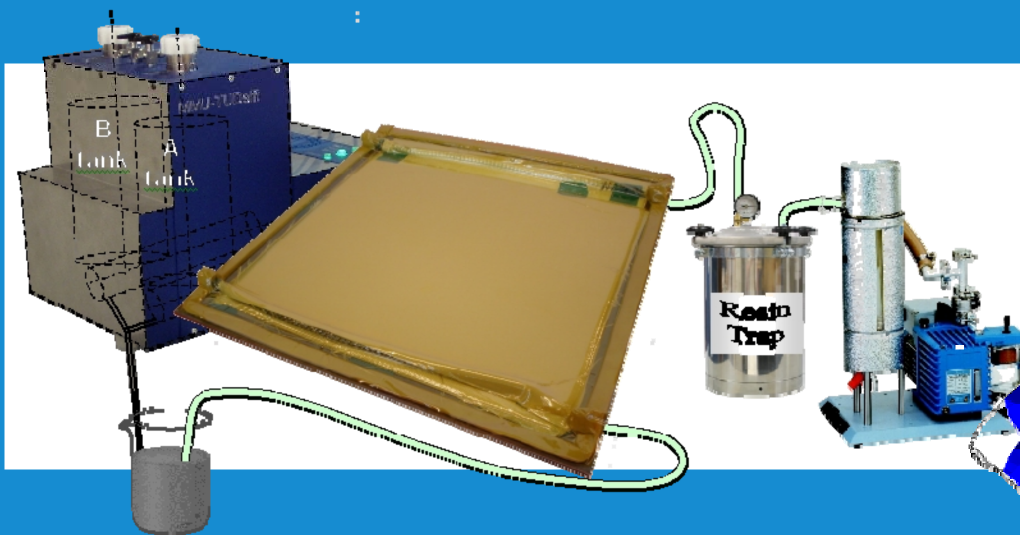
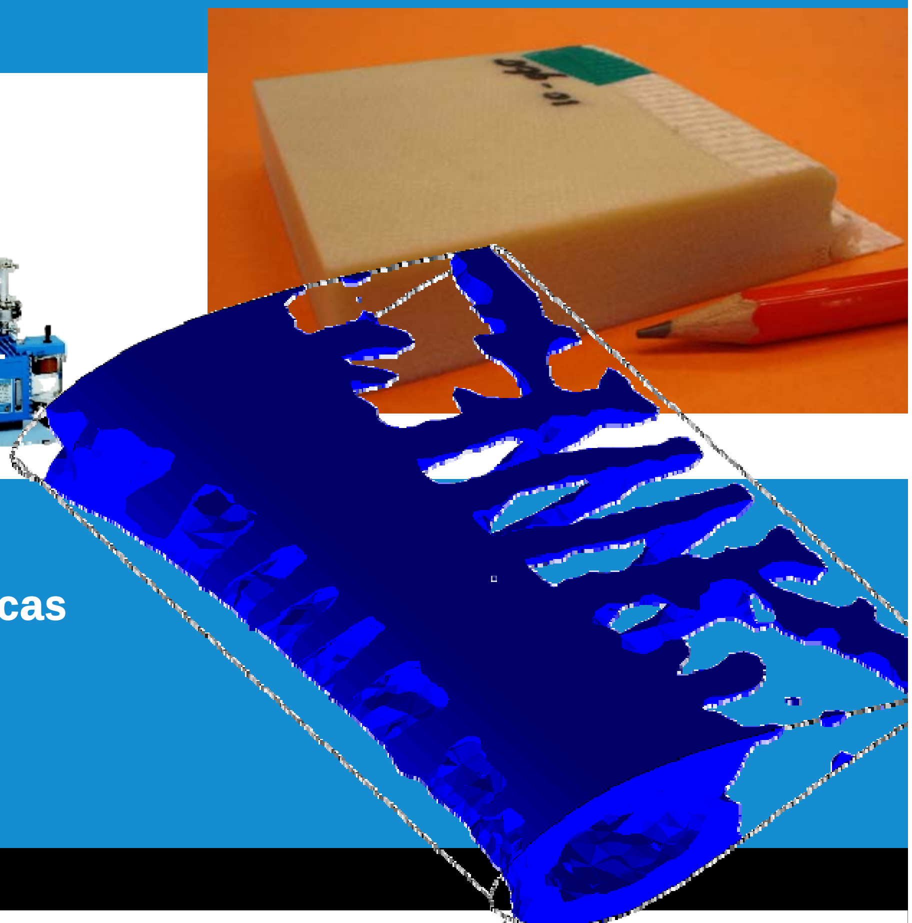
VACUUM INFUSED THERMOPLASTIC COMPOSITES FOR WIND TURBINE BLADES





Julie Teuwen, Kjelt van Rijswijk, Simon Joncas and H.E.N. Bersee

June 3, 2008

DESIGN AND PRODUCTION OF COMPOSITE STRUCTURES

2008 Wind Turbine Blade Workshop
Sandia National Laboratories
12-14 May 2008

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Contents

Large Wind Turbine Blades

Dedicated offshore wind power systems:

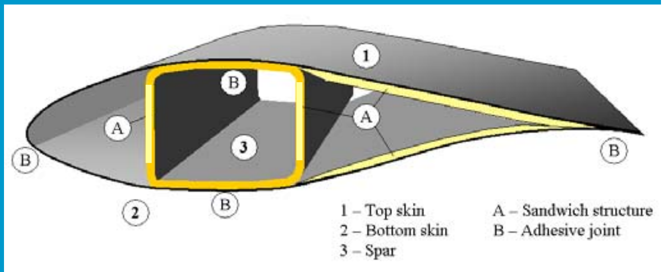
- Stronger and more constant wind.
- Increasingly large blades to increase power output per turbine and reduce costs per kWh.
- No noise-pollution regulations and less aesthetical issues to deal with.

Larger blades require:

$$m_{blade} \sim (R_{blade})^{3 \rightarrow 2.35}$$

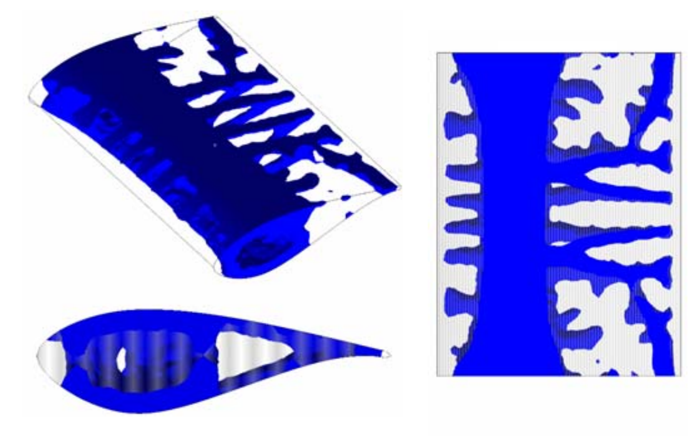
- Materials with higher specific properties (E/ρ, $\dot{\sigma}/\rho$): Carbon fiber composites or hybrid carbon/glass composites.
- More efficient structural designs

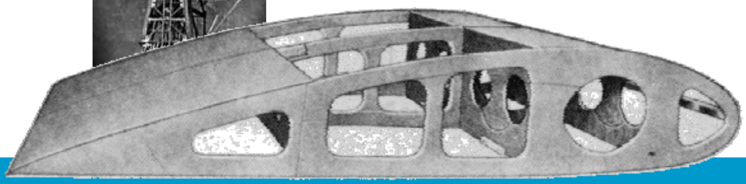
Alternative Structural Design



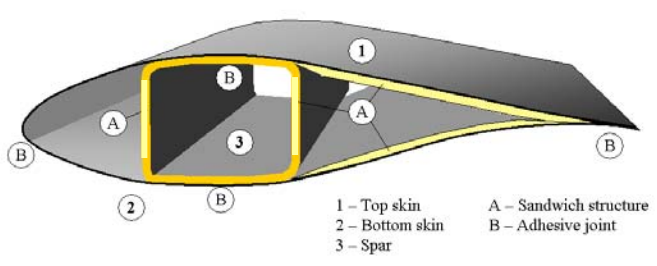
Re-introduction of ribs:

- Higher structural efficiency (E/ρ).
- Reduces local buckling of skin and webs.
- Provides attachment points and load paths for smart actuators/control surfaces and sensors.
- Not entirely new.



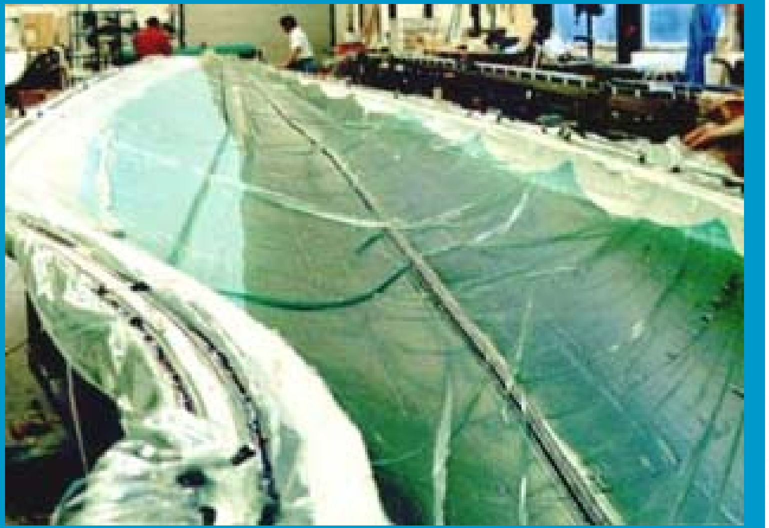


Thermoplastic Composites

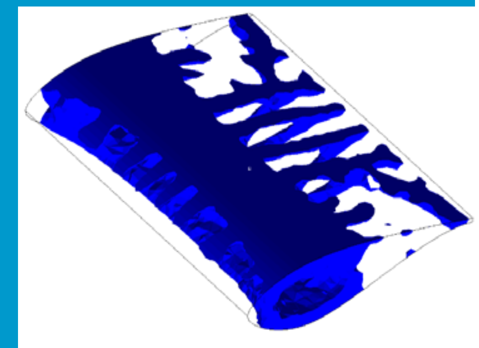


Current blade manufacturing technology:

- Thermoset composites
- 2 skins and 1 spar assembled by structural bonding
- Vacuum infusion or pre-pregging of individual parts

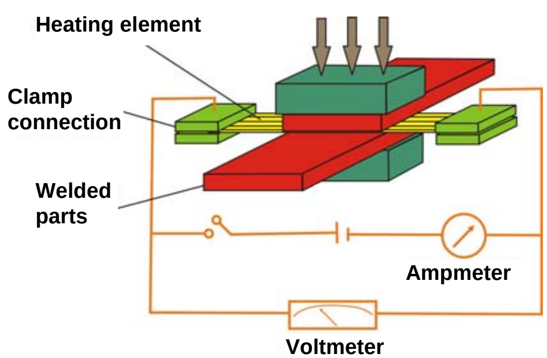


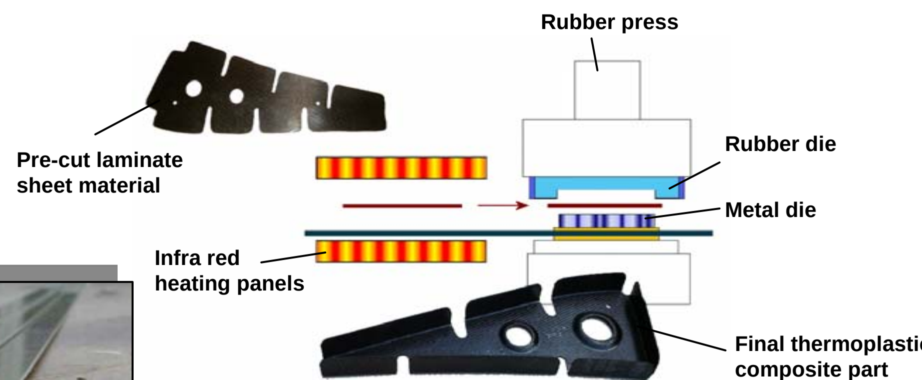
Thermoplastic Composites



Alternative blade manufacturing technology:

- Thermoplastic composites
- 2 skins, 1 spar and many ribs assembled by welding
- Rubber forming and diaphragm forming of individual parts





Thermoplastic Composites

Additional advantages:

- Better impact properties.
- Do not turn brittle at low temperatures.
- Unlimited shelf life of the raw materials.
- Fully recyclable (environmental and economic benefits).

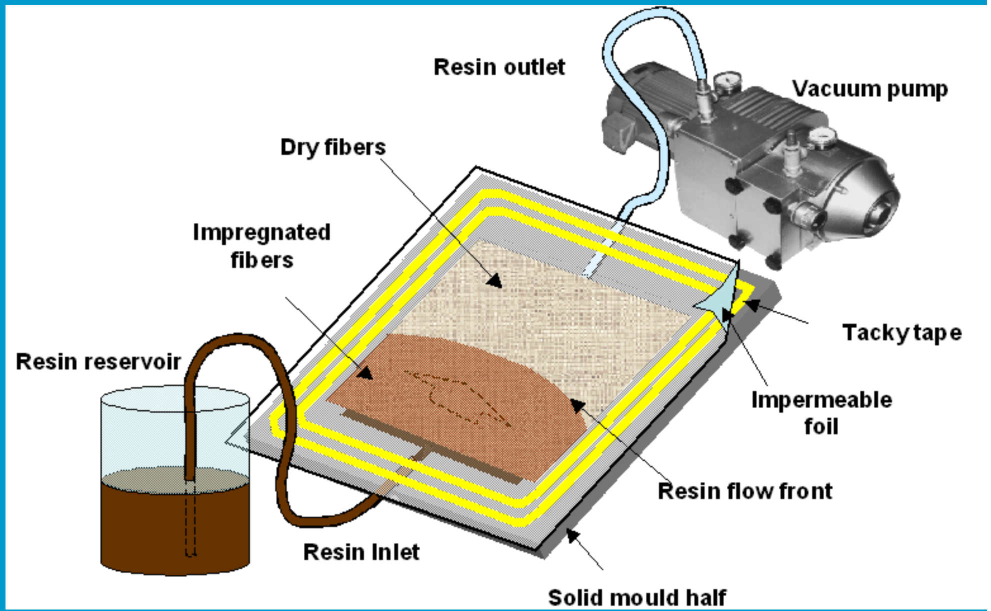
Drawbacks:

- Poor fatigue performance due to weak fiber-to-matrix bond.
- Requires introduction of new technologies and expensive equipment.
- High material costs due to need for intermediates.
- High processing temperatures (>200°C): high costs, thermal stresses.
- Melt pressing technology limits achievable part size and thickness

Vacuum Infusion of Thermoplastic Composites

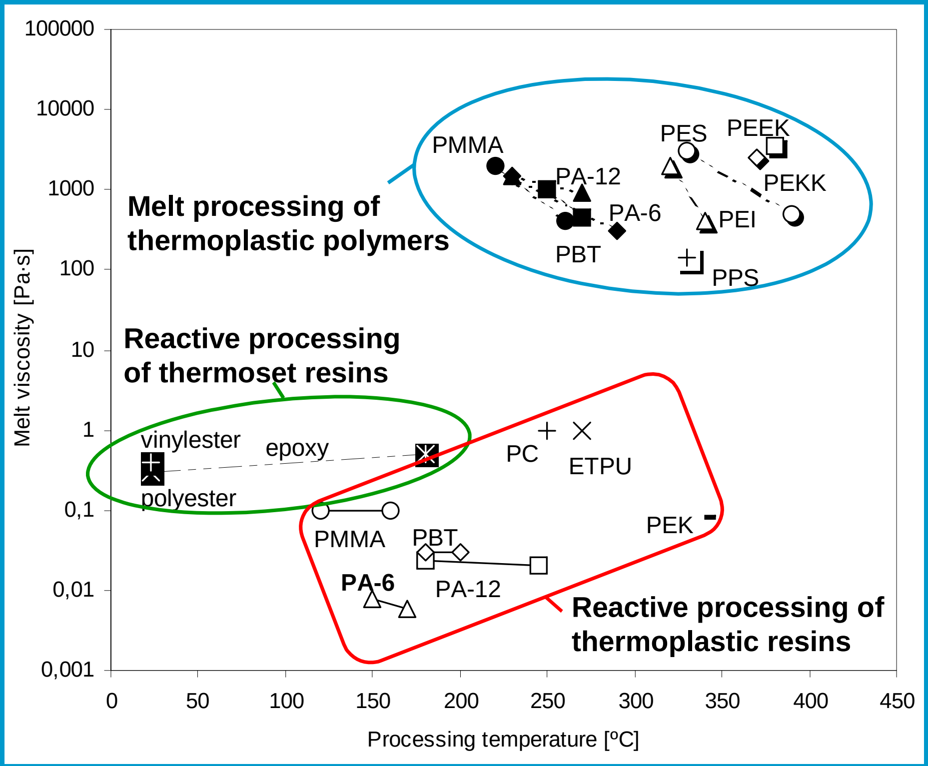
Reactive processing of thermoplastic composites:

- Manufacturing of larger, thicker and more integrated thermoplastic composite parts.
- Improved chemical bonding due to in situ polymerization of the matrix around the fibers.
- Does not require expensive intermediate materials but allows manufacturing of parts directly from the monomer.
- Commonly used technology for blade manufacturing.



Vacuum Infusion of Thermoplastic Composites

Reactive processing of thermoplastic composites:



Anionic Polyamide-6:

- AP-Nylon®,Brüggemann Chemical, Germany.
- Availability of resin, additives and knowledge.
- Price/performance ratio (2-3 €/kg).
- Viscosity of the monomer (10 mPa·s).
- Processing temperatures (150-180°C).

Brüggemann Chemical
L.Brüggemann Kommanditgesellschaft

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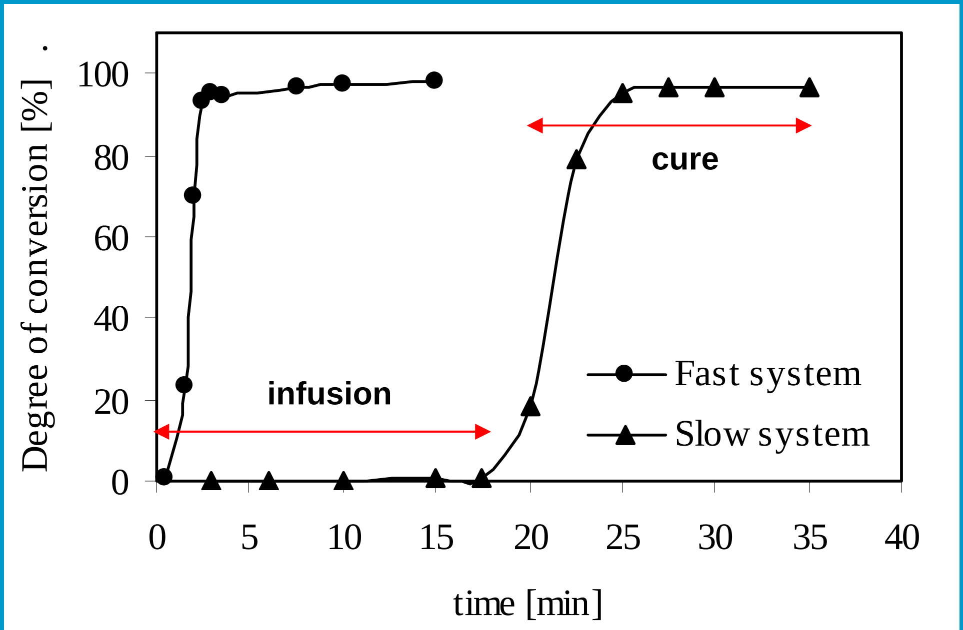
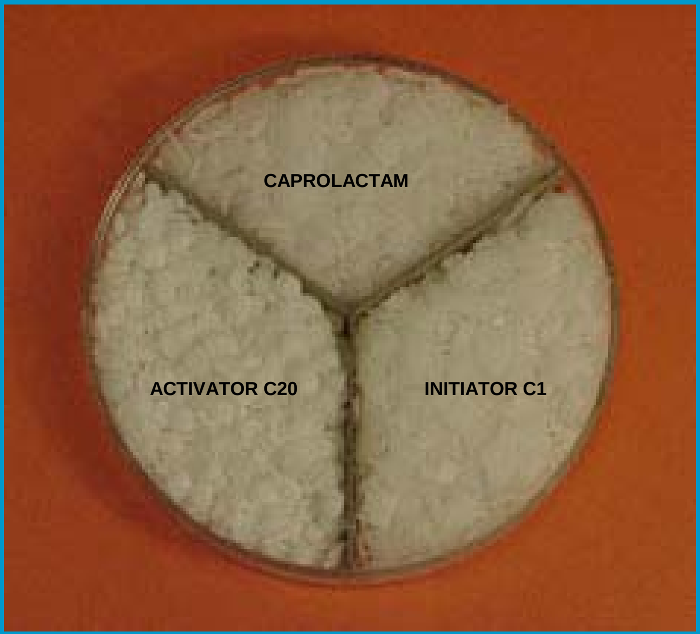
Anionic Polyamide-6

Control of reaction rate





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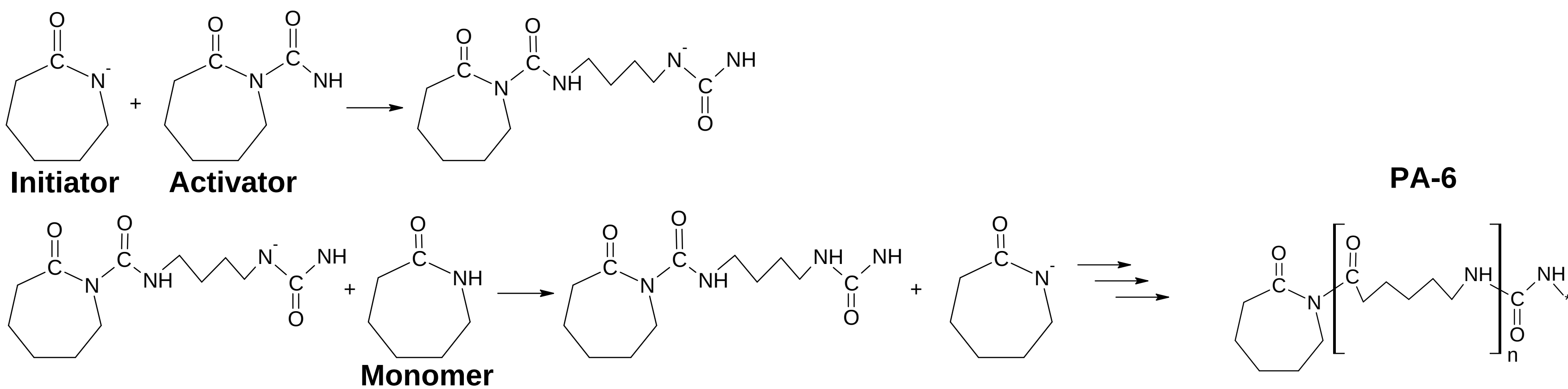
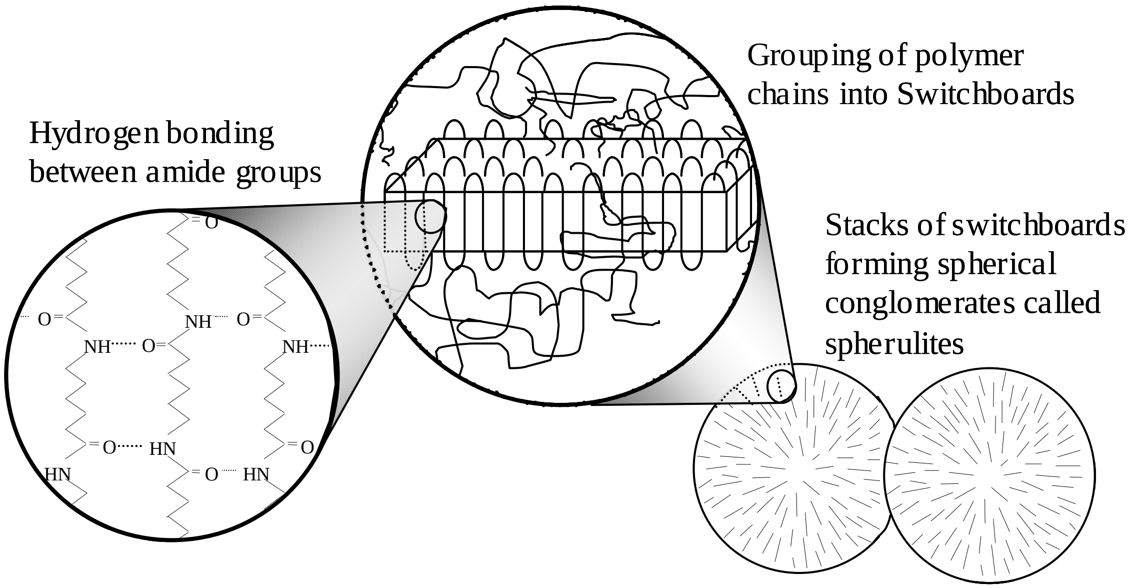
Anionic Polyamide-6

1. Ring-opening polymerization of caprolactam into PA-6

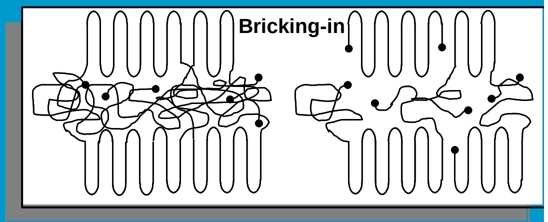


2. Crystallization of PA-6 chains

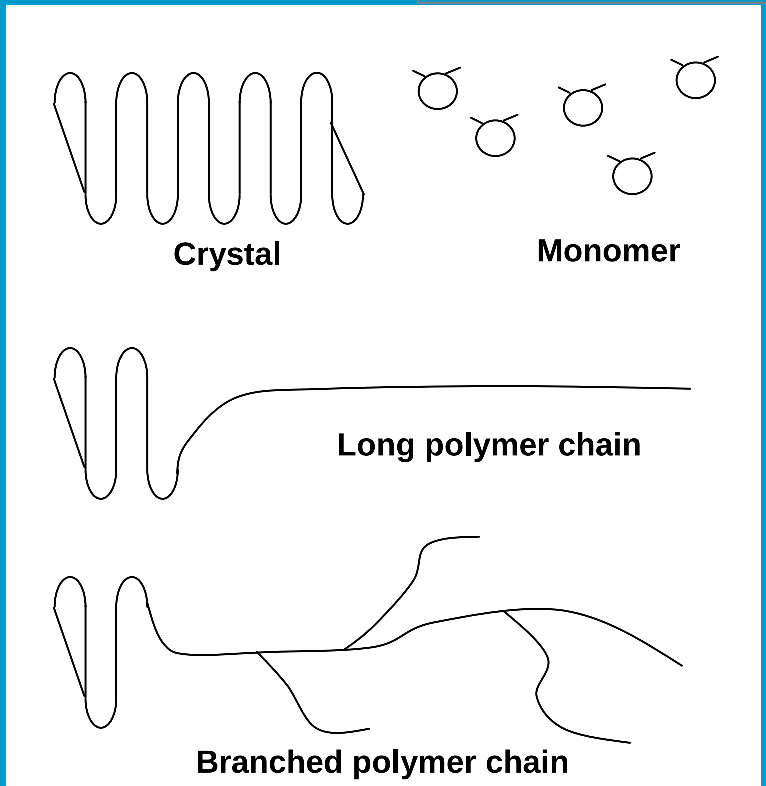


$T_{pol} < T_c \Rightarrow$ Polymerization and crystallization occur simultaneously.

Anionic Polyamide-6



Selecting the optimum polymerization temperature:



➢Temperature too low:
polymerization stops

Temperature too high:
Crystallization difficult

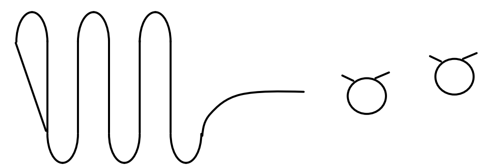
➢Temperature much too high:
Crystallization stopped

Anionic Polyamide-6

Selecting the optimum polymerization temperature:

- Temperature too low:
  polymerization stops

- **Optimum temperature:**
  Continuous polymerization
  & crystallization

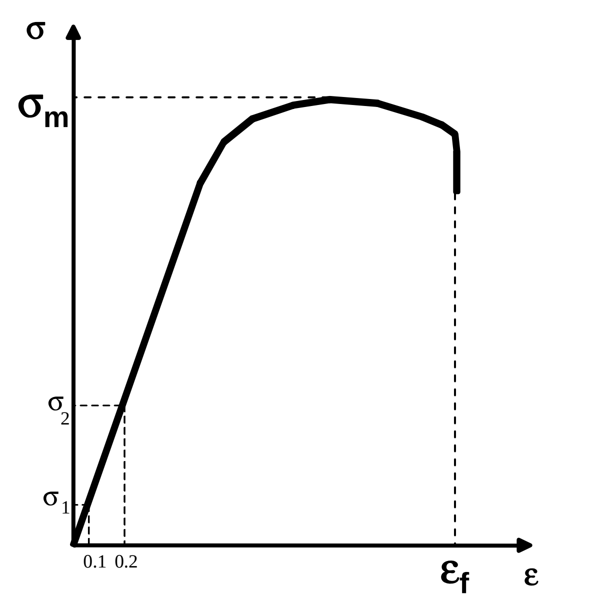


- Temperature too high:
  Crystallization difficult

- Temperature much too high:
  Crystallization stopped

Anionic Polyamide-6

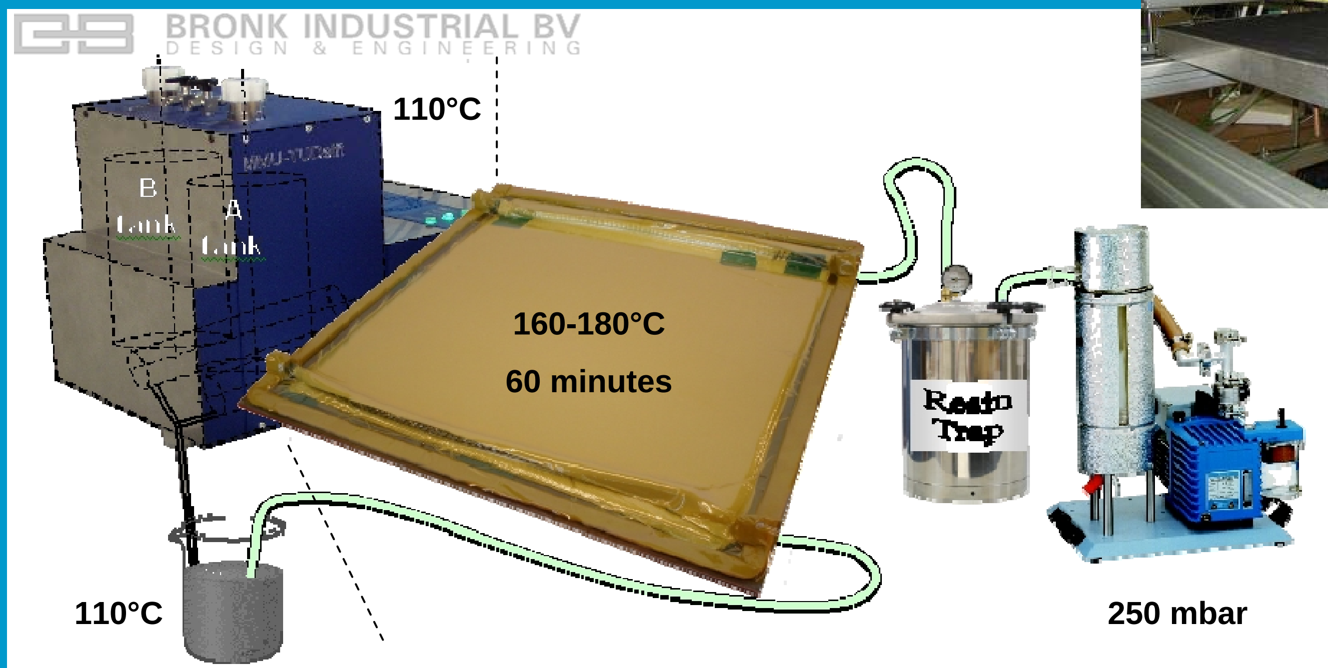
Polymer tensile properties



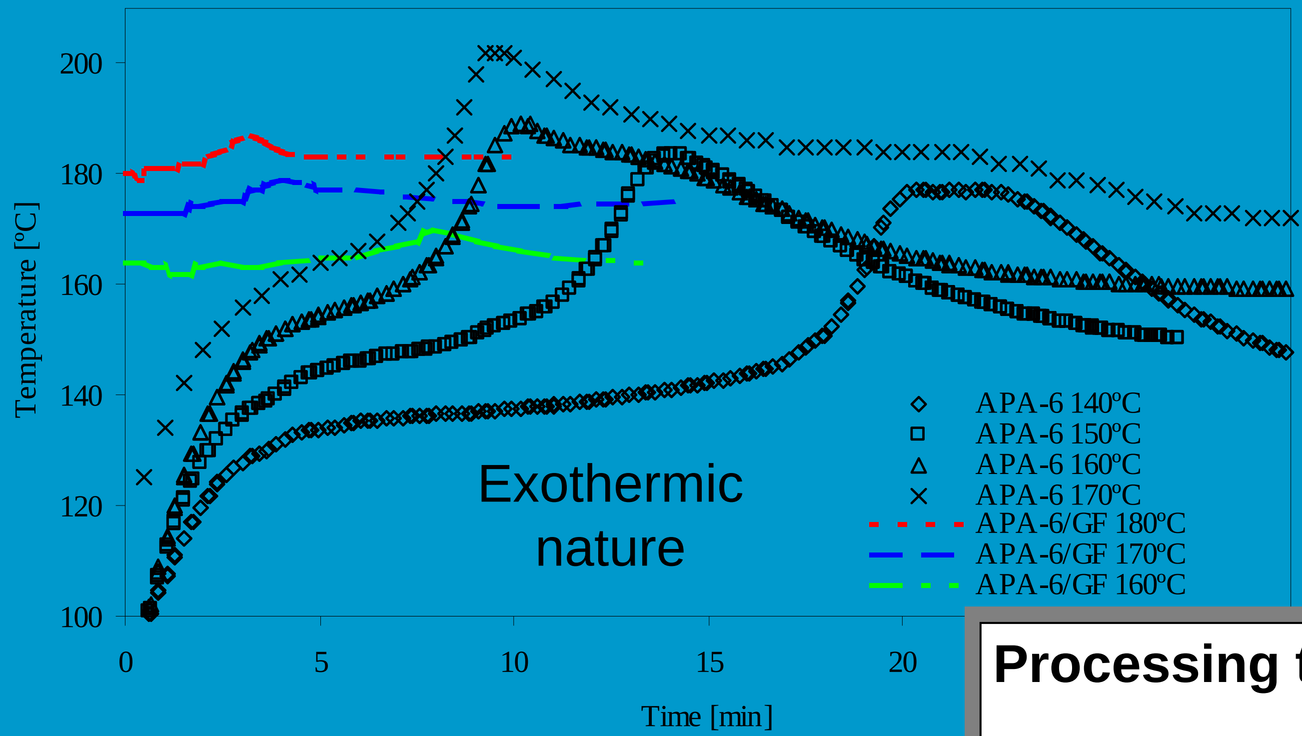
Condition	Young's modulus [GPa]	Maximum strength [MPa]	Strain at failure [%]
23ºC, dry	4.2 (+ 41%)	96 (+ 14%)	9 (-)
23ºC, 50% RH	2.1 (+ 59%)	61 (+ 4%)	28 (-)
80ºC, dry	1.6 (+ 65%)	51 (+ 32%)	29 (-)

Compared to injection molded PA-6

Vacuum Infusion of Polyamide-6 Composites



Vacuum Infusion of Polyamide-6 Composites



Processing temperatures:

Neat APA-6: 150-170°C

APA-6 Composites: 160-180°C

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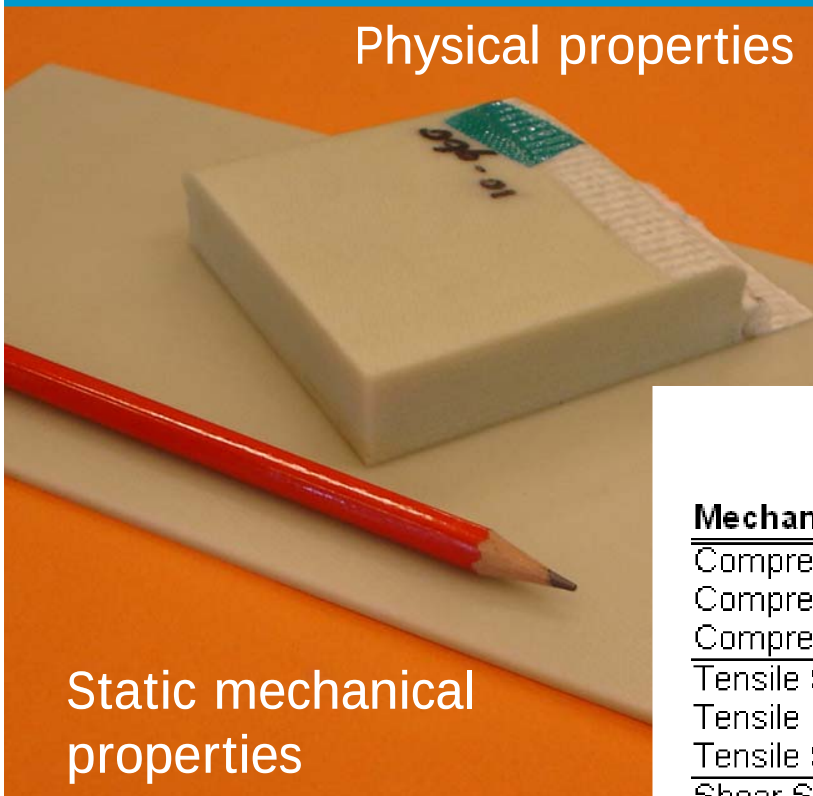
Anionic Polyamide-6 Composites



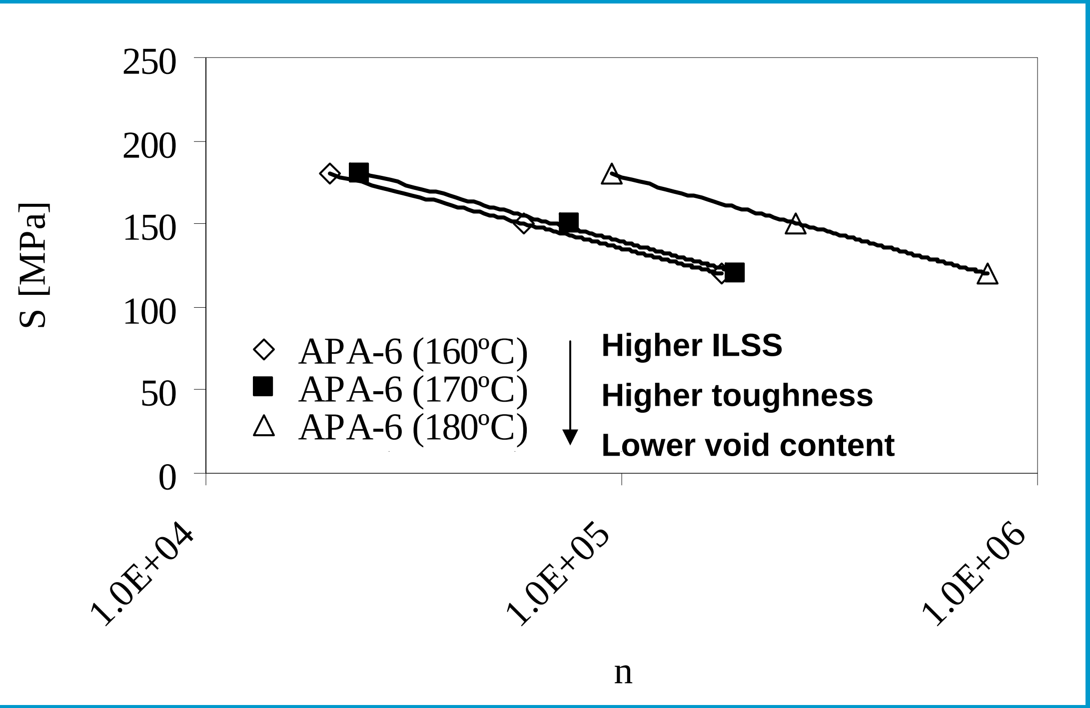
Physical properties

Physical property	APA-6 composite	PA-6 composite	Epoxy composite
Thickness [mm]	2.8	2.7	2.9
Density [g/cm³]	1.8	1.9	1.8
Fiber Volume Content [%]	50	51	48
Void Content [%]	**3.0**	1.3	2.1
Melting point [ºC]	217	220	-
Degree of Conversion [%]	**95**	100	100
Degree of Crystallinity [%]	35	33	-

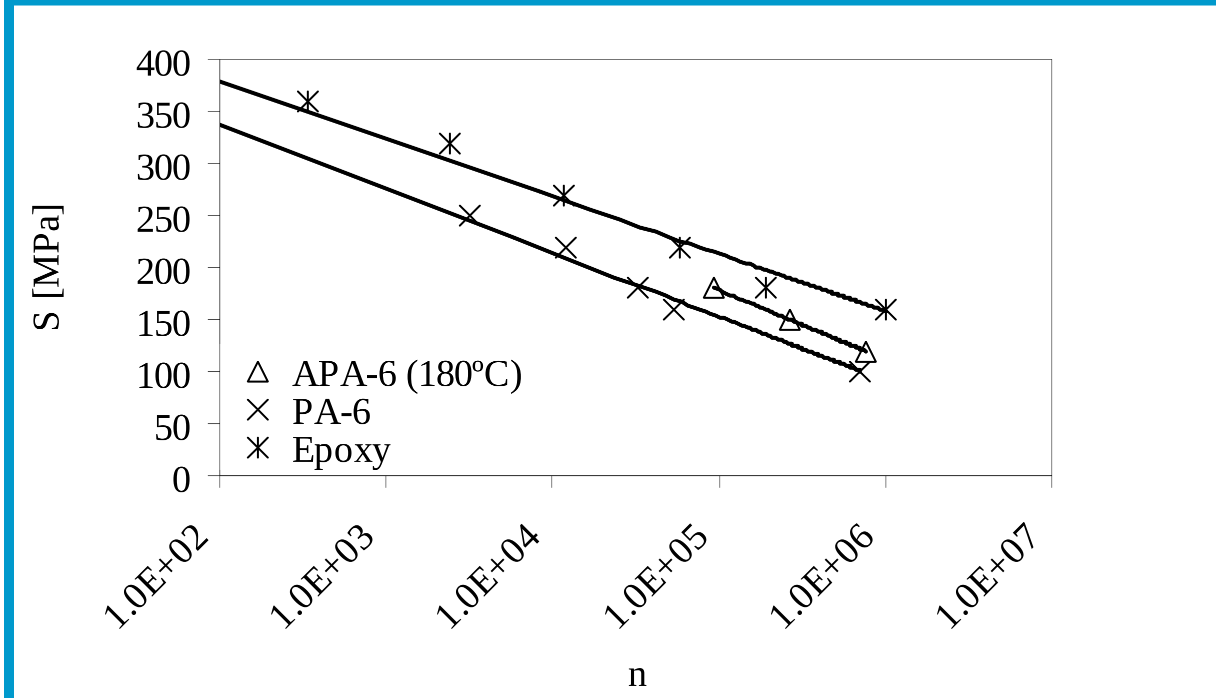
Static mechanical properties

	DAM			23ºC –50%RH		
Matrix material / **Mechanical property**	APA-6	PA-6	Epoxy	APA-6	PA-6	Epoxy
Compressive Strength [MPa]	**473**	390	392	290	314	**376**
Compressive Modulus [GPa]	**26**	25	25	23	23	24
Compressive Strain [%]	1.9	1.5	1.7	1.3	0.9	0.8
Tensile Strength [MPa]	**495**	456	476	430	450	**458**
Tensile Modulus [GPa]	26	26	26	23	24	25
Tensile Strain [%]	2.4	2.5	2.3	2.0	2.0	2.3
Shear Strength [MPa]	**127**	117	94	**105**	100	85
Shear Modulus [GPa]	**4.1**	3.7	3.5	1.9	1.7	**3.0**

Anionic Polyamide-6 Composites



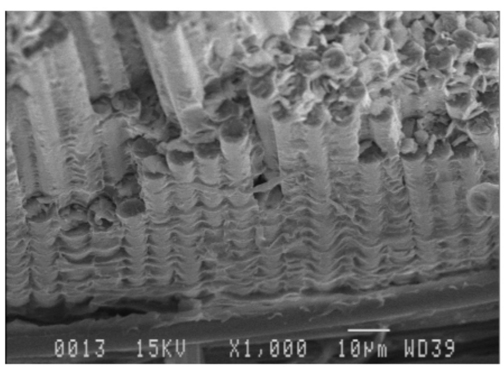
Anionic Polyamide-6 Composites

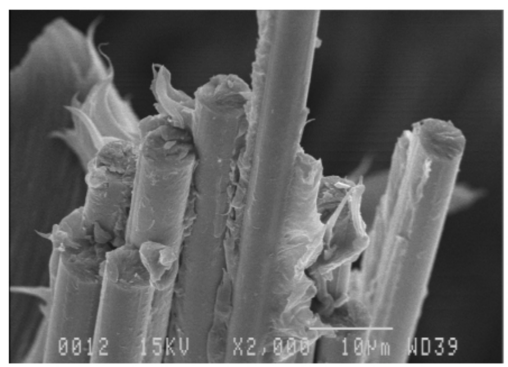


APA-6 composite manufactured at 180C has better fatigue properties than the melt processed PA-6 composite:

- **Same toughness**
- **Higher interfacial bond strength**

The epoxy composite outperforms both thermoplastic composites.





Conclusions

- For increasing blade lengths, switching to more efficient structural designs is inevitable: the re-introduction of ribs is suggested.

- For rib/spar/skin-structures, thermoplastic composites are favoured over thermoset composites. Parts can be rapidly melt processed and assembled through welding. Blades will be fully recyclable.

- Vacuum infusion of thermoplastic composites is introduced to overcome the classical drawbacks of these materials: limited size and thickness of parts, poor fatigue resistance, expensive materials.

- The cure of a semi-crystalline thermoplastic resin is more complicated than of a thermoset resin.

Conclusions

- AP Nylon® has a low viscosity (10 mPa·s), good availability, a low price (2-3 €/kg), and a relatively low processing temperature (150-180°C).

- Reactively processed PA-6 outperforms melt processed PA-6 in all temperatures and humidities tested.

- Static properties of APA-6 composites are better than of their HPA-6 and epoxy counterparts in dry conditions. When moisture conditioned, the performance of APA-6 composites drop rapidly, which is caused by the low conversions and high void contents.

- Reactive processing of thermoplastic composites results in a strong interfacial bond strength and leads consequently to better fatigue performance compared to melt processing.

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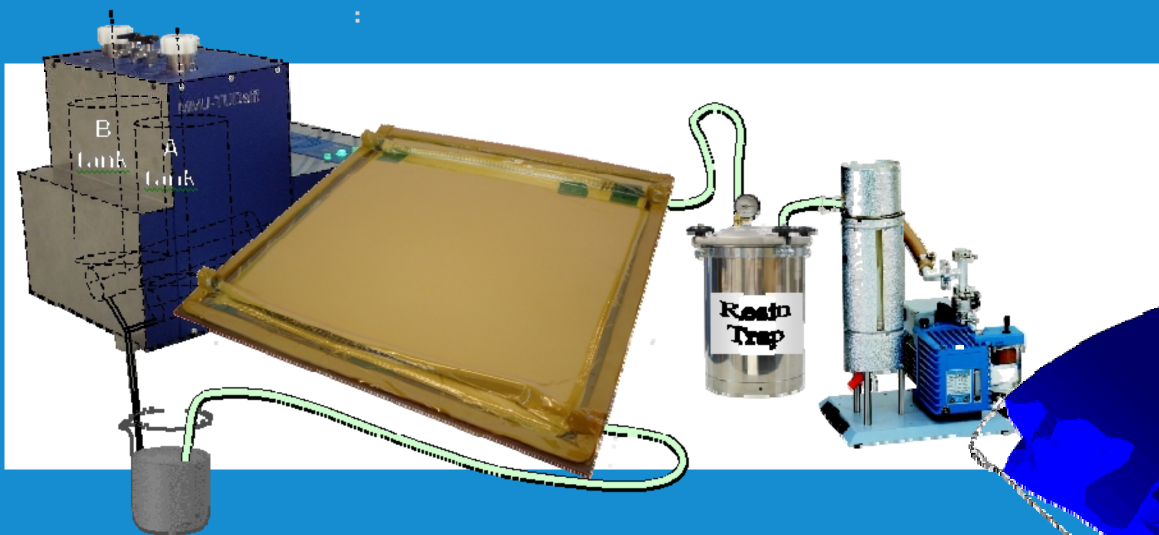

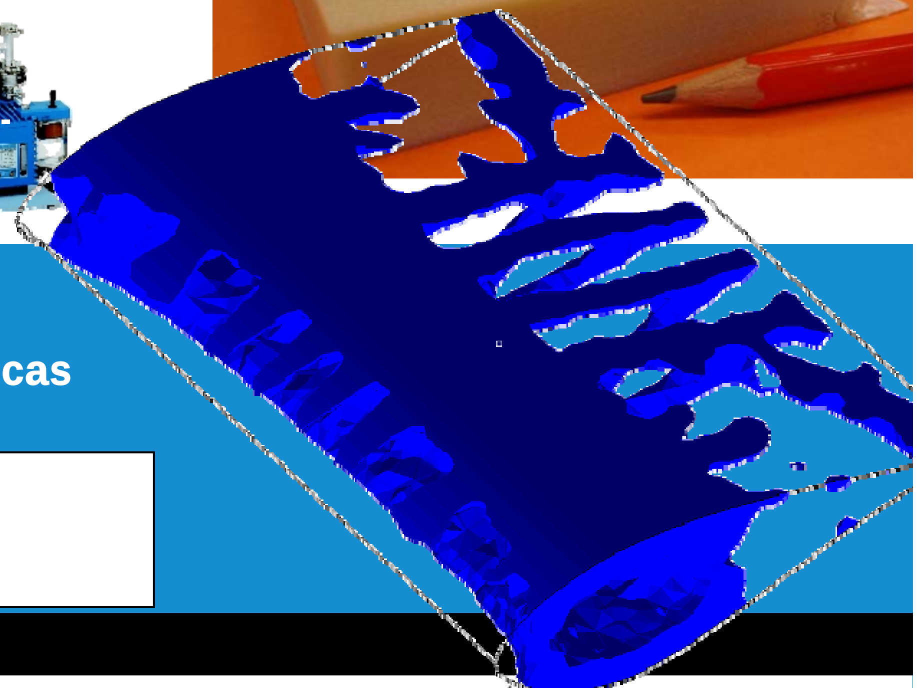

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Questions?

DESIGN AND PRODUCTION OF COMPOSITE STRUCTURES

TENCATE
materials that make a difference

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DESIGN & ENGINEERING

BrüggemannChemical
L.Brüggemann Kommanditgesellschaft

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