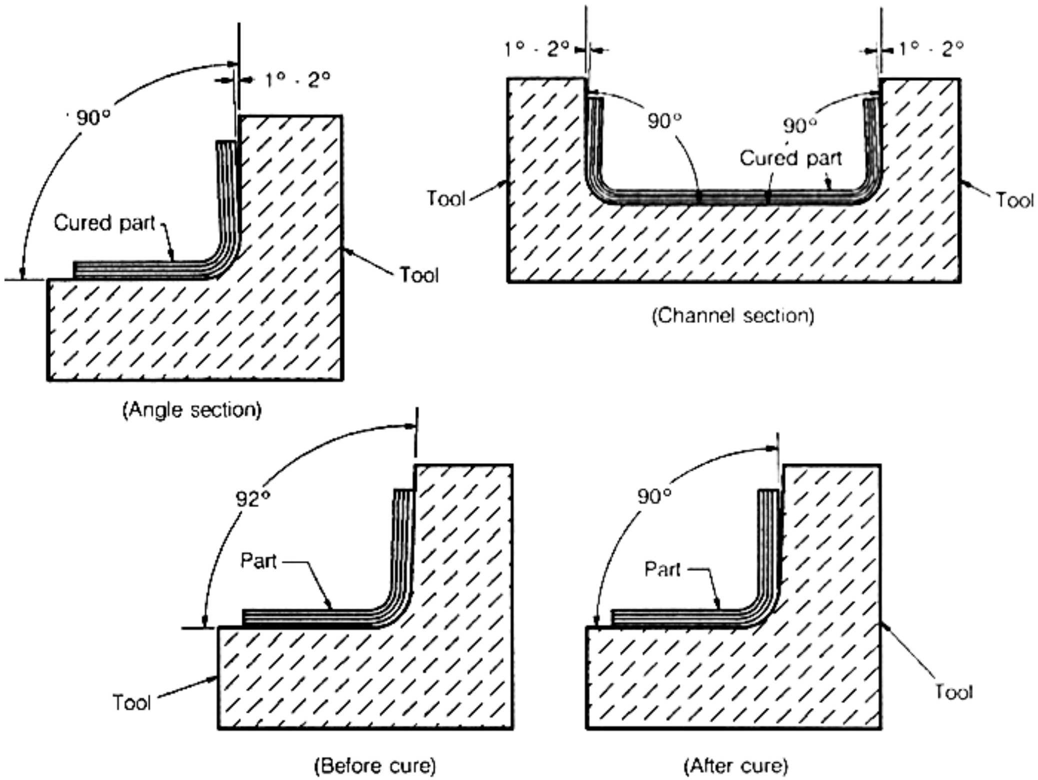
Co-bonding
Stringer (uncured) +
Skin (cured)

Secondary bonding
Stringer (cured) +
Skin (uncured)

- Pros & cons of the co-bonding process
  - No mechanical couplings (e.g. rivets) are required ➔ weight saving, less assembly work
  - Low tooling effort compared to separate curing of individual stringers
  - High tooling effort to handle long stringer moulds

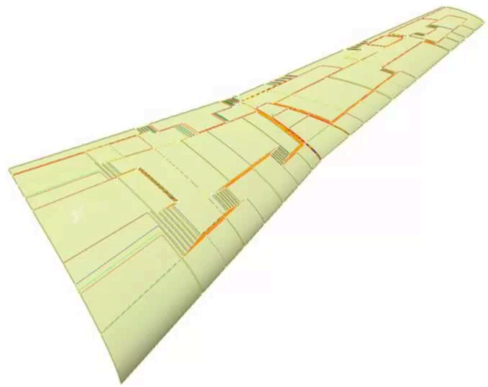
Curing issues

- Spring-in
  - Resin’s chemical shrinkage + thermal distortion ➔ High through-thickness shrinkage



Ref. Michael CY Niu, Composite Airframe Structures

- Tool compensation
  - Using software tools



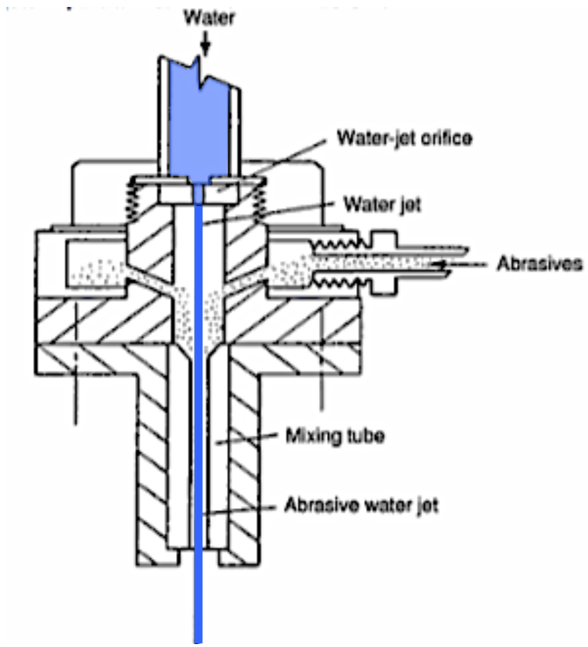
https://youtu.be/OOmKmrcdM-M

Composites machining - Water jet cutting

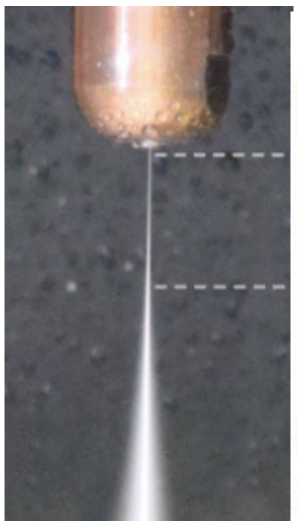
https://www.youtube.com/watch?v=QpCH9mUUEnY

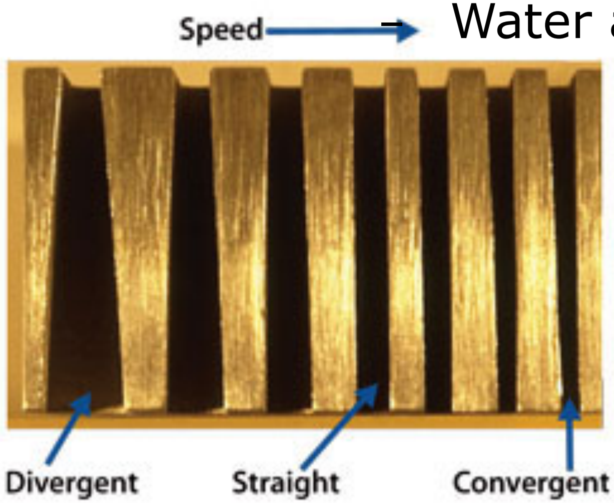
http://videos.airbus.com/video/84217417394s.html

Composites machining - Water jet cutting



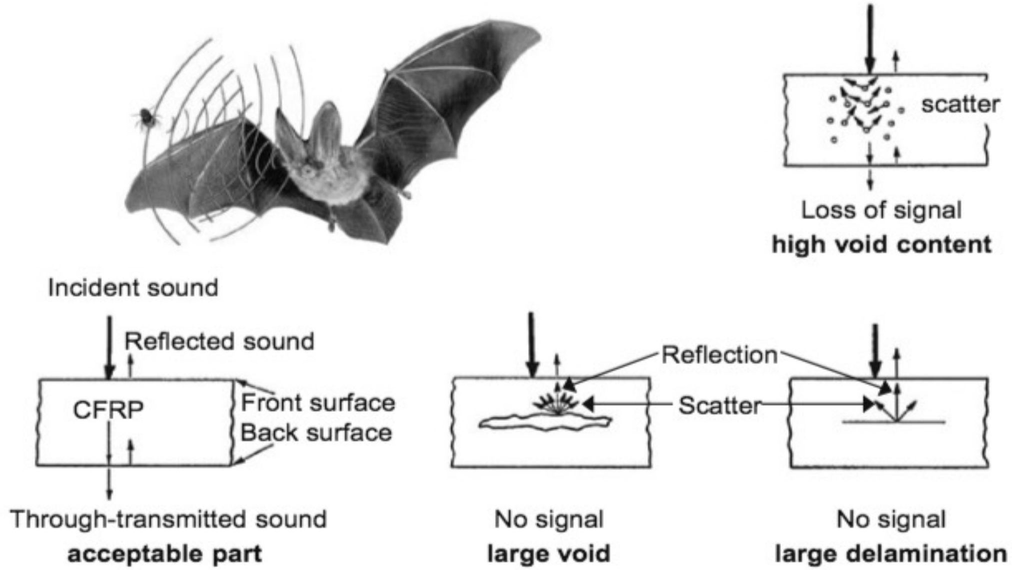
- Water-jet pressure 3,000-6,000 bars
- Abrasive particles are mixed with the water jet
- Advantages
  - No heat generation, lower probability of damage (delamination) compared to mechanical machining
  - Does not workload material
  - Suitable for large and complex shapes
- Disadvantage
  - Kerf taper issue: Lower accuracy compared to mechanical machining (a few hundreds micron)
  - Water absorption



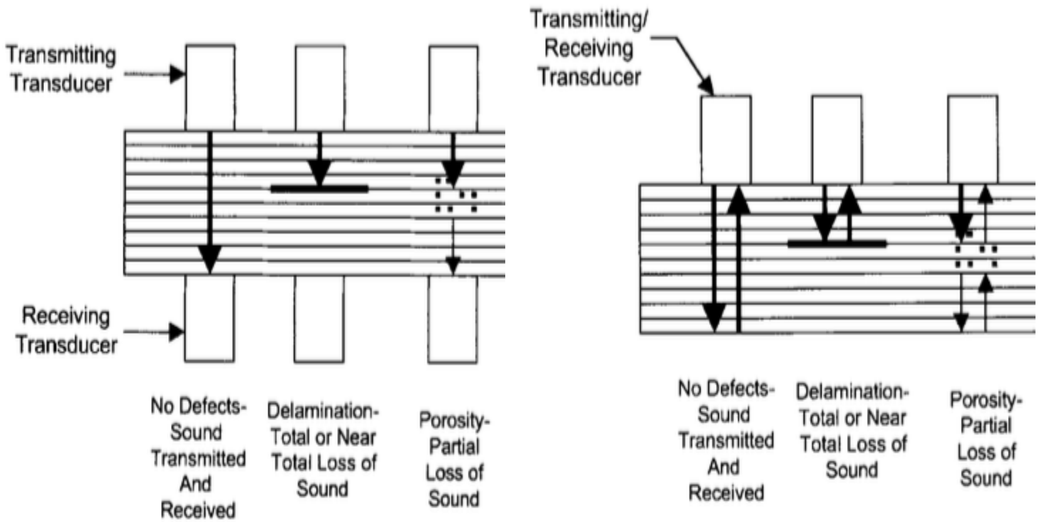


Tilt head for taper compensation (Flow3D, USA)

Composite NDT



Ref. Commercial Aircraft Composite Technology



Through-Transmission Ultrasonic vs. Pulse Echo Ultrasonic

- Water is used as a coupling agent to transfer the sound waves.
- The sound wave freq. is dependent on the part thickness (5 ~ 50 MHz).
- Interpretation of the signals requires special knowhow, and CFRP parts with artificial defects are used for calibration.

Next Lecture

<u>Mechanical Joining</u>