

# MSE 214 Composites B

## Les matériaux composites

- . Les fibres, les matrices
- . Micromécanique et **anisotropie**
- . **Les procédés de mise en oeuvre**
- . **Les développements récents**

**Biocomposites**

**Composites fonctionnels**

**Nanocomposites**

...

## Références:

TRAITÉ DES MATÉRIAUX

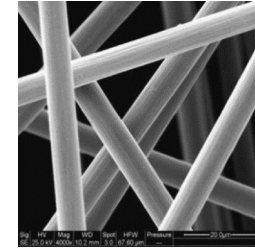
**15**  
MATÉRIAUX  
COMPOSITES  
À MATRICE ORGANIQUE  
Constituants, procédés, propriétés

Pierre-Etienne Bourban · Leif Carlsson  
Jean Pierre Mercier · Jan Anders E. Månson

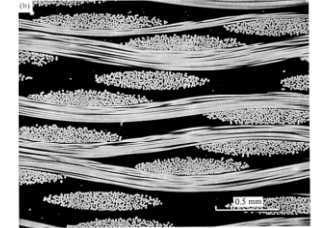
Traité des Matériaux, vol. 15

" Matériaux composites à matrice organique"

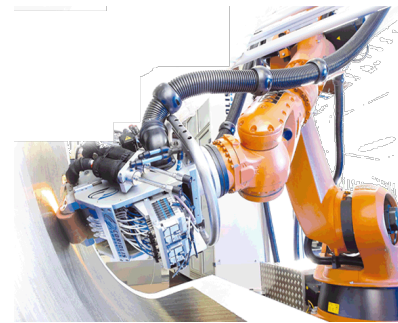
Presses Polytechniques et Universitaires Romandes



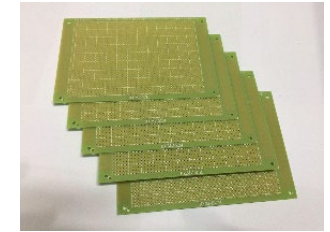
[www.reinforcedplastics.com](http://www.reinforcedplastics.com)



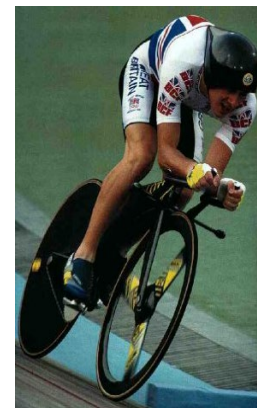
## Des fibres aux stratifiés



[www.coriolis-composites.com](http://www.coriolis-composites.com)



**Rigidités et anisotropies exploitées**



[BMW i8 automobile.challenges](http://BMW i8 automobile.challenges)

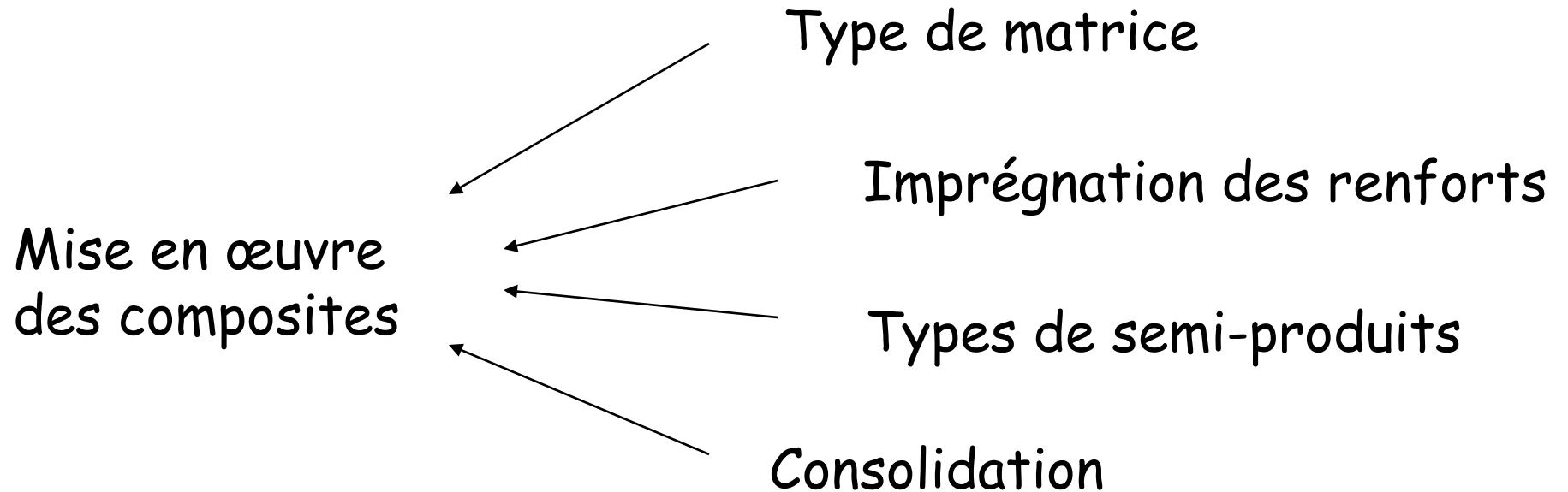
**EPFL**

[pierre-etienne.bourban@epfl.ch](mailto:pierre-etienne.bourban@epfl.ch)

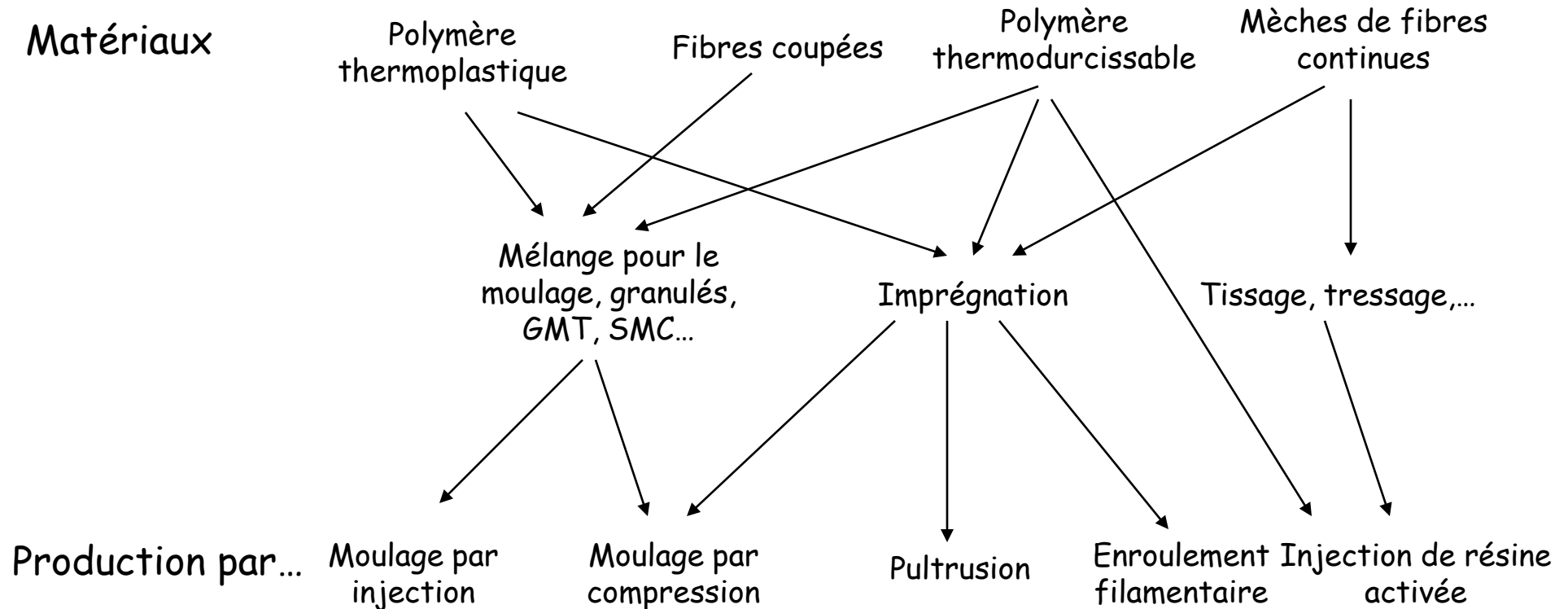
# Mise en œuvre des composites

- Introduction
- Transformation des thermodurcissables (TD)
- Techniques de fabrication des TD
- Transformation des thermoplastiques (TP)
- Techniques de fabrication des TP
- Comparaison et sélection des techniques

# Introduction



# Des matériaux aux produits

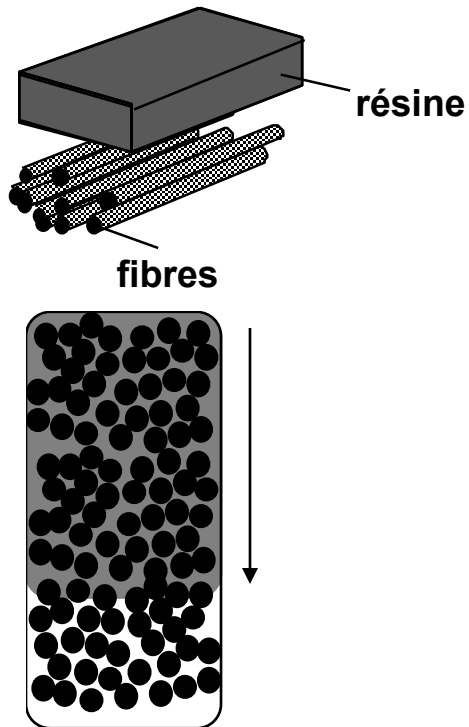


# Mise en œuvre des composites

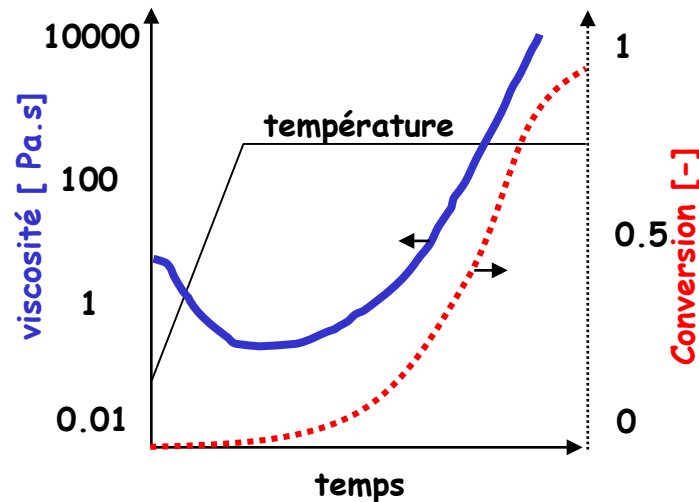
(a) Préimprégnés → moule → mise en forme

(b) Fibres → renfort textile  
Résine → moule → imprégnation par moulage

# Les phénomènes

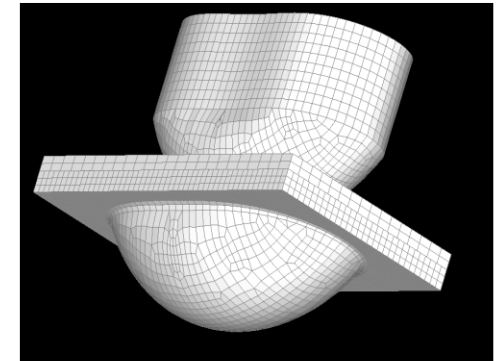


Imprégnation



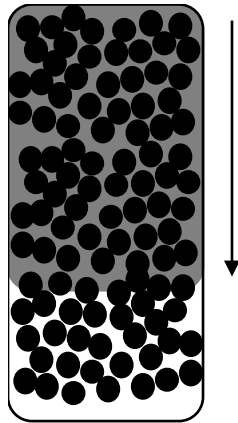
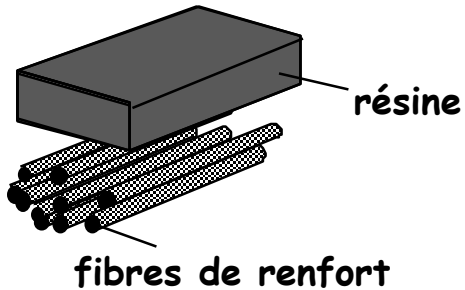
Transformation de la matrice

- Polymérisation, réticulation des thermodurcis
- Fusion et consolidation des thermoplastiques



Tranfert de chaleur,  
écoulement, formage...

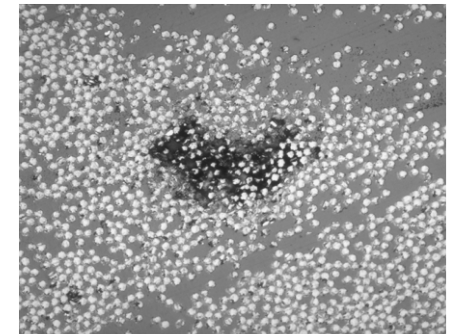
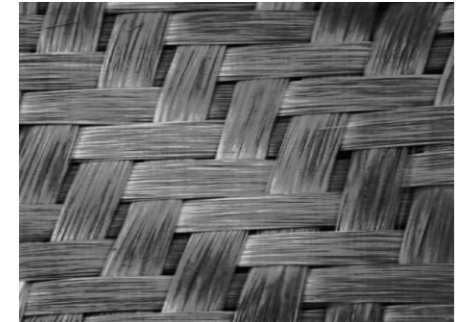
# Imprégnation



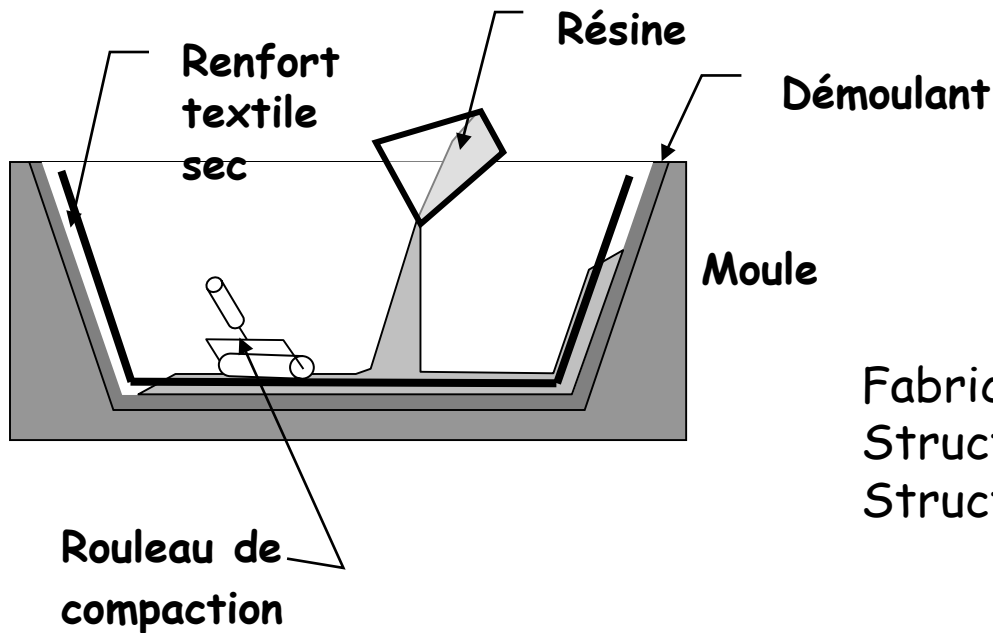
$$t_{\text{imprégnation}} = \eta \frac{(1 - V_f)L^2}{2K(P_a - \Delta P_c)}$$

Loi de Darcy

Temps d'imprégnation  
Volume à imprégner  $1 - V_f$   
Viscosité de la résine  $\eta$   
Distance à imprégner  $L$   
Perméabilité du renfort  $K$   
Pression appliquée  $P_a$   
Pression capillaire  $P_c$   
Contre-pression du lit de renfort



# Moulage au contact



Fabrication de bateaux  
Structures d'avions  
Structure du génie civil

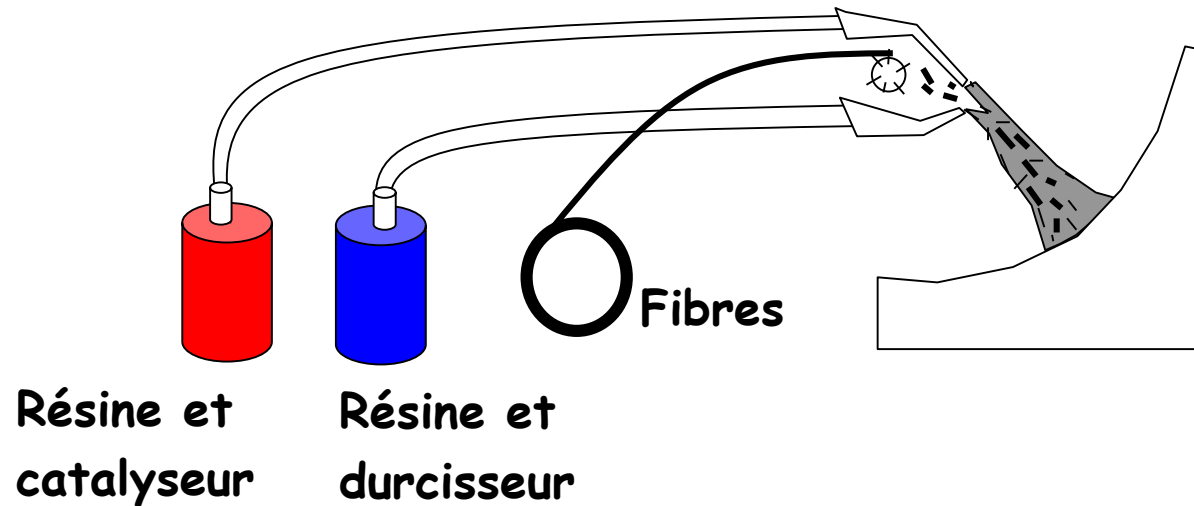


Avantages :	Inconvénients :
Facilité de mise en oeuvre	Faibles cadences de production
Investissements très faibles	Main d'oeuvre importante
Sans limitation de dimensions	Epaisseur difficile à contrôler
Main d'oeuvre peu qualifiée	Une face brute

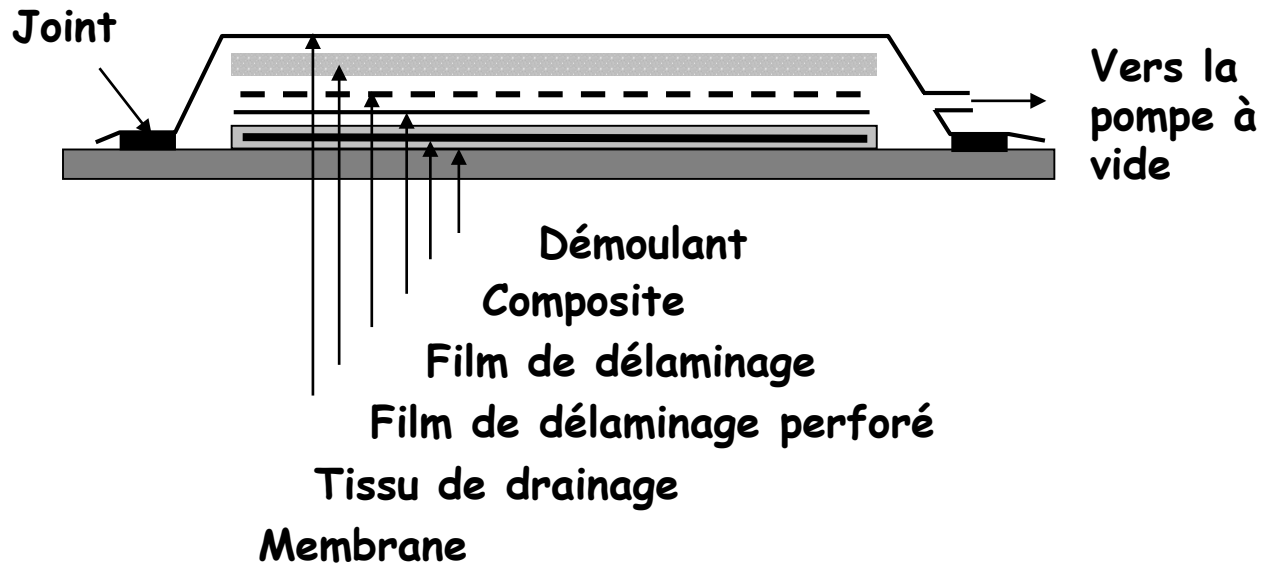
# Moulage au spray

Avantages :	Inconvénients :
Cadence plus rapide que le moulage au contact Sans limitation de dimensions Equipements pas trop importants	Main d'oeuvre importante et qualifiée Peu de constance dans l'épaisseur Propriétés mécaniques pas très élevées

## Découpeuse de fibres

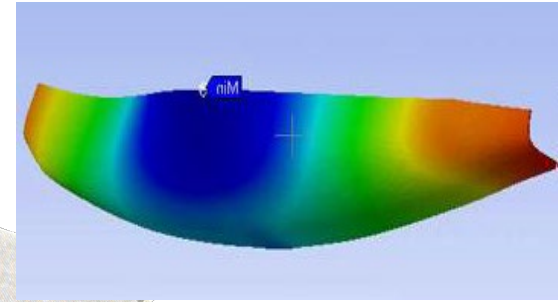
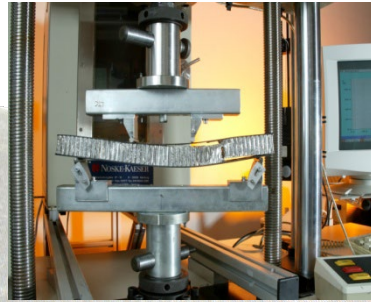
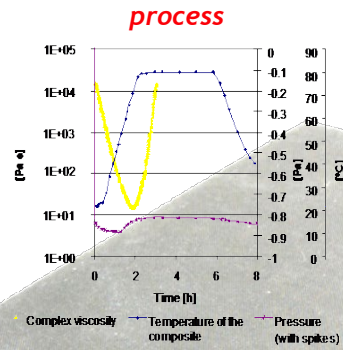
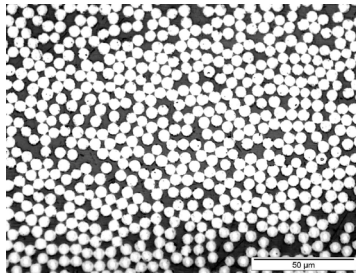


# Moulage sous vide

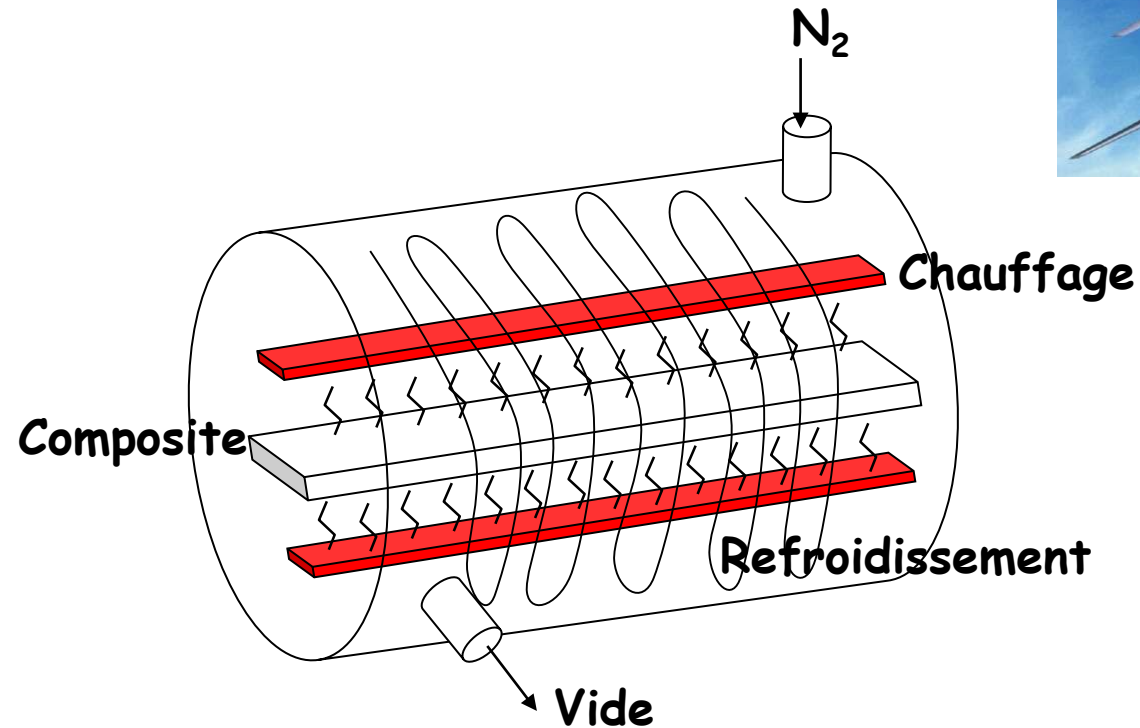


<b>Avantages :</b>	<b>Inconvénients :</b>
Facilité de mise en oeuvre Investissements faibles	Faibles cadences de production Main d'oeuvre importante

# De la fibre à la coque

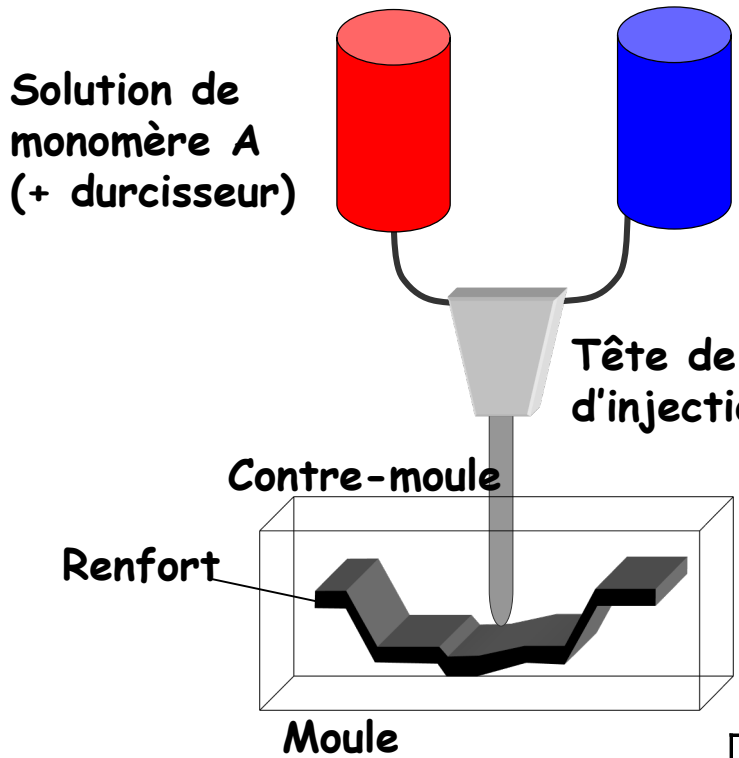


# Moulage à l'autoclave



Avantages :	Inconvénients :
Contrôle des paramètres Bonne qualité des composites	Investissements Faibles cadences de production

# Transfert et injection de résine



Reaction injection moulding (RIM)  
Resin transfer moulding (RTM)

TD et TP (Polyuréthane, PA)

Prépolymères réactifs

Version avec fibres courtes RRIM

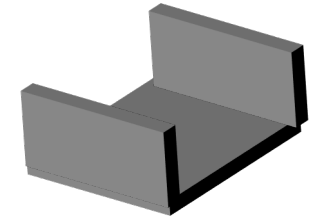
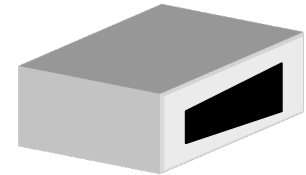
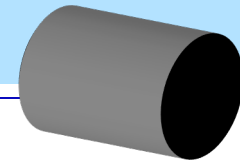
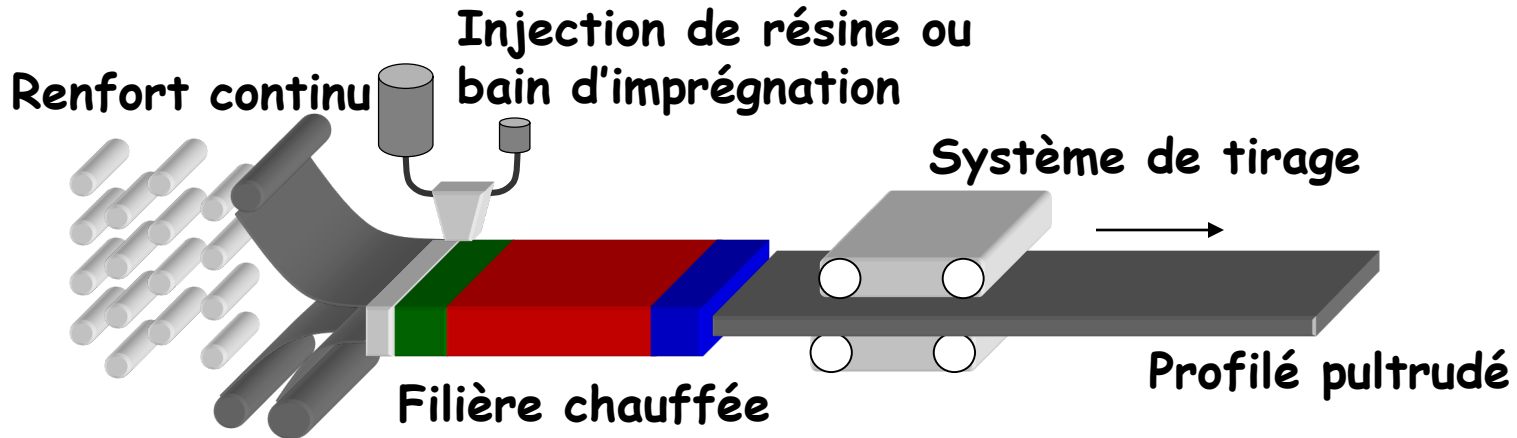
ou fibres longues dans le moule SRIM

Réaction dans le moule, après imprégnation



Avantages :	Inconvénients :
Faible consommation d'énergie Pression de moulage faible Possibilité de fabrication de grandes pièces complexes Cycles de moulage courts	Performances thermiques limitées

# Pultrusion

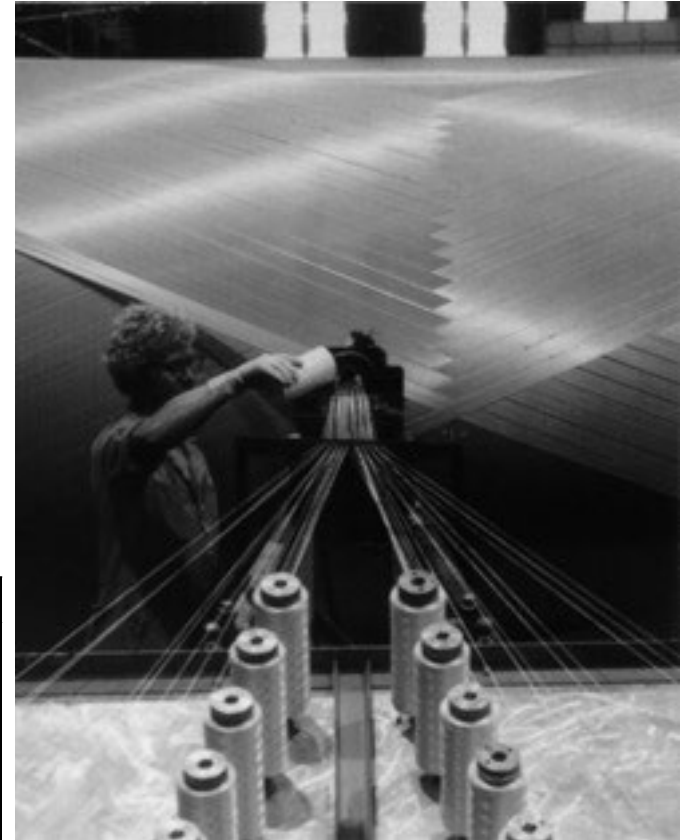
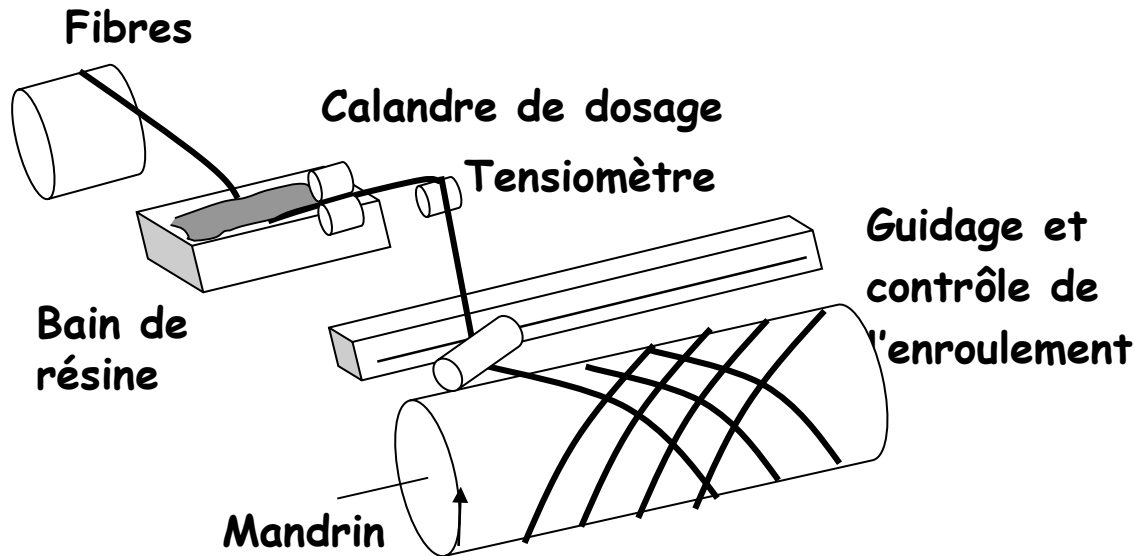


Surtout thermodurcissables et thermoplastiques  
Fibres sèches ou fibres préimprégnées

Avantages :	Inconvénients :
Méthode de production en continu Bon contrôle du pourcentage de renfort Grande automatisation possible Vitesses de production élevées Réalisation de formes variables	Investissements assez importants Limitations dans les variations d'épaisseur.

# Enroulement filamentaire

Réservoirs, réservoirs sous pression, tubes...



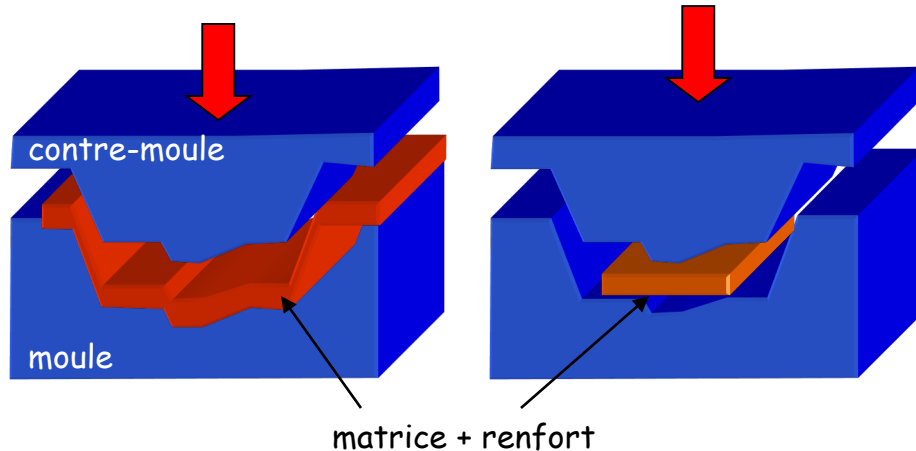
## Avantages :

Moulage de pièces de révolution, sans limitation de dimensions  
Face intérieure lisse  
Taux de fibres jusqu'à 80%  
Orientation des fibres dans le sens préférentiel

## Inconvénients :

Investissements importants  
Cadence de fabrication faibles  
Face extérieure brute

# Moulage par compression



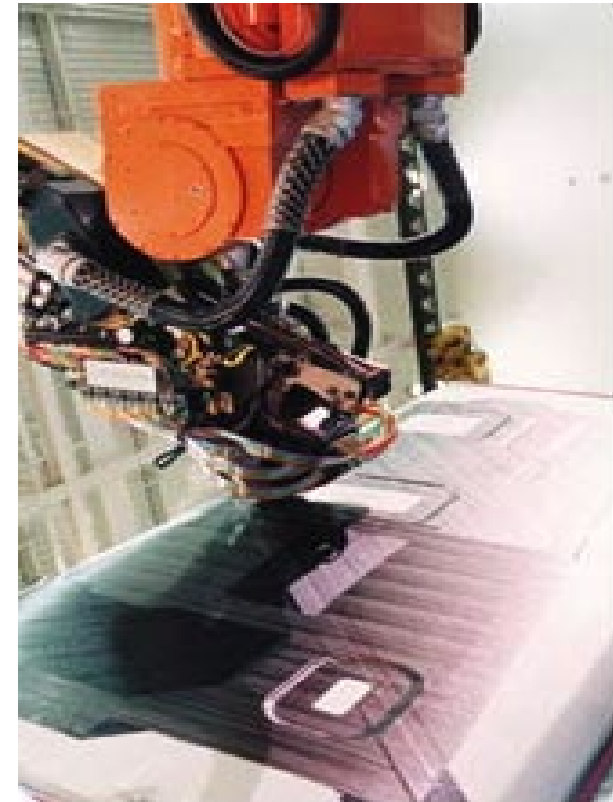
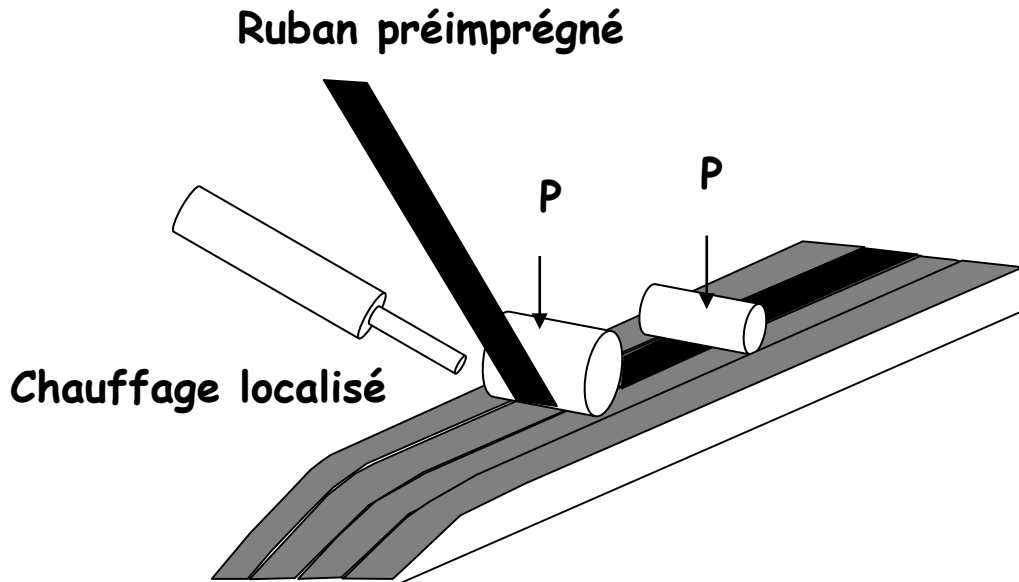
Thermodurcissables et surtout thermoplastiques  
Semi-produits à fibres longues :  
SMC: sheet moulding compound, verre+ polyester  
GMT, TRE: glass mat thermoplastiques, verre + PP

**Sans écoulement**    **Avec écoulement de matière**

Capots, carrosserie de voiture, camion, plaques semi-finies....

Avantages :	Inconvénients :
Moulages de pièces de grandes dimensions Qualité des pièces Cadences élevées	Coût de l'outillage Bavures importantes Dosage préalable nécessaire pour chaque empreinte

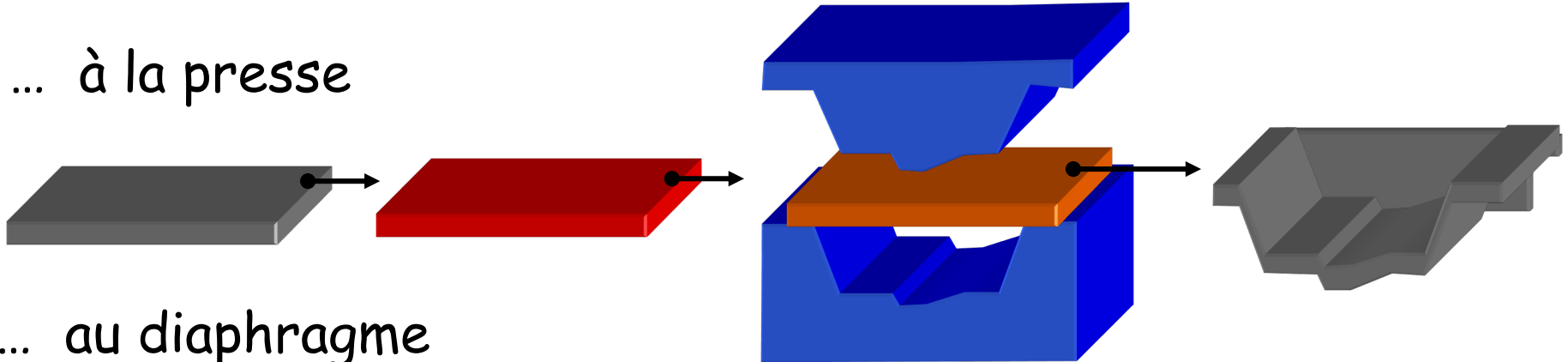
# Dépose de ruban



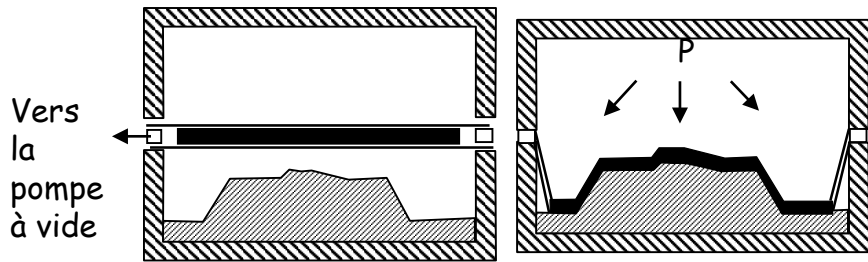
Avantages :	Inconvénients :
Automatisation Placement préférentiel des renforts Pièces convexes et concaves	Investissements importants Contrôle du soudage entre les rubans

# Thermoformage

... à la presse

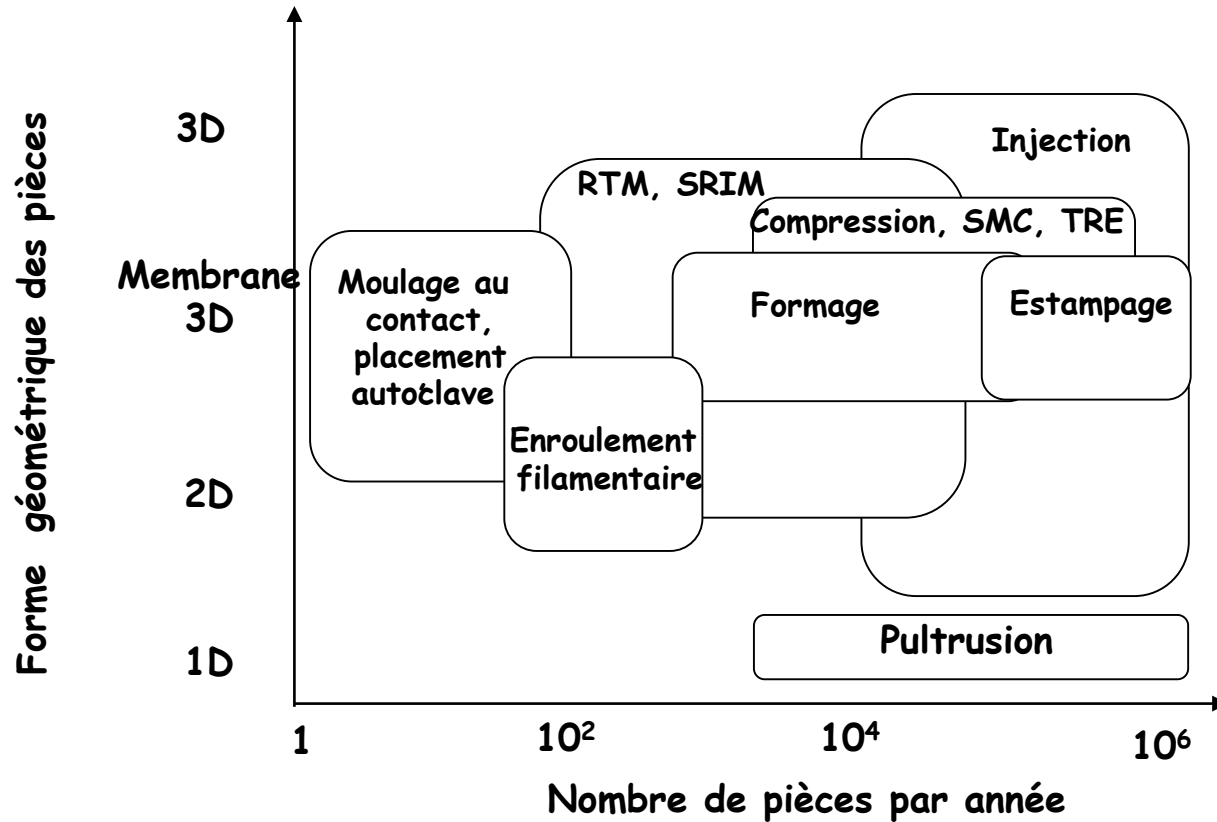


... au diaphragme



Avantages :	Inconvénients :
Formes complexes Cadences élevées Bonne qualité des pièces	Investissements importants Contrôle des transferts de chaleur

# Sélection

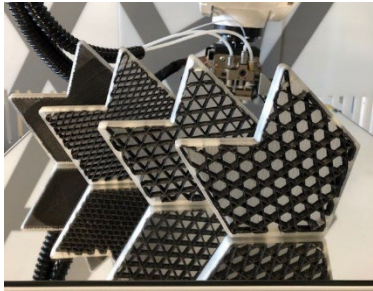


# Sélection

	Faibles volumes	Grands volumes
<b>Types d'industries</b>	Aérospatiale, militaire	Transport, ind. mécanique
<b>Performances désirées</b>	Rigidité et résistance spécifique élevées	Liberté de conception et de géométrie complexe
<b>Coût</b>	'peu' important	très important
<b>Prix des matériaux</b>	50 à 200 CHF/Kg	2 - 20 CHF/Kg
<b>Matériaux dominants</b>	Thermodurcissables et thermoplastiques avec des fibres continues	Thermoplastiques et thermodurcissables avec des fibres courtes
<b>Techniques de fabrication</b>	Dépose de préimprégnés, autoclave, RTM	Moulage par injection, moulage par compression, pultrusion

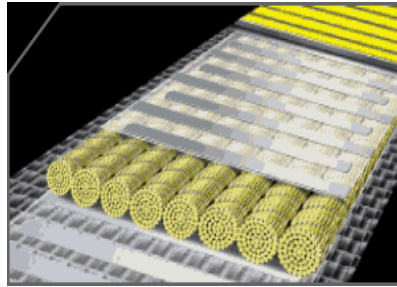
# R&D&A

## 3D printing

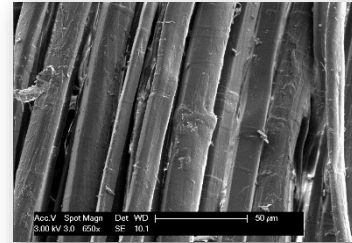


Anisoprint

## Functional composites

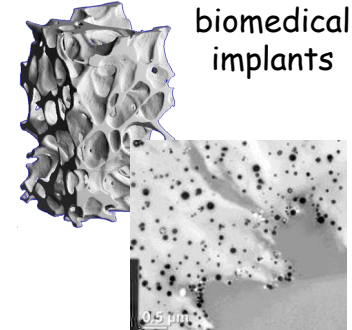


## Natural fibres composites

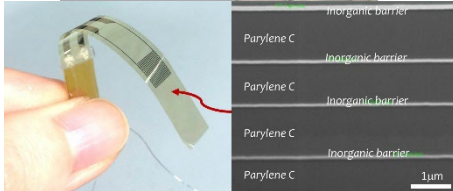
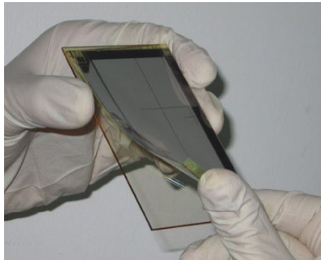


## Biocomposites

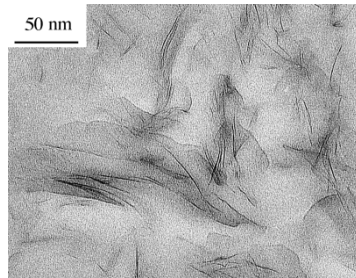
### Resorbable biomedical implants



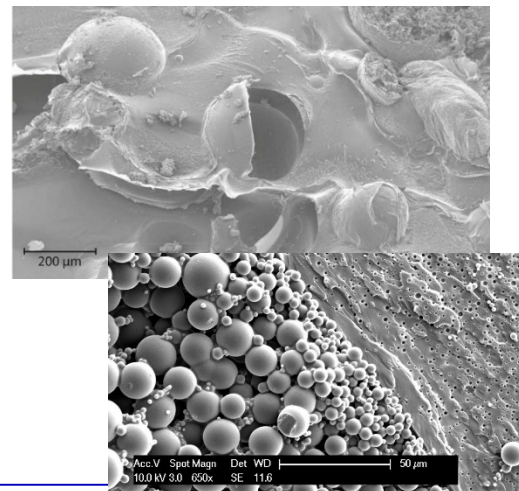
## Thin films and micro devices



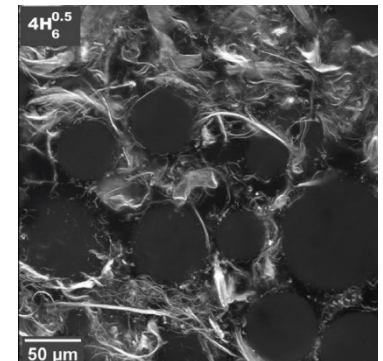
## Nanocomposites



## Self-healing composites



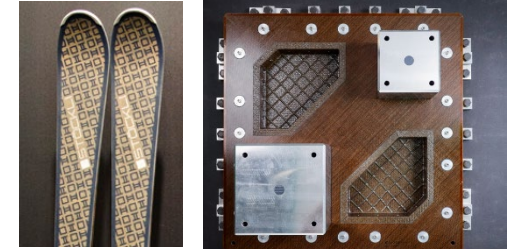
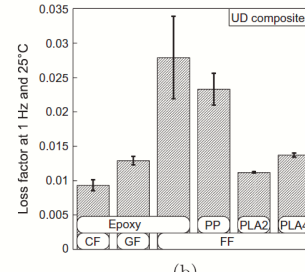
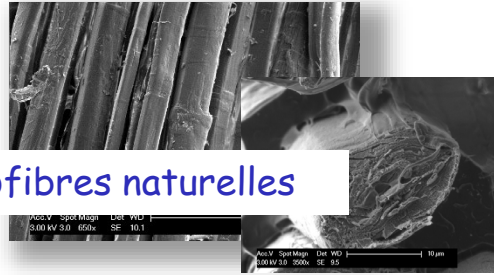
## Hydrogel composites



# Biocomposites

## Biocomposites à fibres naturelles

Amortir avec des biofibres naturelles



## Composites biodégradables

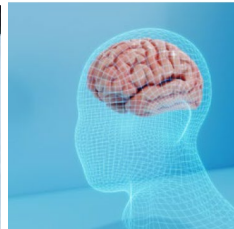
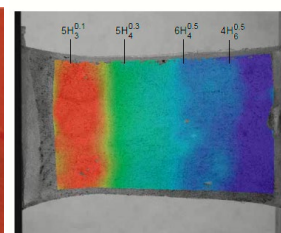
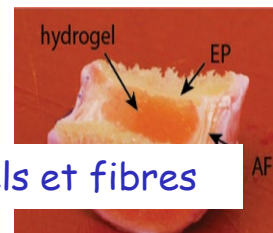
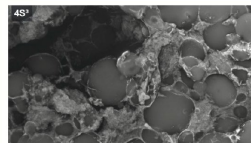
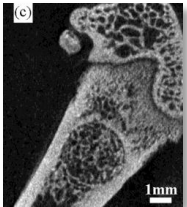
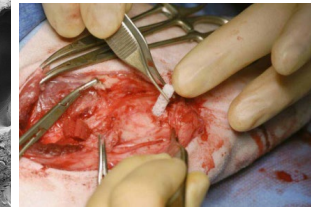
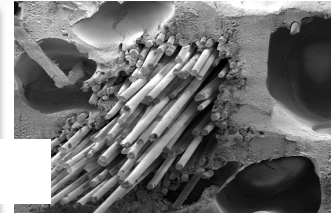
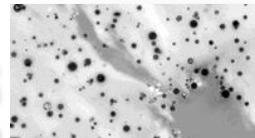
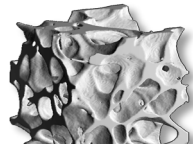
Mousses dégradables renforcées de fibres naturelles pour l'emballage



COMPOSI SMART-X natura

## Composites polymères pour le biomédical

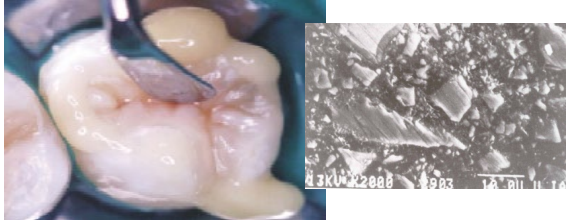
Implants résorbables de polymères et céramiques



Composites déformables et dissipatifs d'hydrogels et fibres

# Composites for dental restoration

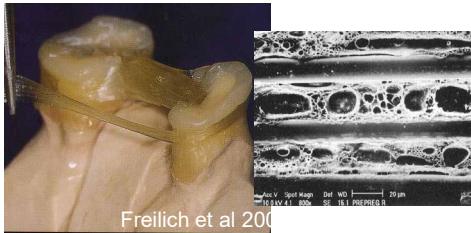
- Dental filling:** Acrylate resin +33-78 wt% (quartz, baryum glass, colloidal silica)



Material	$E_c$ (GPa)	$\sigma_c$ (MPa)
Composite resin	10-16	170-260
Dentin	11.0	39.3

**Challenges :** wear, brittleness, shrinkage

- Dental bridge, crowns, restorations:** dental resins + glass fibers, Kevlar or UHMWPE



Fibers	vol%	$\sigma_{\text{transverse}}$ (MPa)
UHMWPE	48	188
glass	33	265

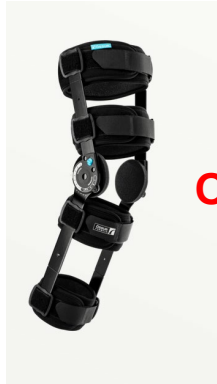
**Challenges :** impregnation, interfaces, shrinkage, conversion degree...



<https://www.dentapreg.com>

# Orthoses and prostheses

## Prostheses for sports



Orthoses

<https://www.ossur.com>



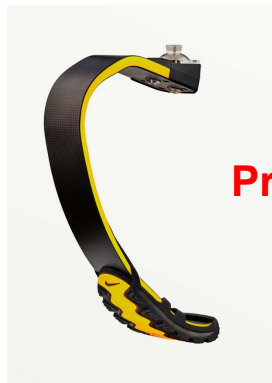
<https://www.ottobock.ch>



<https://www.plusport.ch/fr/>



<https://www.sofia-g.ch/>



Prostheses



## Preimpregnated carbon-epoxy

- (+) • lightness, tailored stiffnesses, minimum dimensions
  - fiber quality, quantity and orientation : prices
  - deformable parts, very elastic, strain energy
  - improved reliability and comfort
- (-) longer manufacturing, cost, testing device required



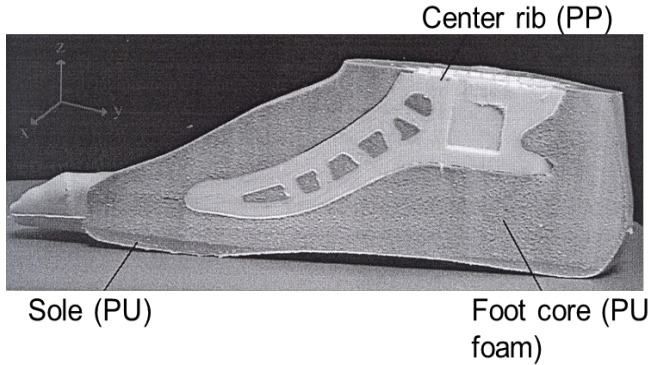
# Affordable Prostheses

ICRC

Minimal cost and maximal life time: feet for ICCR



http://www.icrc.org/eng/assets/files/other/eng-transnarral.pdf



Improve comfort via spring effect

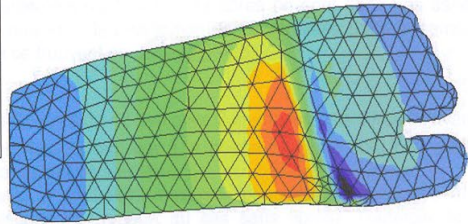
## Affordable all-terrain feet: ICRC's Agilis prostheses

5 May 2019, Health care / New technologies

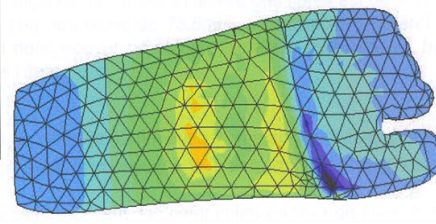
Challenge: fatigue cracks at the top of the center rib



Principal  
St.: 75%



S, Max. Principal  
(Ave. Crit.: 75%)



Without additional reinforcement  $\sigma_{max}=1.2$  MPa

With UD glass fibers  $\sigma_{max}=0.85$  MPa

### Reduction of stress concentration by adding fibres

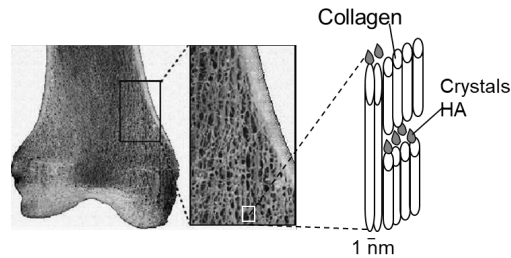
Gugolz, Rion, EPFL

<https://blogs.icrc.org/inspired/2019/05/05/affordable-feet-icrc-agilis-prostheses/>

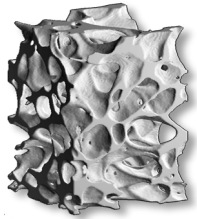
# Biocomposites

## Implants résorbables de polymères et céramiques

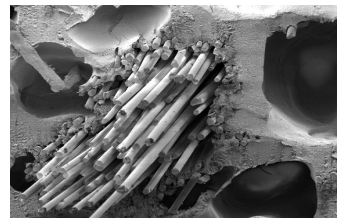
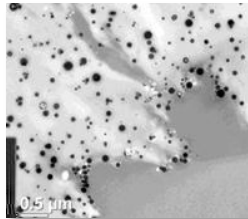
## Composites polymères pour le biomédical



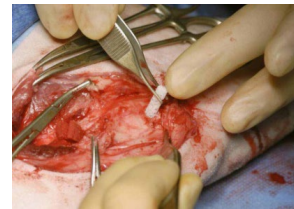
### Polymère biorésorbable



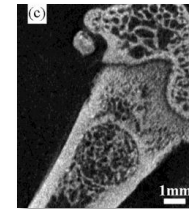
Procédé de moussage  
physique au CO<sub>2</sub>  
supercritique



Moussage avec  
particules et  
fibres de  
biocéramique



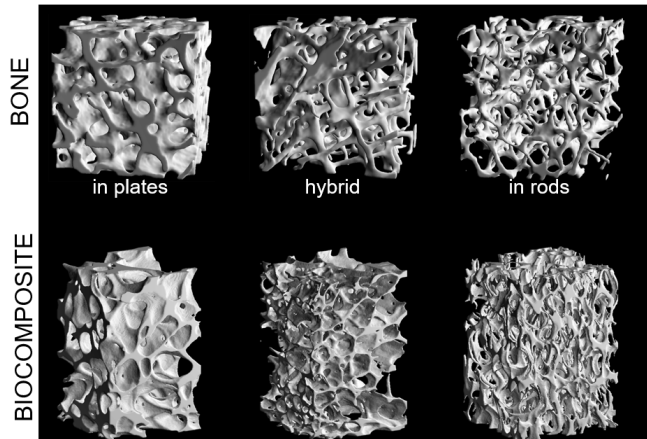
Propriétés in  
vitro et in vivo



Croissance de  
l'os naturel

# Cellular composites

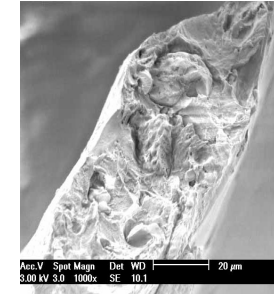
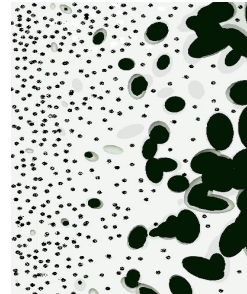
## CO<sub>2</sub> Physical foaming of thermoplastic polymers



Porosity gradient

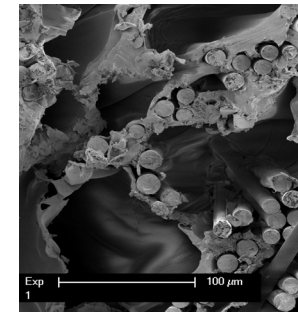


...with fillers

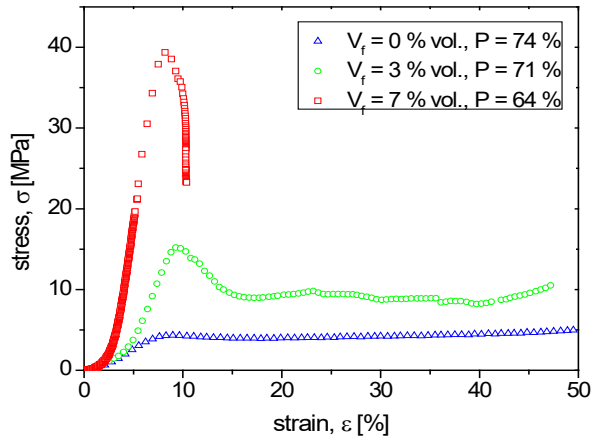


...MPa

+ gradient of long and continuous fibres



...GPa

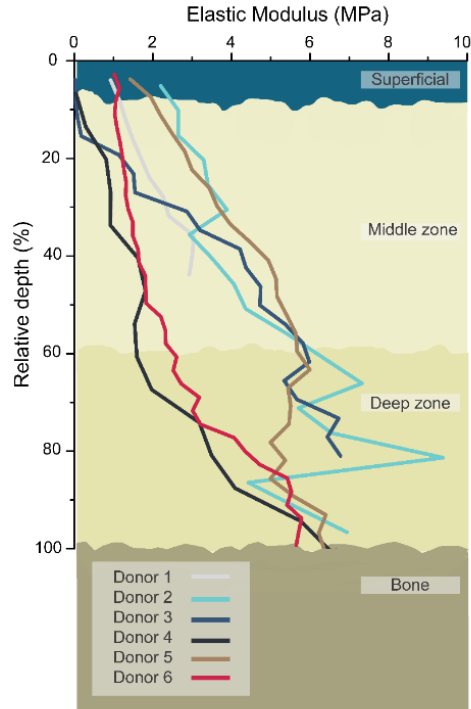


L. Mathieu

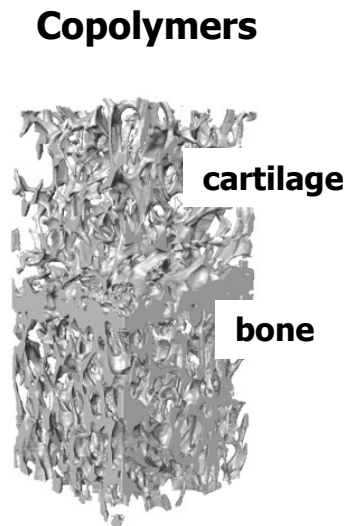


# Cellular composites

## Gradients of stiff and soft cellular implants

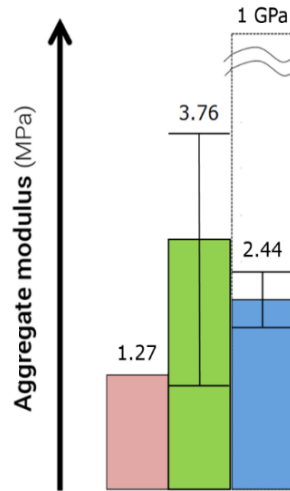


**Variation of modulus in cartilages**

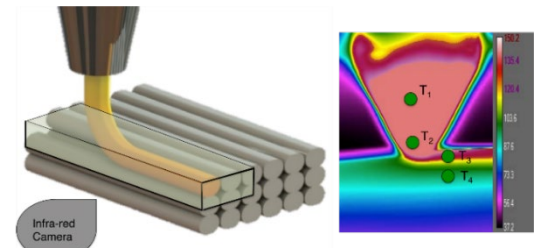


**Polymer composites**

M. Cuénoud



- PLAPCL raw
- Articular cartilage (literature)
- Articular cartilage (Chapter 4)
- Multi material foam PLAPCL - PLABTCP

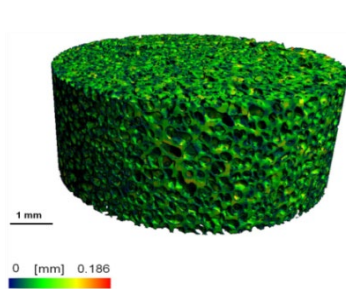


**Direct 3D foam printing**

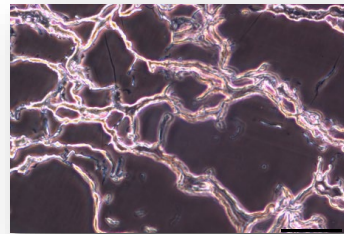
M. Marascio

# Biocomposites

## Composites **bi**odégradables



Procédé de moussage  
physique de biopolymères



Composites cellulaires de  
fibres de cellulose et bois



Emballages et structures  
temporaires



C. Boissard

# Biocomposites

## Implants déformables et dissipatifs d'hydrogels et de fibres

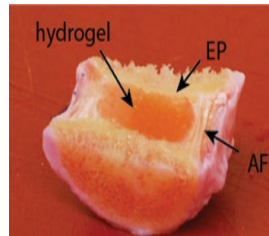
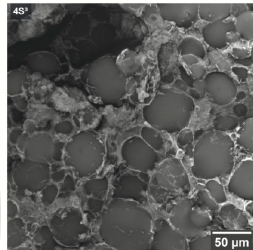
## Composites polymères pour le biomédical



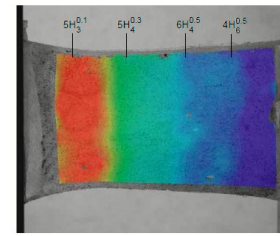
Hydrogels  
polymères



Auto renforcés in  
situ par des fibres  
de soie.



Propriétés  
dissipatives et de  
fatigue pour les  
disques  
intervertébraux



Gradients de  
déformation imitant  
ceux des tissus  
vivants



Iono-hydrogels pour  
atténuer les  
dommages au  
cerveau

C. Wyss et al, *Soft Matter*,  
2021,17, 7038

C. Wyss et al, *Extreme Mechanics  
Letters* 24 (2018) 66-74

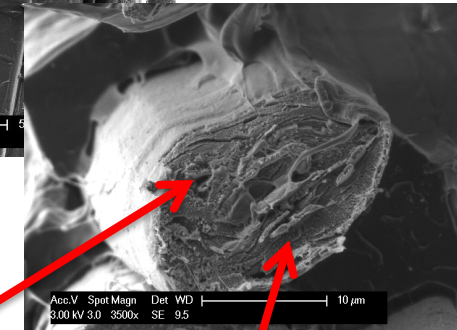
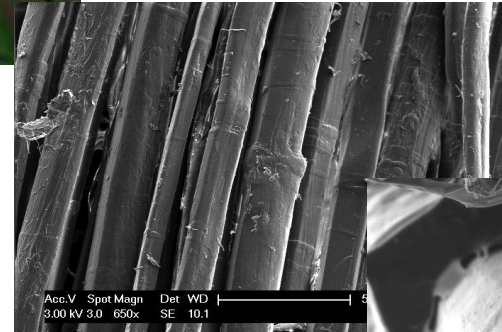
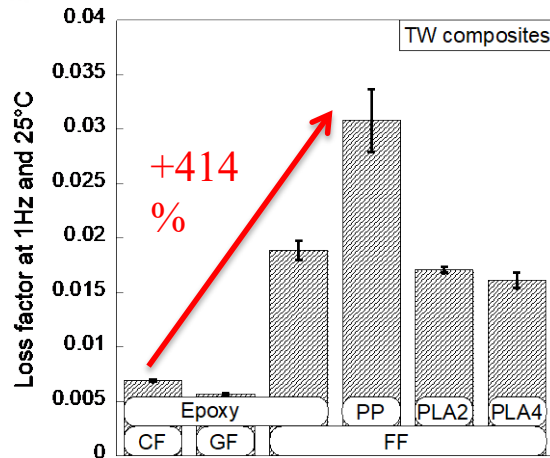
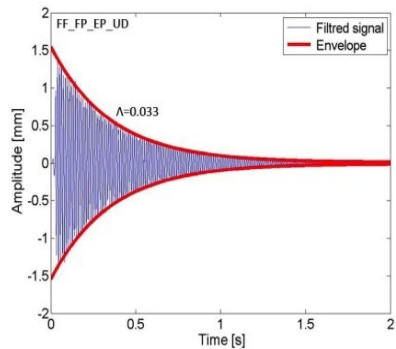
P. Karami et al, *Macromol. Rapid  
Commun.* 2021, 42, 2000660

V. Varanges et al, *ACS Appl. Eng.  
Mater.* 2024, 2, 2369-2378

# Biocomposites

## Biocomposites à fibres naturelles

Amortir avec des biofibres naturelles



**Inter-cell wall friction**

Friction between the cell walls

**Intra-cell wall friction**

Friction between cellulose and hemicellulose

Fabien Duc

# Natural Fibres Composites

## Thermoset NFC

- SMC, prepreg
- UP, Epoxy, VER, Phenolic
- Jute, flax, hemp...
  
- Modulus E ~ 10-20 GPa
- Strength ~ 200-300 MPa
- With fibre treatment : + 15-50% E



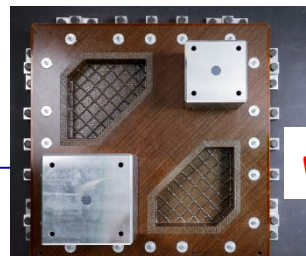
**Museeuw:**  
flax/carbon epoxy



**Artengo:** flax(5%)/  
carbon epoxy



**Stockli**



## Thermoplastic NFC

- Mainly GMT
- PP, PET, PE
- Flax, wood...
  
- E ~ 6 GPa (PP), 20 GPa (PET)
- Strength ~ 100 MPa
- specific properties higher than GF/PP



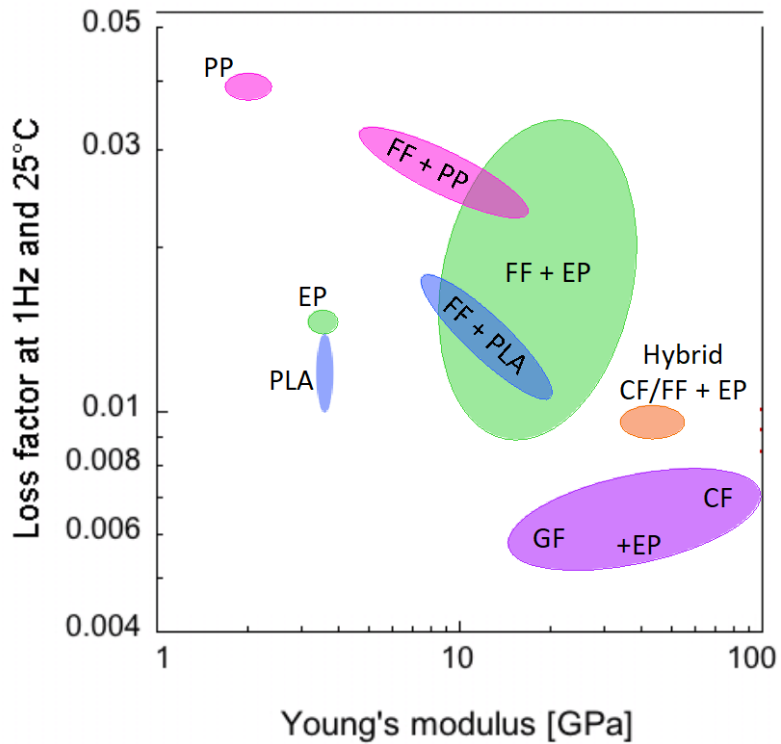
**Quadrant load**  
floor of the  
Porsche Cayenne:  
PP reinforced with  
40% kenaf, flax,  
wood and glass



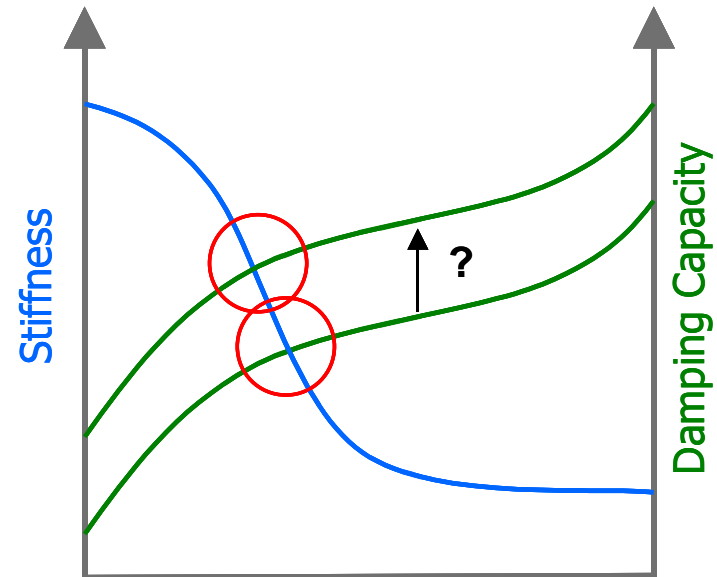
**FlexForm** door panel  
from the Mercedes M-  
Class and R-class:  
jute(50%)/glass PP

# Damping and stiffness

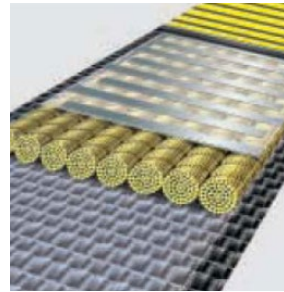
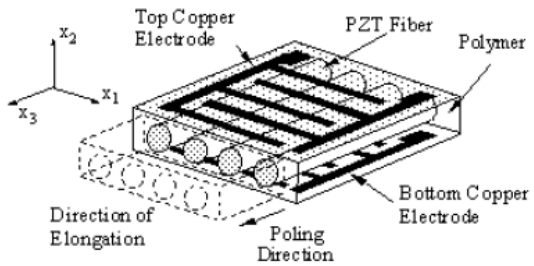
## Feel and control



Fabien Duc



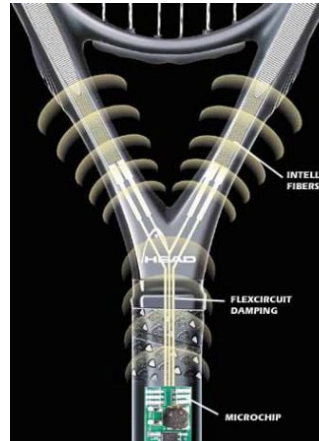
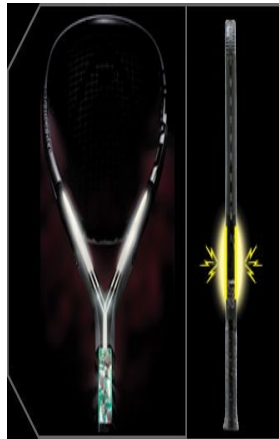
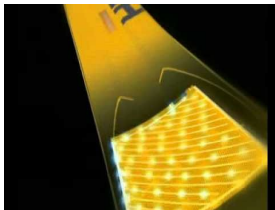
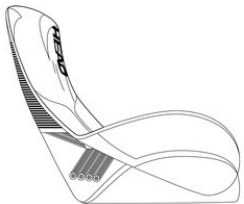
# Composites actifs



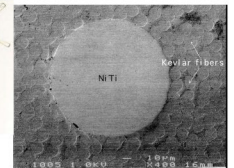
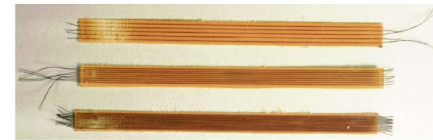
**Matériaux piézoélectriques**  
**Alliages à mémoire de forme**

**Vibrations et amortissements**

**Changement de formes**



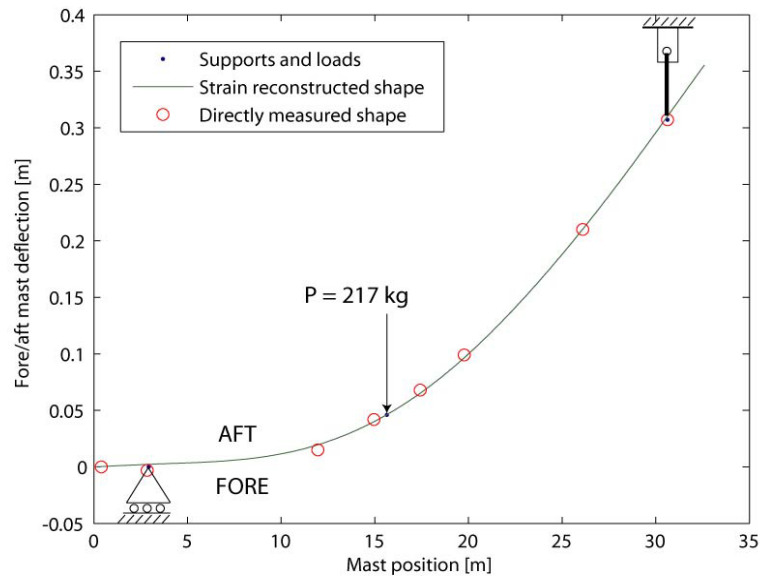
Head Intelligence Technology



Demonstrator manufactured in the ADAPT project

# Fibres optiques pour des mesures en temps réel

Déformations de matériaux,  
flexion de structures...



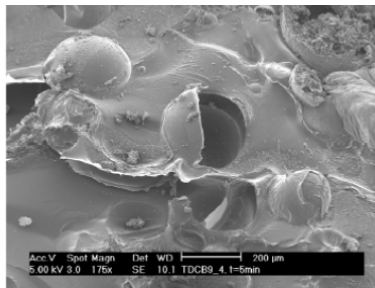
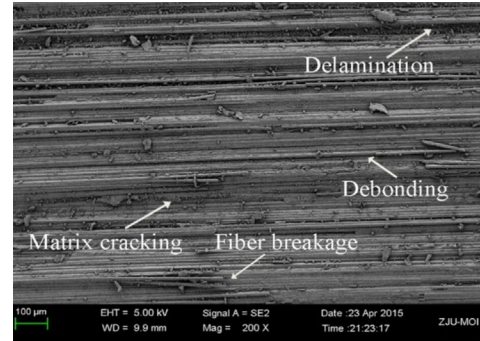
IOA-EPFL, D. Costantini  
Antoine Sigg Fiber Optic



# Composites auto-réparants

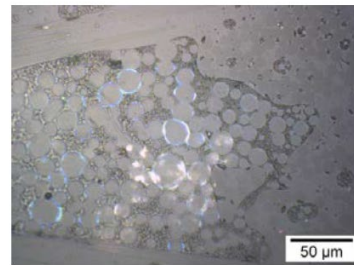
Cicatrisation, réparation des dommages engendrés lors d'impacts

Réparation des griffures de surface



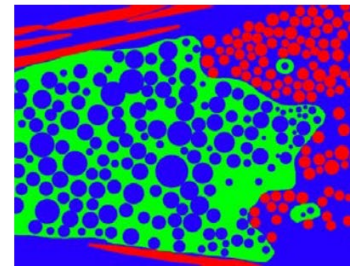
Kirkby, 2005

Microcapsules de monomères



Cohades, 2017

Mélange de polymères TD et TP



# Why polymer nanocomposites ?

**Increased strength and stiffness:** while maintaining the high elongation of the matrix.

**Permeation Resistance:** (plate-like fillers e.g. exfoliated clays) interest in nanocomposites barriers from packaging companies.

**Transparency:** low loadings and filler dispersion maintain inherent polymer transparency in thin sections (again interest for packaging)

**Recyclability:** nanofillers are not affected or degraded during processing → physical properties not seriously affected by recycling

**Flame resistance:** rapid char layer formation, excellent flame resistance

**Transport properties:** percolation at very low loadings in high aspect ratio systems, important for thermal, electrical conductivity (e.g. carbon nanotubes)

**Functionality:** bioactivity, hydrophilicity, magnetic and electrical properties etc. etc.

And all at loadings of a few wt%  
**weight saving!!**

Are nanofillers worth it? Examples (2019)

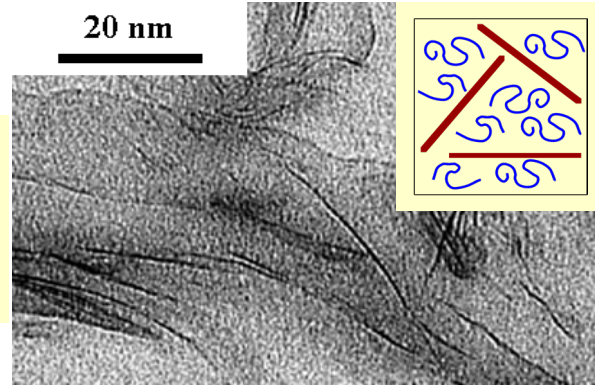
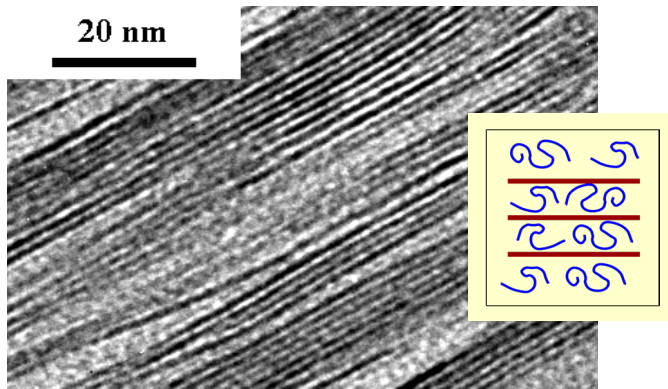
- Natural clays (mined, refined, and treated)—\$3–\$15/lb.
- Synthetic clays—\$10–\$20/lb.
- Nanostructured silicas—\$5–\$200/lb.
- Nanoceramics—\$100–\$280/lb.
- Nanotubes (carbon based, MWNT)—\$100–\$200/lb.

*Applications now include packaging, automotive, and wire and cable industries, and huge increase in demand for these fillers is projected*  
→ **Lower prices in the future**

# Nanocomposites

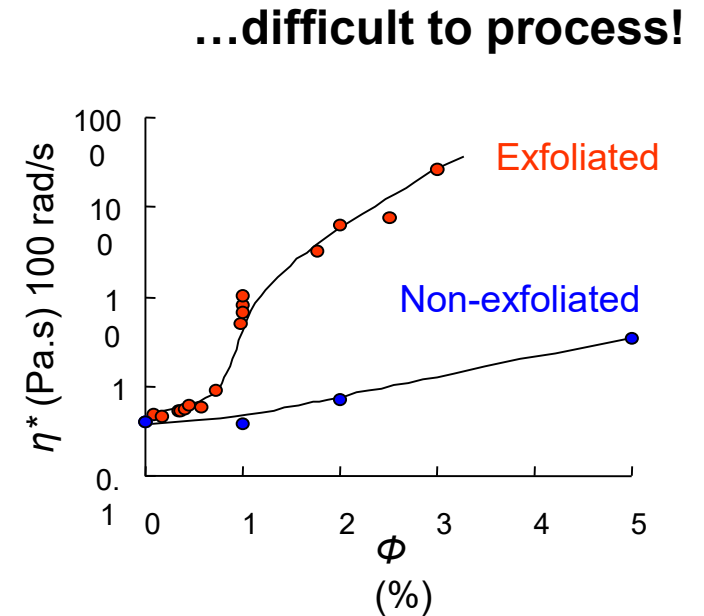
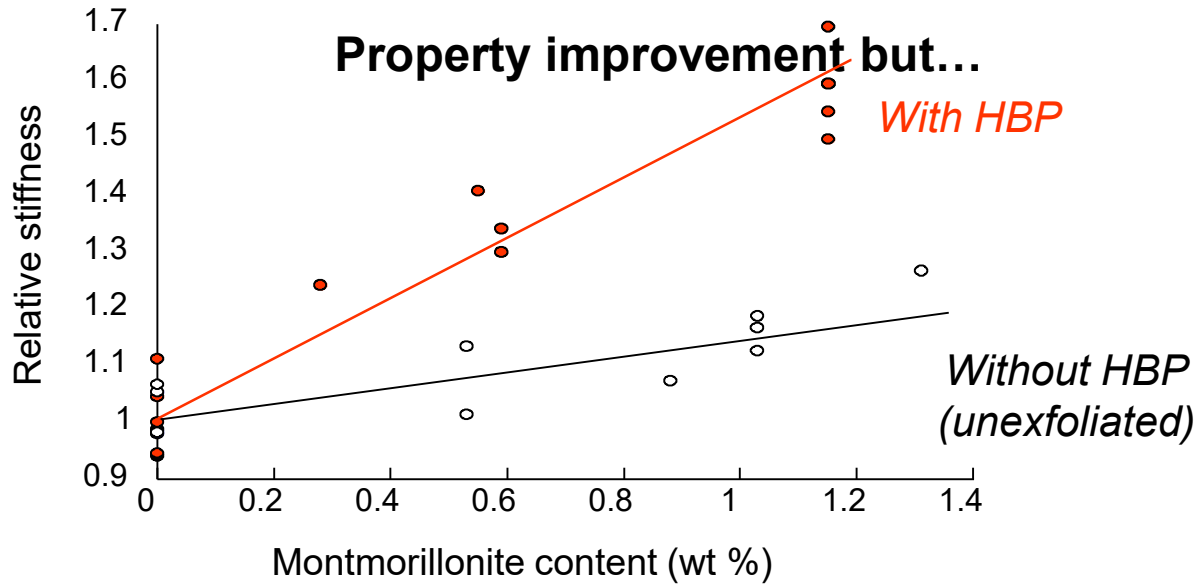
## Clay-based thermoplastic nanocomposites

Without HBP  
Non-exfoliated  
Silicate layers



With Hyper Branched  
Polymer HBP

Exfoliated

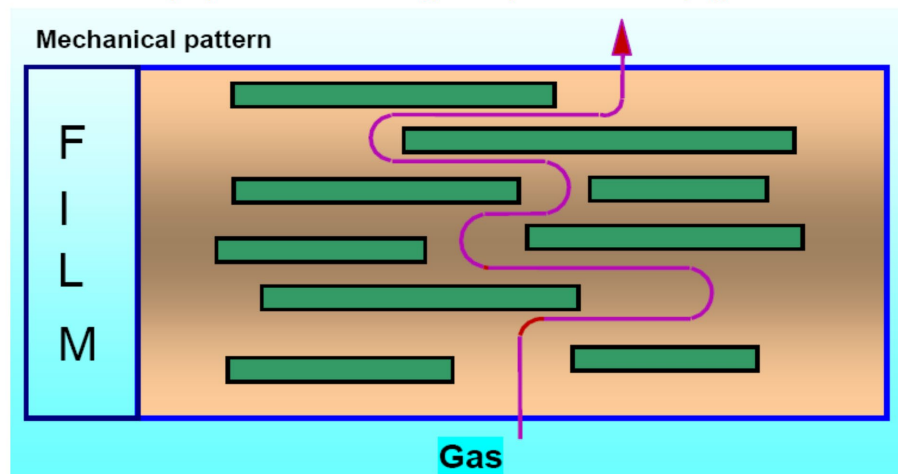


# Nanocomposites

Flame retardant properties

Barrier property improvements

*Improvement of barrier properties with montmorillonite layers oriented perpendicular to the diffusion path: "tortuosity effect"*

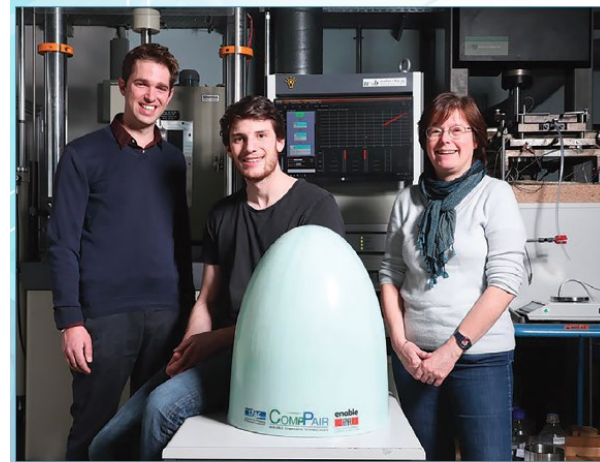


Electrical conductivity with carbon nanotubes or graphene

# à... de... avec... l'EPFL



<https://www.startup.ch/flyability>



Self-repair part developed at LPAC (JCM issue 128, May-June 2019)

**COMP**PAIR  
HEALABLE COMPOSITE TECHNOLOGIES

<http://www.comppair.ch>



Hublot watches

## Consumer electronics

Bcomp's powerRibs™ technology is also entering consumer electronic sector. With the outstanding stiffness-to-weight ratio combined to the high damage tolerance and low carbon footprint, powerRibs™ composite material is a novel solution for industrial designers and architects for reaching the best performance in a sustainable way. We are constantly working with the leading consumer electronic brands to come up with fully bio-based thermoplastic solutions in order to influence the market and make our world a better place to live.

<http://www.bcomp.ch/>

 **Bcomp**®

# Latest applications

## JEC Composites Magazine

### Observe and race

The Bolt disrupts the drone racing market with an easy-to-use and affordable carbon-fibre frame drone (US\$200 starting pack). This drone makes First Person View (FPV) piloting and racing available to everyone, as it offers three different control mods: Line of Sight, Screen on Controller, and First Person View (FPV) goggles. That means that drone racing is not left just to the pros, but is accessible to audiences of all skill levels. The Bolt Drone is the only complete set on the market that includes the carbon-fibre drone, an HD screen, FPV goggles, controller, and more.

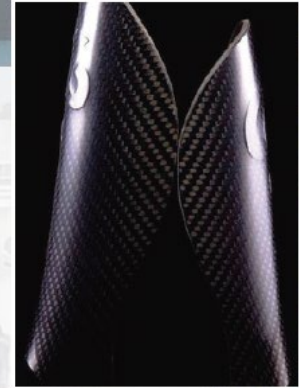
[www.boltdrones.com](http://www.boltdrones.com)



### Protect your body

The C6 weighs only half as much as other current shin guards (34 g vs. 74 g). The fourth generation of these shin guards feature a 100% aerospace-grade prepreg carbon fibre/epoxy shell. The increased carbon content for Gen 4 further improves its strength and shock resistance. The shin guards come with a lifetime guarantee and have been reviewed by the specialized soccer community and sports magazines as being the best ones on the market.

[www.c6agility.com](http://www.c6agility.com)



### More lightweight for off-road uses

The new HD Sport Edition Camera from Xcel is a user-friendly tactical action recording device, ideal for active outdoor enthusiasts and perfect for mounting on a car, boat, ATV or a helmet. Designed by the same company as SpyPoint range cameras, the Xcel HD camera captures beautifully sharp, full high-definition 1080p videos with sound and takes stunning 5 Megapixel high-resolution images. In the air, on land, or under water, the HD Sport Edition camera from Xcel allows you to replay, enjoy and share every moment of your action-packed day in virtually all weather conditions. Thanks to its carbon-fibre camera body, the Xcel Sport Edition weighs in at only 85 grams.

[www.spypoint.com](http://www.spypoint.com)



### Sturdy and shockproof

UAG iPhone Xs Max (6.5-inch) cases are ready to protect your iPhone from all drops, shock, and impact. The Pathfinder Series case encompasses a premium design and precise engineering to provide a case that meets double the Military Standard for drop & shock protection. Urban Armor Gear iPhone 10 MAX cases are an example of high-level engineering, boasting military-grade drop & shock protection for your iPhone. These also meet double the Military drop-test standards (MIL STD 810G 516.6). The Pathfinder Series Cases feature composite construction with an armour shell and impact-resistant soft core. Each case is equipped with scratch-resistant skid pads and screen surround for maximum device protection.

<https://urbanarmorgear.com>



# MSE 215

## Implementation (Mise en oeuvre (MEO))

MEO. Metals	MEO. Polymers	MEO. Ceramics
TPA	TPB	TPC
Heat treatments, Hardening	3D printing	Atomization, Dispersion of powders

## Properties (Propriétés (Pro))

Material Selection	Pro. Thermal	Pro. Mechanical	Pro. Optical
TPD	TPE	TPF	TPG
Selection of materials, Edupack	Expansion, Internal stresses	Stiffness, Toughness	Wave transmission