"Fusion based additive processing of biopolymers"

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AMIG 3.12.14

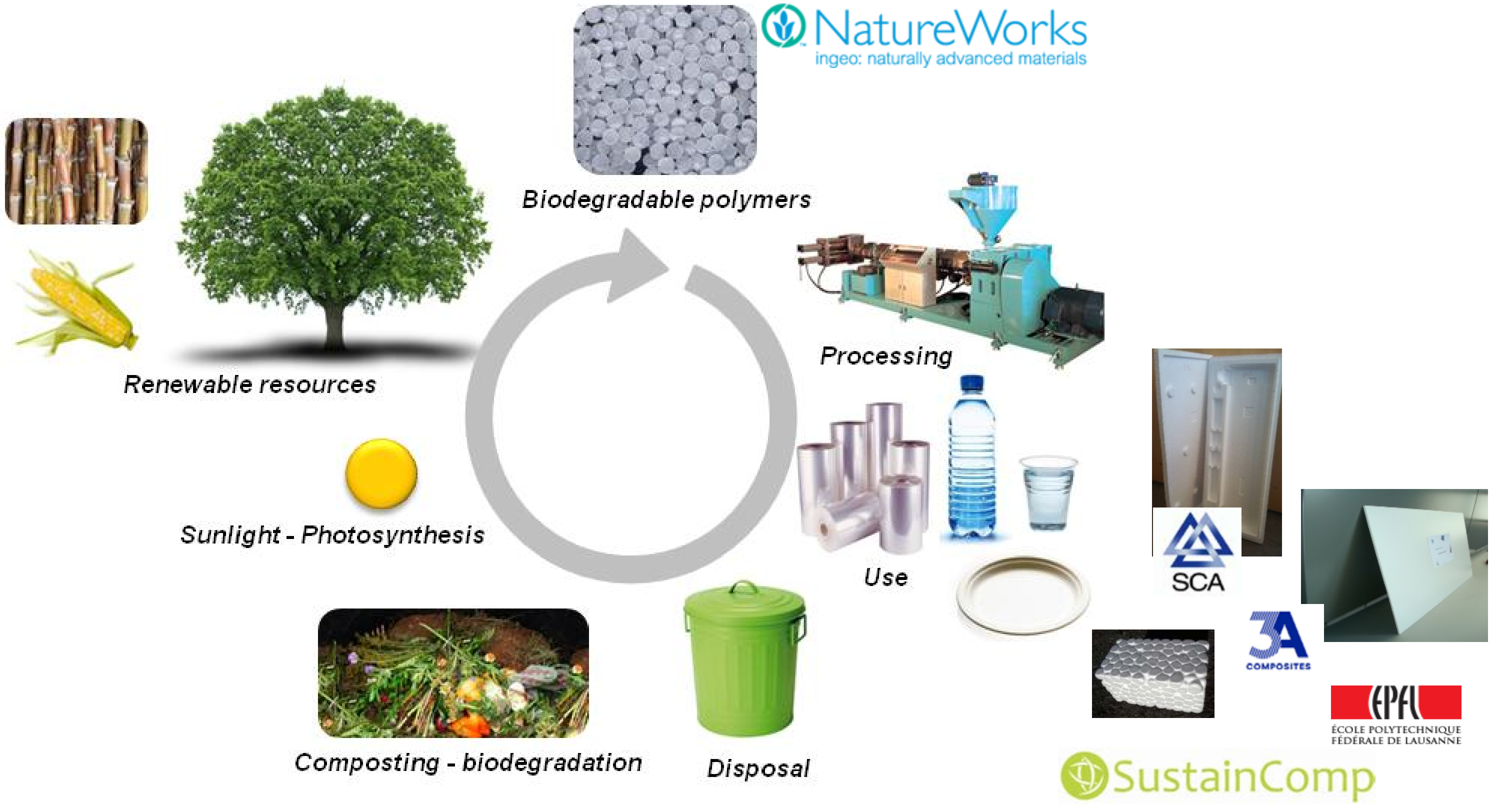
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Outline

- **Biopolymers**
  - **Renewable polymers**
  - **Biomedical grade polymers**
- **Processing**
  - **Fusion of thermoplastic polymers**
  - **Materials transformation phenomena**
  - **Processing biopolymer composites**
- **Additive manufacturing**
- **Current R&D**
- **Applications**

Biopolymers

- **Renewable polymers**
  - **From petroleum and from waste vegetables**
  - **The ‘ Polylactide (PLA) ’ family**



Biomed polymers

- **Biocompatible polymers**
- **Bioresorbable polymers**

Composite
ortho and prostheis

ICRC Limb prosthesis

Stryker Primary Knee
Replacement System

Medtronic Talent
Abdominal Stent Graft

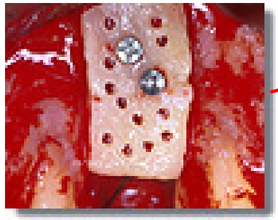
RootReplica®
(Sunstar DS AG)

Biomed polymers

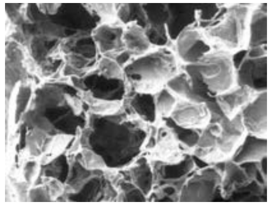
Custom-made complex shapes

Sutures

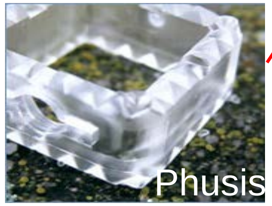
Dental membranes

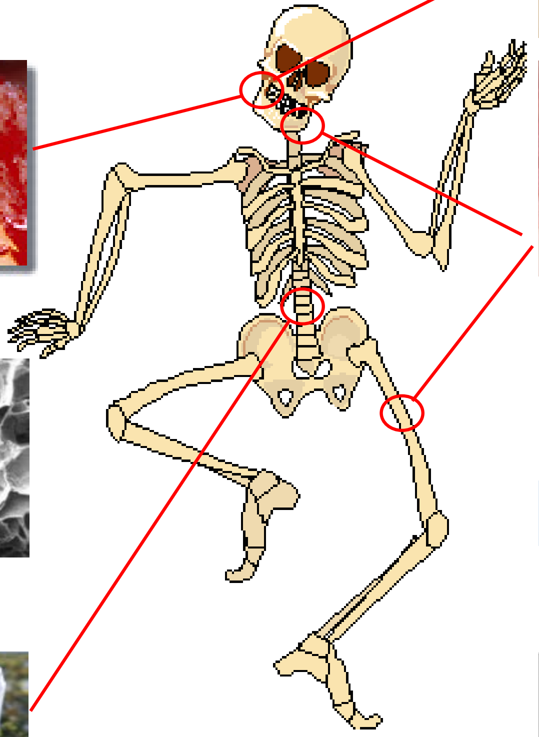


Matrices for tissue engineering



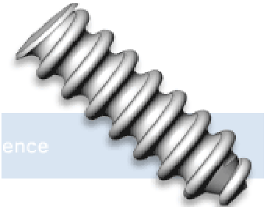
Vertebral cages



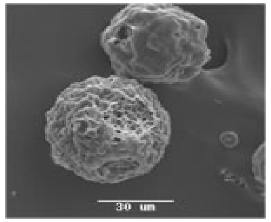


Fixation elements for maxillofacial surgery

Biomaterials for bone augmentation



Bioresorbable screws (fixation)



Drug release

It’s about scale

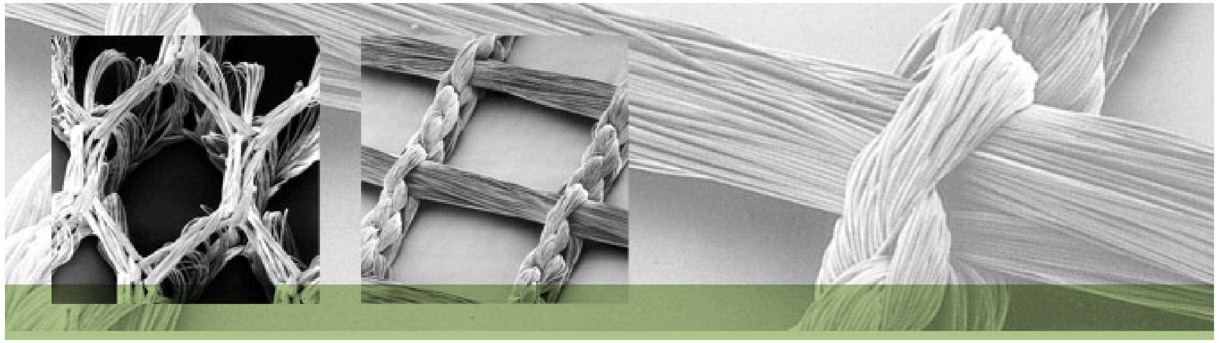
- **Material structure at different scales**
- **Processing steps to control the structure and properties**
- **Scaling up to product**

Macro-meso-micro

Fibres

- **Textiles**

http://www.bmsri.com



Sofradim Covidien.com

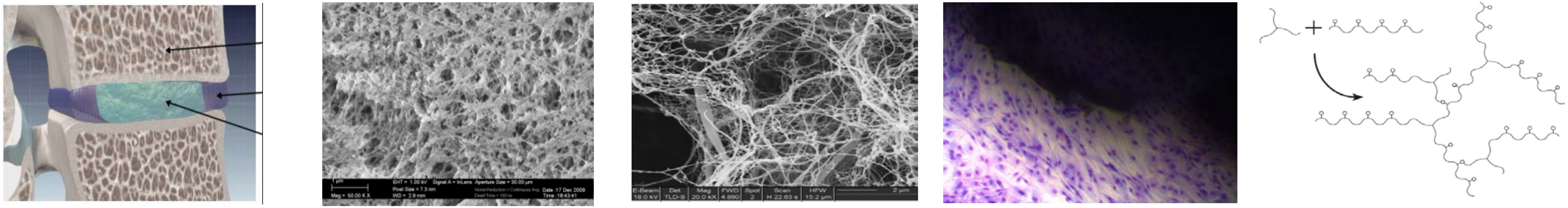
cm mm µm

- Yarns of fibres are placed and oriented to optimize local stiffness
- Non-wovens, wovens, knitted, embroidered textiles
- Angiogenesis, vascularization

Macro-meso-micro-nano

Hydrogel

- **Hydrogel Biocomposites**



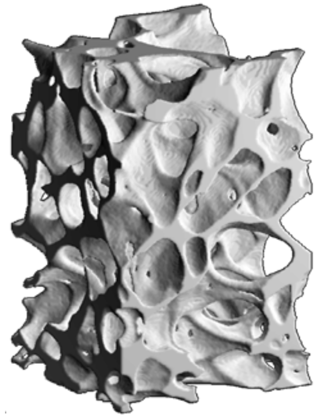
cm mm µm nm

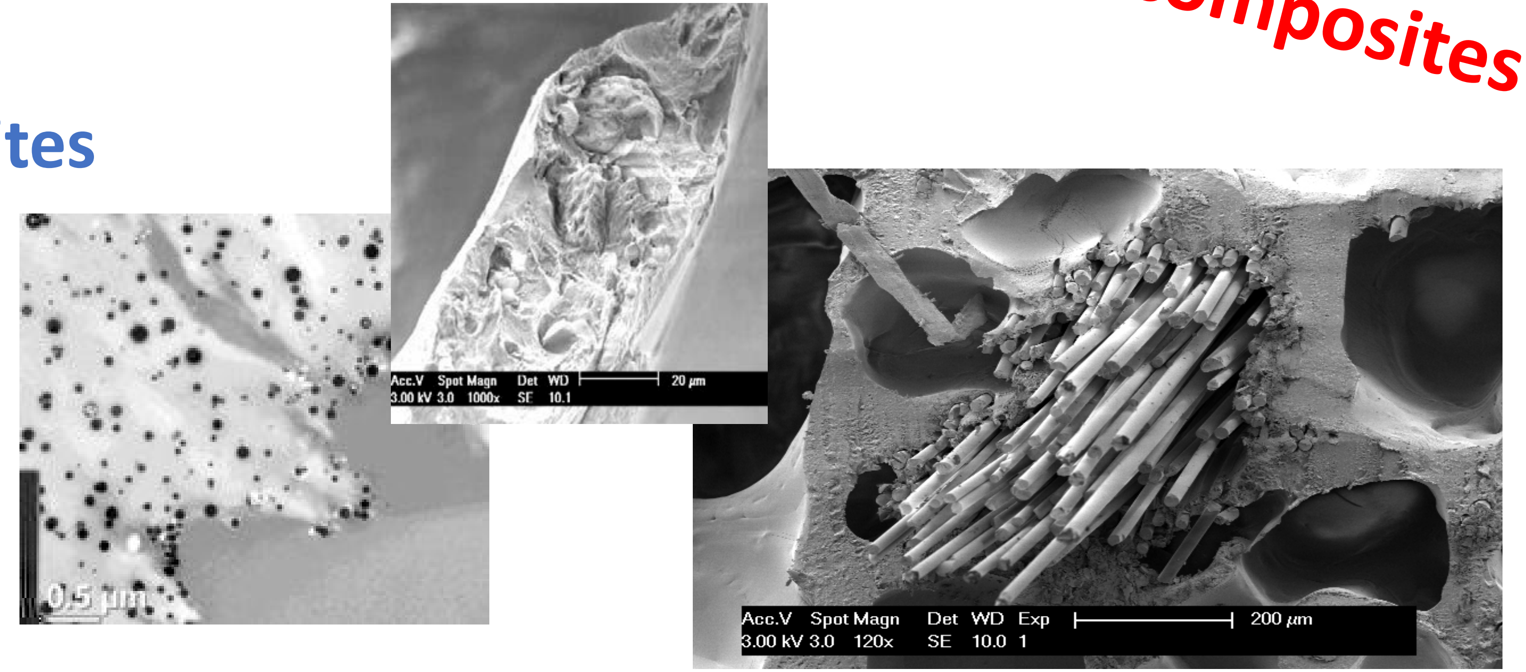
- Soft porous polymers containing liquids
- Photo-hydrogels reinforced by a network of cellulose microfibrils
- Stifness, swelling… tailored by the level of molecules crosslinking

Macro-meso-micro

Bioresorbable polymers and composites

- **Polymer Cellular Biocomposites**





cm mm µm

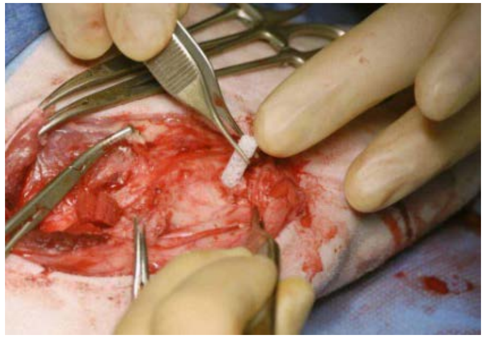
- Particles are processed into polymers for stiffness and osteoconductivity
- Yarns of fibres provide anisotropic composite foams
- Bone regeneration

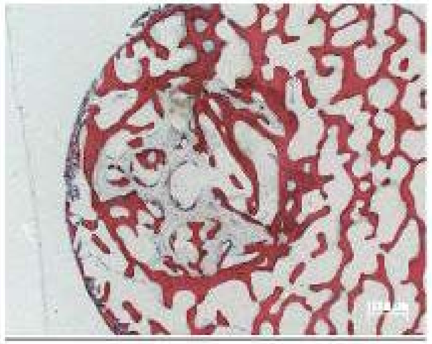
EPFL: LTC-LBO

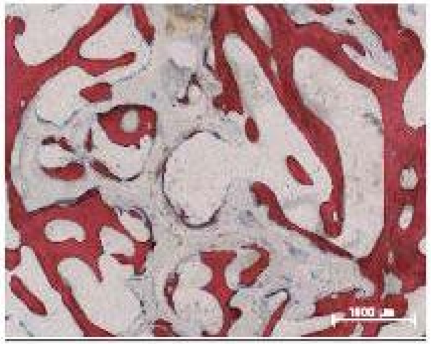
Macro-meso-micro

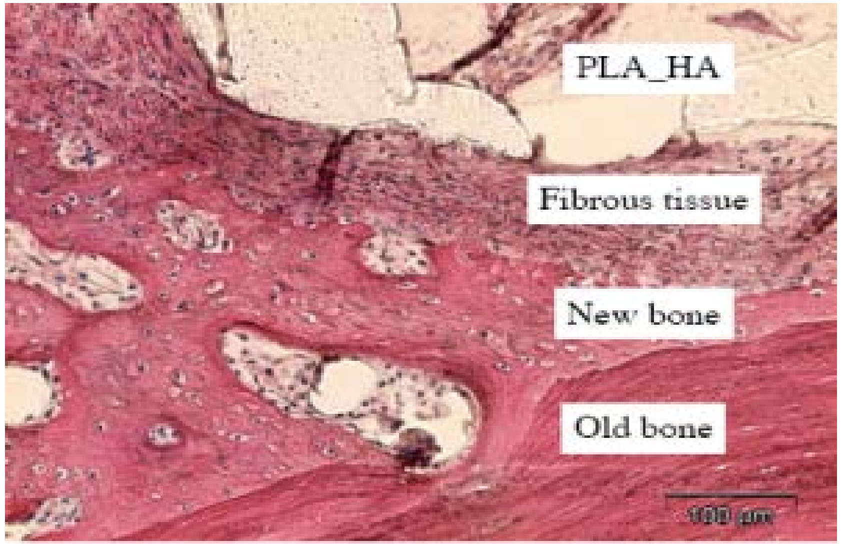
Bio-performance

- **Interfaces: Material-Living tissues**









cm

mm

µm

EPFL: LTC-LBO

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AM of polymers

Processes

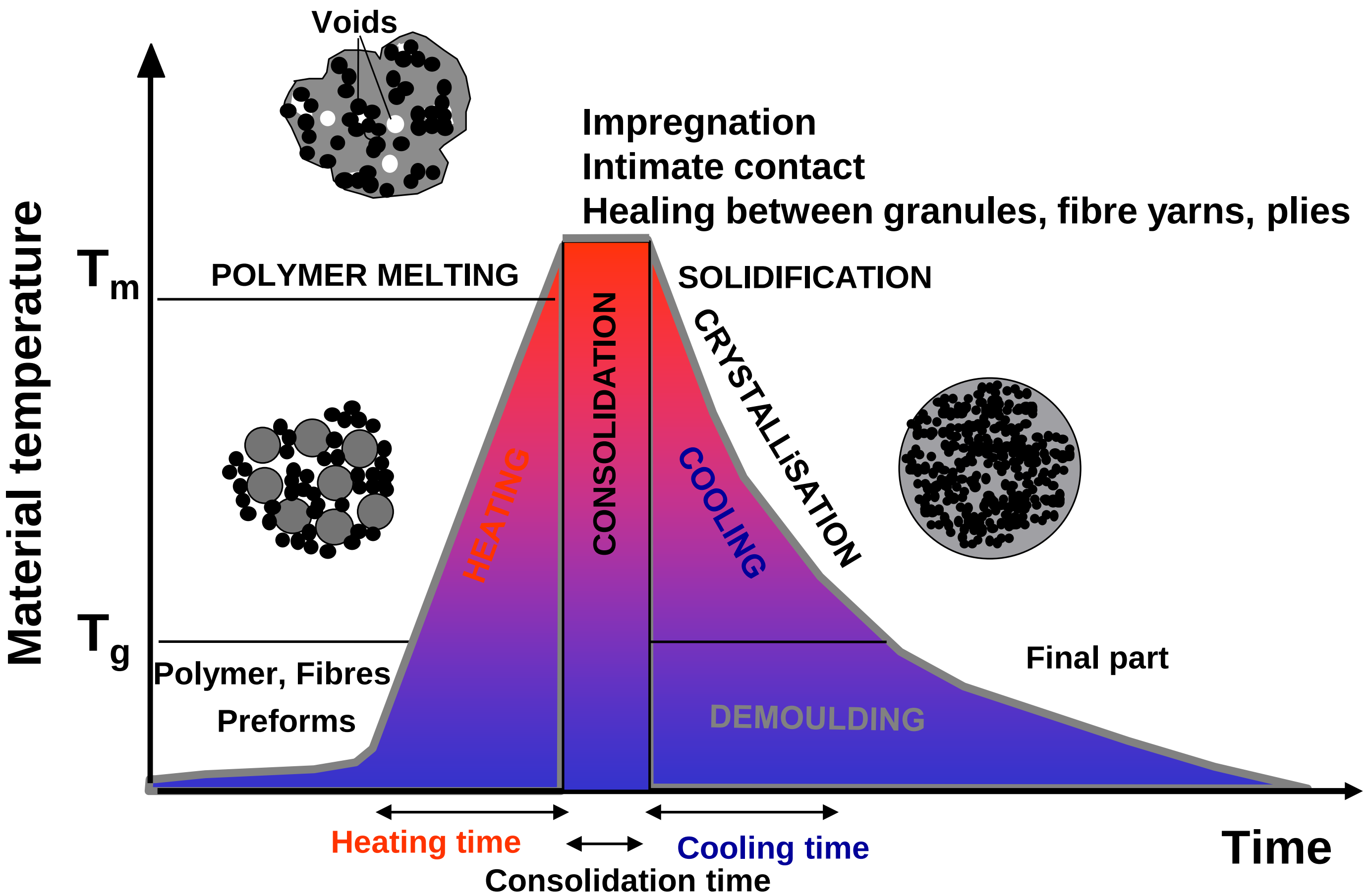
- **Nozzle based processes**
  - **Molten polymer**
    - **Extrusion**
    - **Fused Deposition Modelling, FDM**
    - **Filament Deposition**
  - **Liquids, binders**
    - **3D printing**
- **Light-based processes**
  - **Stereolithography, SLA**
    - **Mask-based or direct writing methods**
  - **Selective laser sintering SLS**

Materials

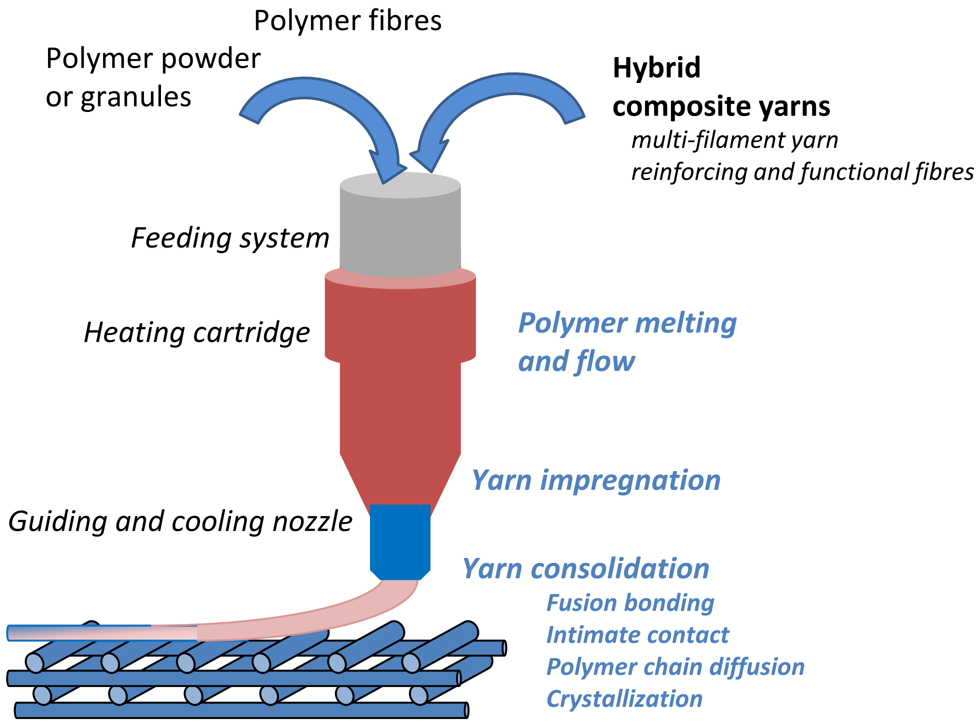
- **Thermoplastic polymers**
  - **ABS**
  - **PC**
  - **PA**
  - **PEEK**
  - **Polycaprolactones PCL**
  - **Polylactides PLA, PGA,**
  - **Copolymers, blends**
  - **PEOT/PBT**
- **Photo-polymers**
  - **Hydrogels, PEG, PEG-MA, PLA-PEG**
  - **Modified PCL, polytrimethylcarbonate…**
  - **Limited choice of photo-polymerizable biomaterials**
- **Conductive polymers**
  - **Polyacetylene**
  - **Polypyrrole**
  - **Polythiaphene**
  - **Polyaniline**

Processing thermoplastic polymers

- **Material transformation phenomena and window**
- **Processes and processing windows**

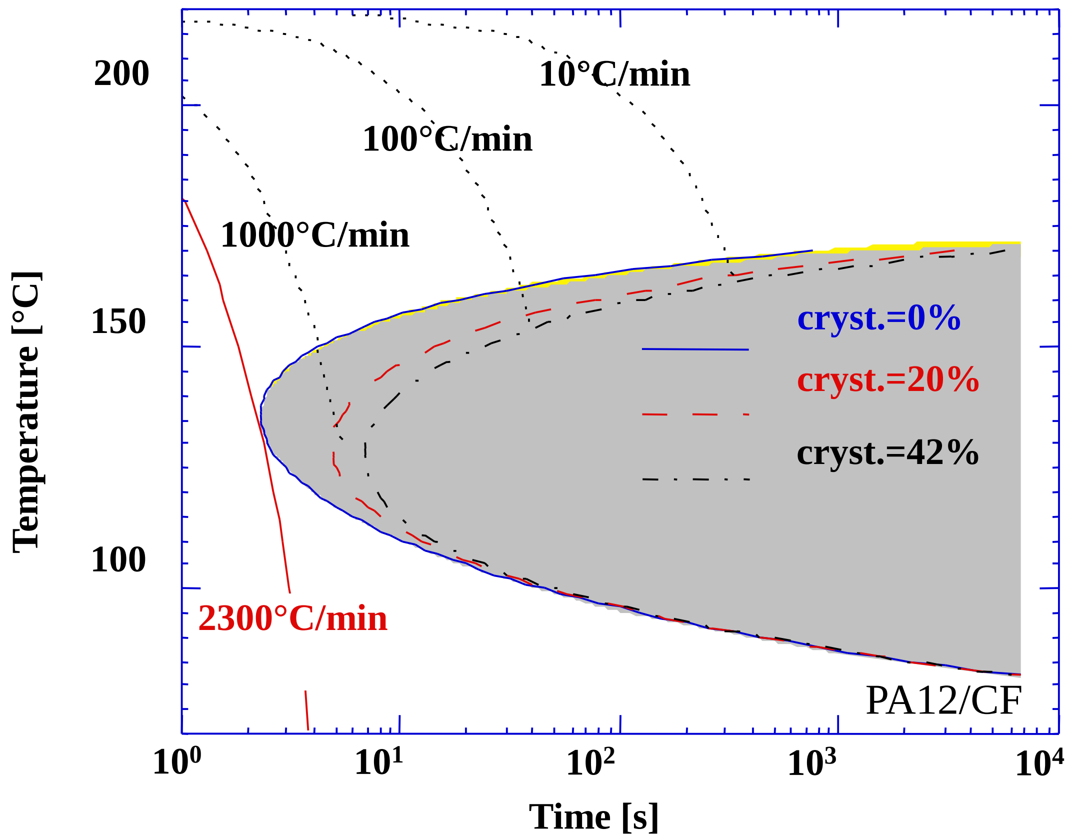


Fused Deposition Modelling

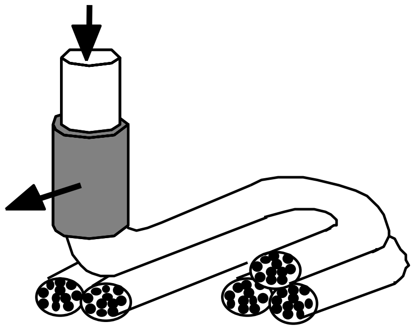


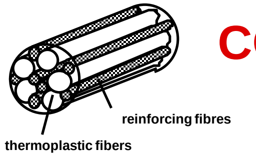
Consolidation : crystallization

PA12

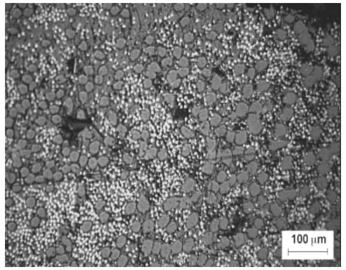


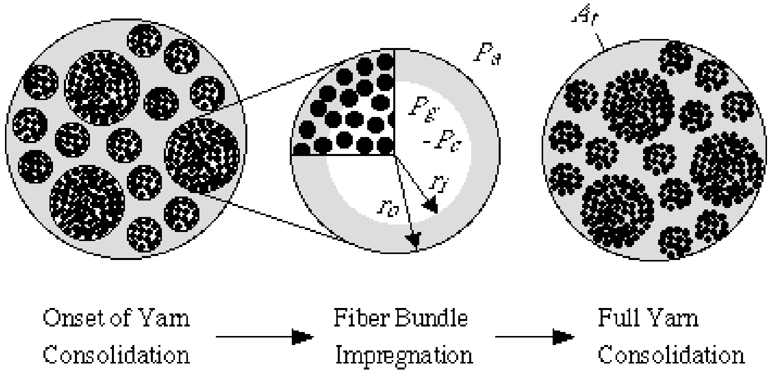
Consolidation : porosity content





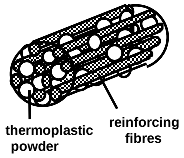
COMMINGLED YARN (CY)



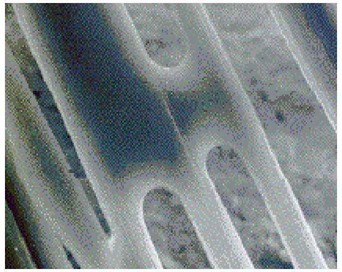


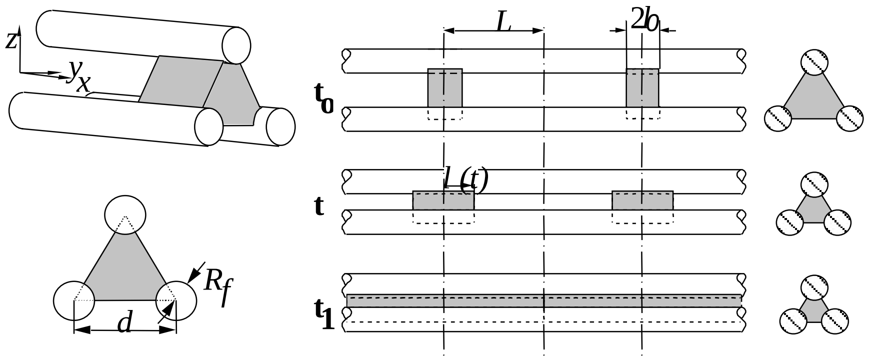
$$\Delta t = \frac{\eta(1-V_f)}{K\ (P_a + P_c - P_v(r_i))}\left[\frac{r_i^2}{2}\ln\left(\frac{r_i}{r_o}\right) - \frac{R_i^2}{2}\ln\left(\frac{R_i}{r_o}\right) - \frac{r_i^2}{4} + \frac{R_i^2}{4}\right]$$

$$X_v = \frac{\sum_{k=1}^{n} \pi N_b^k r_k^{k\,2} (1-V_f)}{A_t + \sum_{k=1}^{n} \pi N_b^k r_k^{k\,2} (1-V_f)}$$



POWDER IMPREGNATED TOW (PIT)



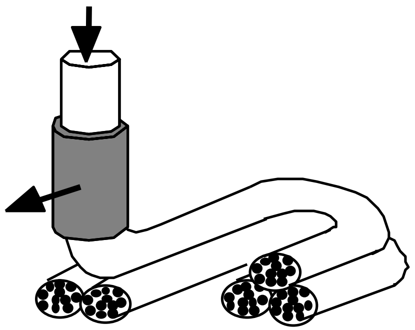


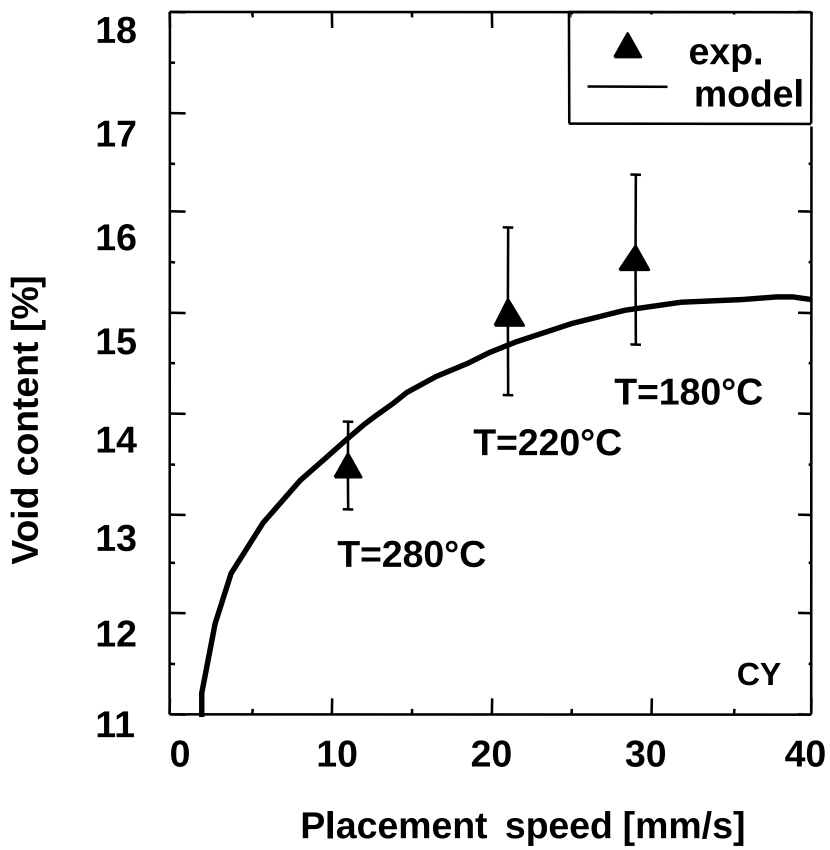
$$t_{impregnation} = \frac{128}{135}\frac{\eta}{P_a}\left(\frac{V_{fl}}{V_{ml}}\right)^4 \left(\frac{R_m}{R_f}\right)^6 \left[\left(\frac{l}{L}\right)^5 - \left(\frac{l_o}{L}\right)^5\right]$$

$$X_v = \frac{1-\left(\frac{l}{L}\right)}{1+\left(\frac{l}{L}\right)\left(\frac{V_{fl}}{V_{ml}}\right)}$$

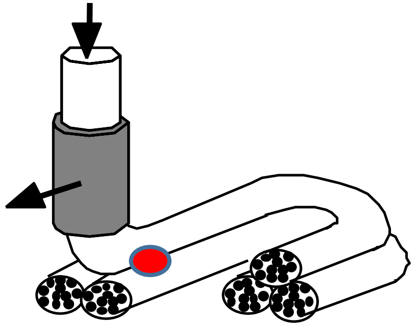
Processing thermoplastic polymers

An example: Yarn placement

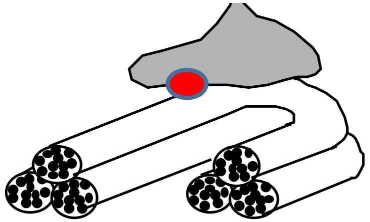


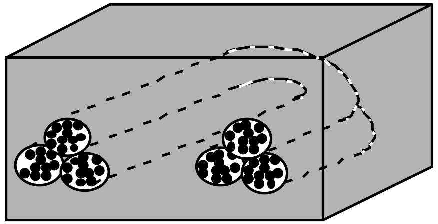


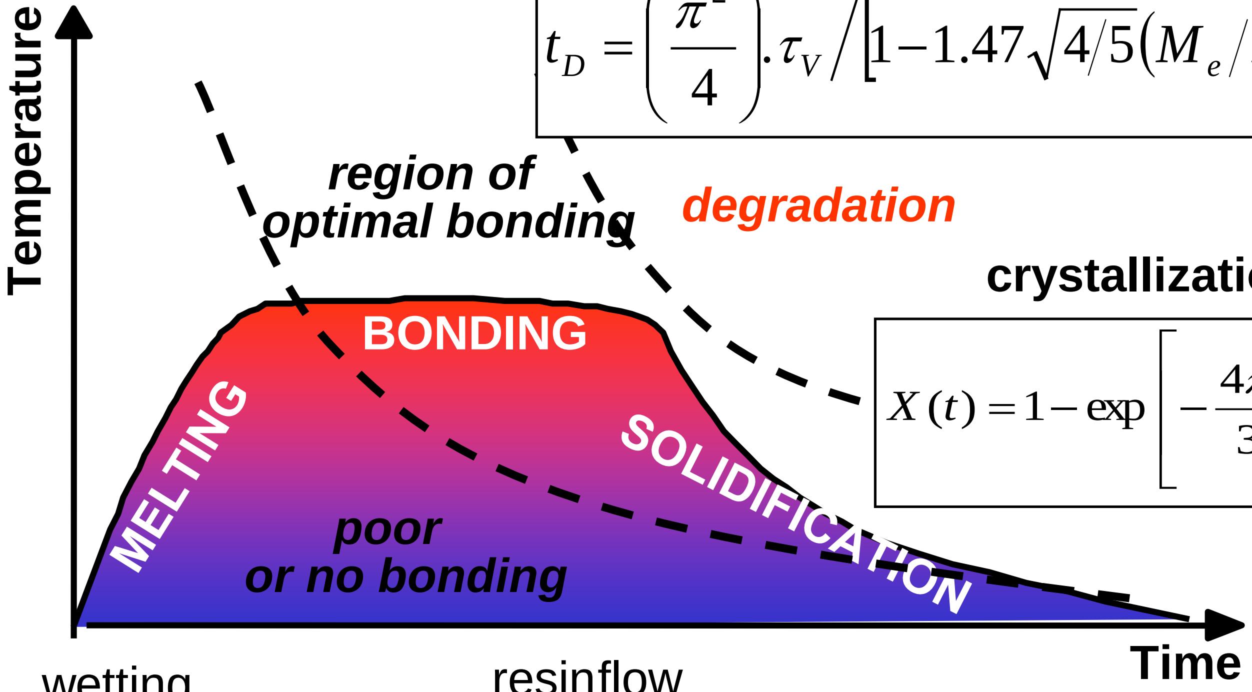
Fusion bonding



Polymer injection



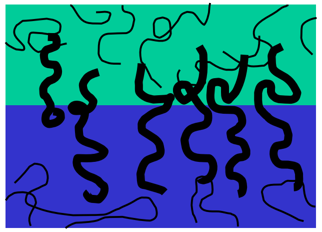




wetting
intimate contact
interdiffusion
resinflow
healing
consolidation
crystallization

interdiffusion

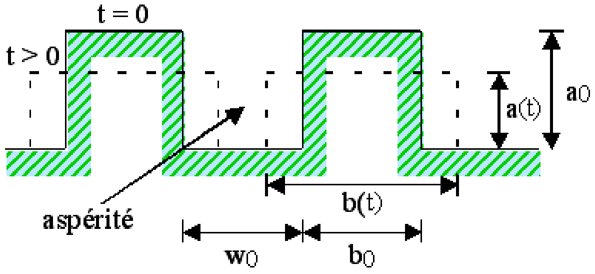
$$t_D = \left(\frac{\pi^2}{4}\right) . \tau_V \Big/ \left[1 - 1.47\sqrt{4/5}\left(M_e/M\right)^{1/2}\right]^2$$



crystallization

$$X(t) = 1 - \exp\left[-\frac{4\pi}{3} N_o(t_d)\left(\int_{\tau_d}^{t} G(\xi)d\xi\right)^3\right]; \quad t \geq t_d$$

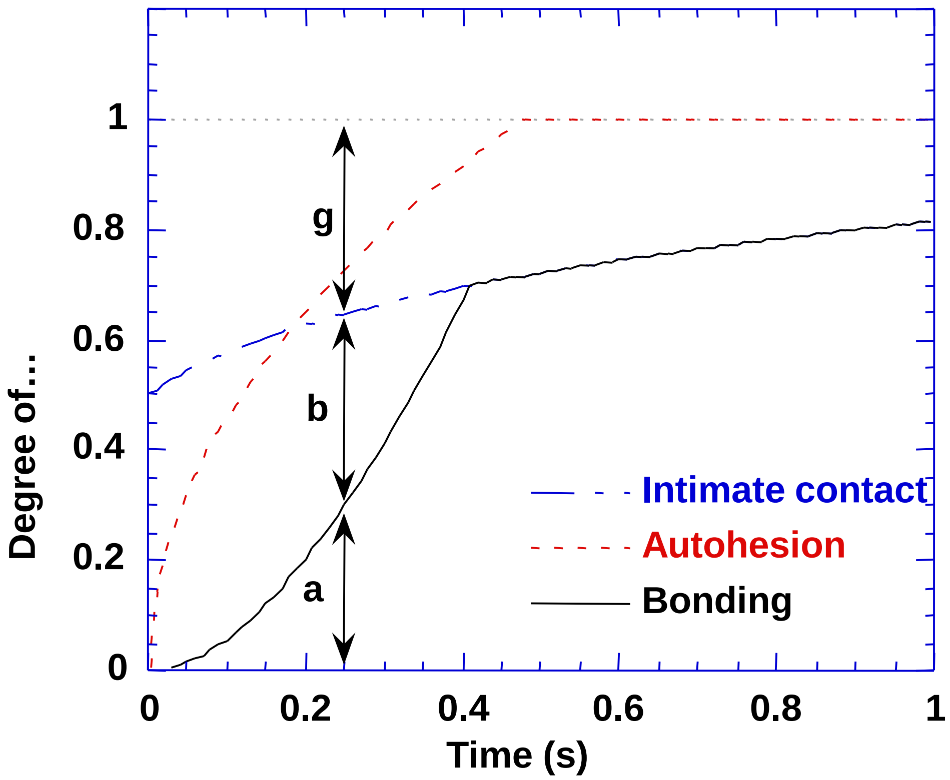
•



intimate contact

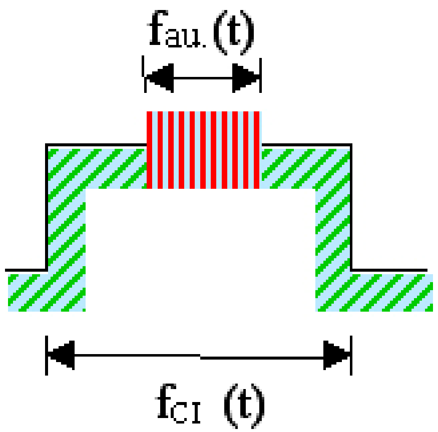
$$t_{CI}(T) = \frac{\eta(T)}{5P}\left(\frac{f_0 + \omega_0}{f_0}\right)^{-1}\left(\frac{a_0}{f_0}\right)^{-2}\left[\left(\frac{f_0 + \omega_0}{f_0}\right)^5 - 1\right]$$

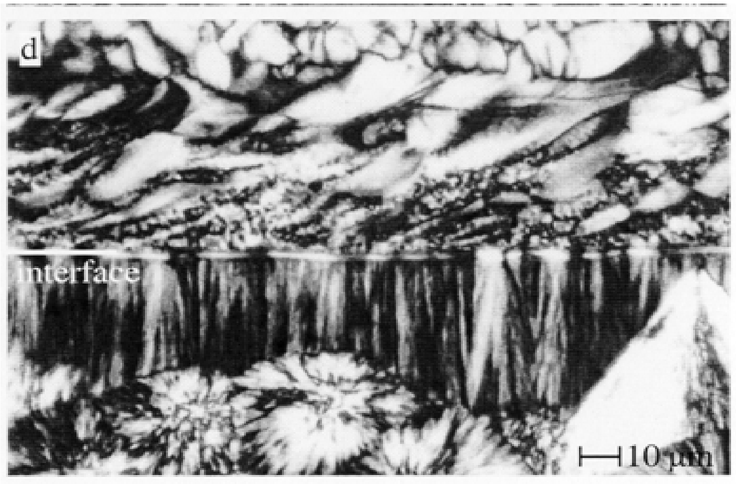
Fusion bonding : kinetics



Degree of progression for intimate contact, autohesion and thus bonding for polyamide 12 at 180°C under 2 MPa of contact pressure.

$$D_s(\tau) = \sum_{i=1}^{\tau_{c.i.}/dt} \left[\Delta D_{c.i.}(\tau_i - \tau_{i-1}) \cdot \sum_{j=i+1}^{\tau_{au.}/dt} D_{au.}\left(\tau_j, T_j\right) \right]$$

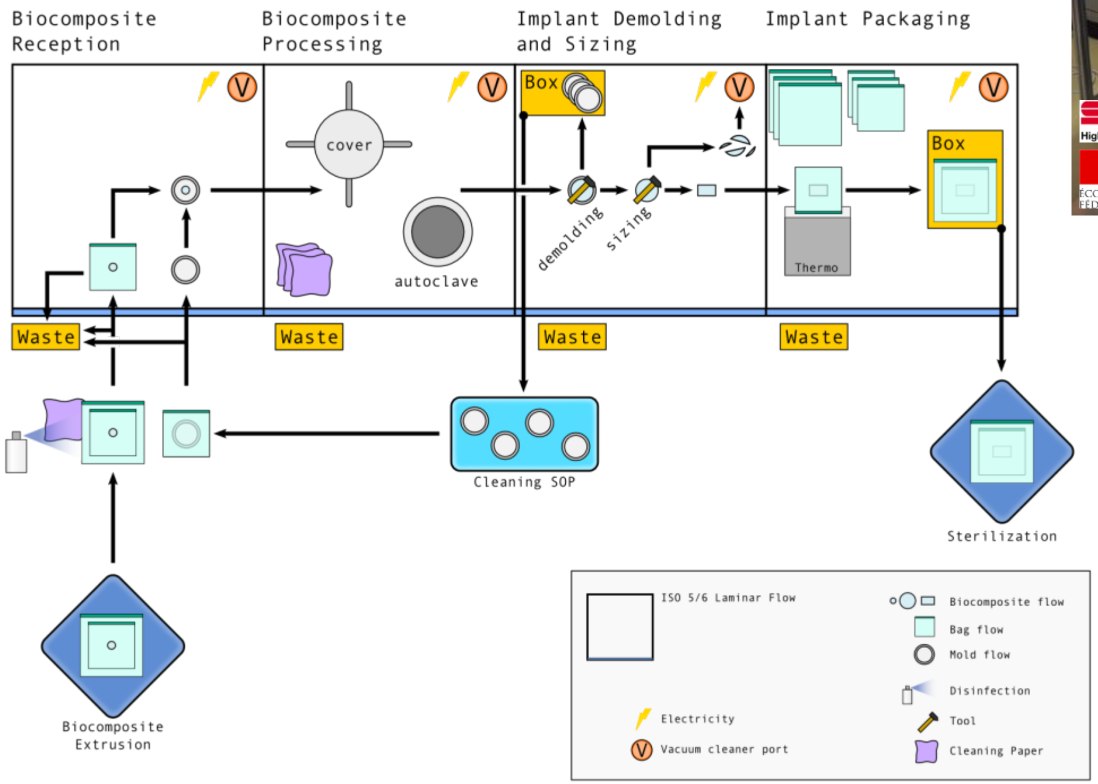




Non isothermal interfacial crystallization in PP

Processing biomed polymers

- **Additional phenomena**
  - **Degradation during processing**
    - **Drying**
    - **Molecular weigth drop**
  - **Contamination**
    - **Environment**
    - **Tools**
  - **Sterilization**
    - **EtOH**
    - **Gamma**



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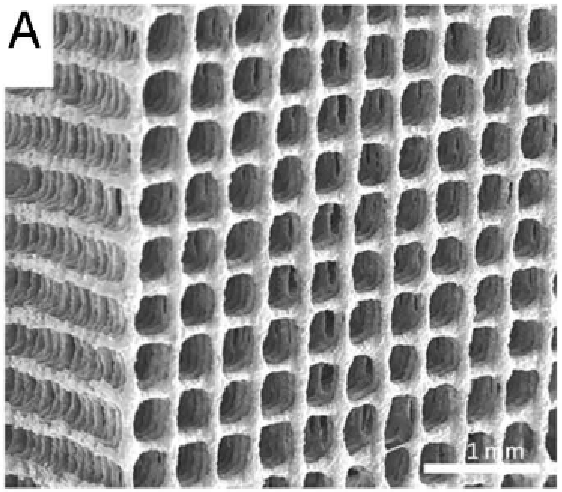
Additive manufacturing : polymer solutions



Melba Navarro, 2013, IBEC Barcelona

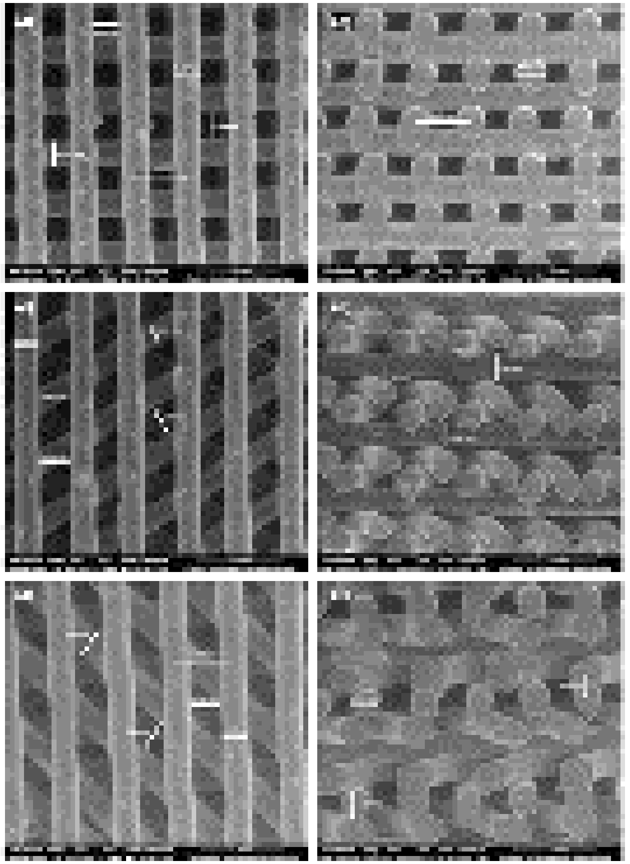
- **3D printing based on nozzle-deposition system**
- **Polymer solutions (solvent!)**
- **3mm/s, 5 bar**
- **500µm between 70 µm struts**
- **Get the right set of temperature/plastiziser/printing parameters**
- **Post-processing : shrinkage of struts during solvent evaporation !!**
- **Hydrogels : + in-situ crosslinking and swelling : final resolution !**

Additive manufacturing : molten polymer + composites

- **Polymers and composites :**
  - **less shrinkage,+ higher viscosity, + higher mechanical properties**
  - **+ different degradation rates**
- **'Bioextruders' :**
  - **deposition velocity (volume, nozzle diameter), with or without screw, pumping**

- **Each constituent material requires specific processing conditions**
- **Access to the design freedom of the composite, multi-material deposition**

- **Bulk and surface properties**
- **Thermoplastic scaffold and bioactive hydrogel**



P.Bartolo, 2013

Applications

- **Custom-made 3D structures**
  - **Reproduce geometry of body parts, surgeon support, replica of in vivo milieu**

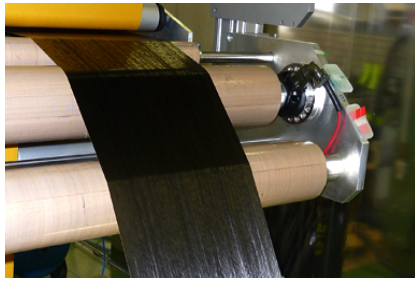
- **In vitro platforms to study cell response and drug screening**
  - **scaffold pore size, geometry, wettability, adhesion, mechanical loading on cells behavior**

- **Templates/scaffolds for tissue regeneration**
  - **Building inner architecture and surface properties**
  - **Mechanical performance, permeability, nutrients diffusion,cell response…**

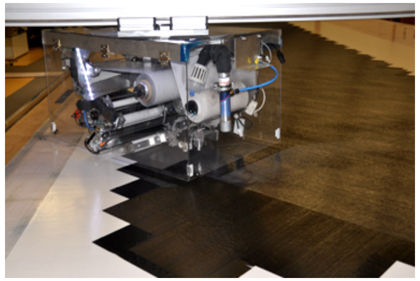
Conclusions

Building up from mm scale : 0.1-10 mm

- **Processing fibre composite today**
  - **Tape and tow directional placements**
  - **Towards thinner ply (2-3 fibre thickness)**
  - **Towards 3D shape in cost-effective one-step process**



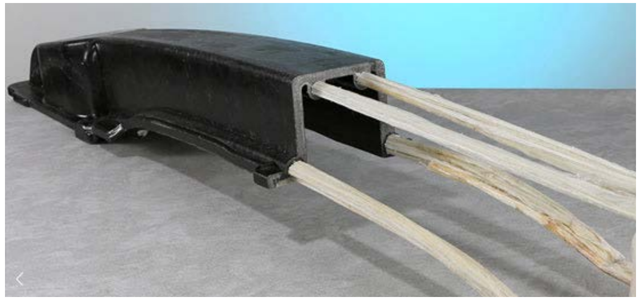
Spread Tow



Tape placement

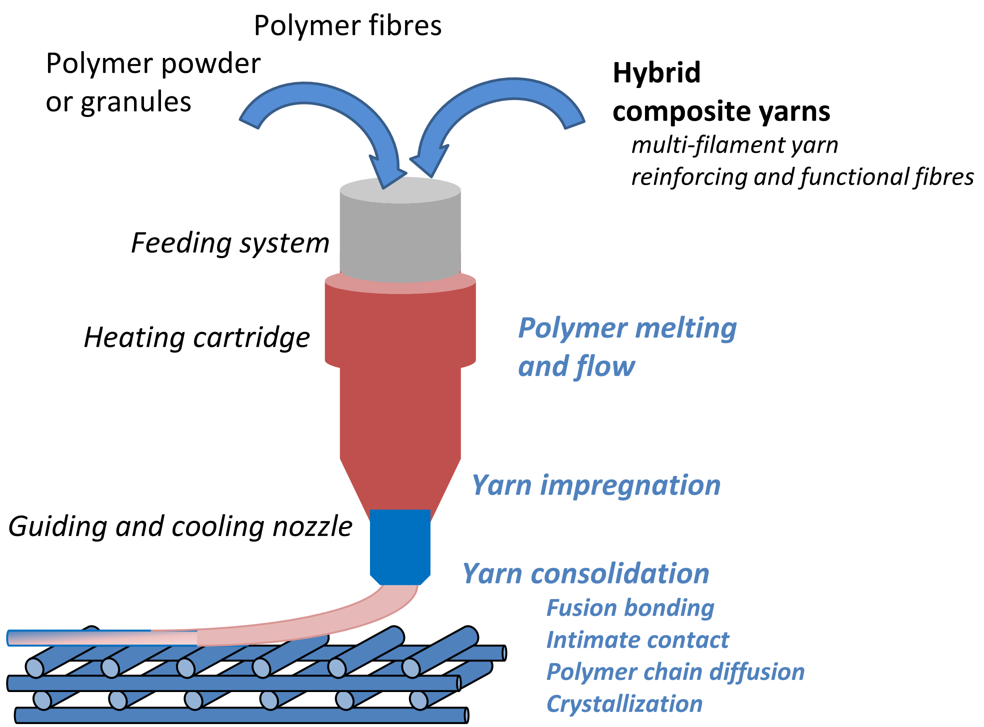
www.thinplytechnology.com

- **Additive processing**
  - **of laminate (ply by ply)**
  - **tow composite (placement and overinjection)**



www.eelcee.com www.inxide.se

Building up from µm scale : 5-200 µm



Fibres

Hydrogels

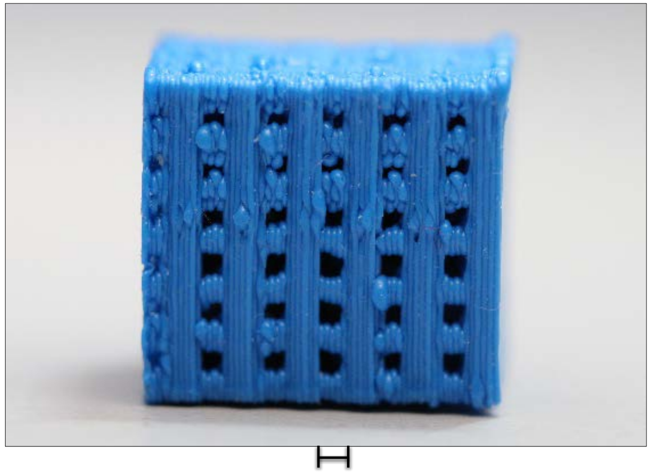
Resorbable polymer and biocomposites

Bio-performance

3D cellular biocomposites for implants, cells platforms and degradable devices

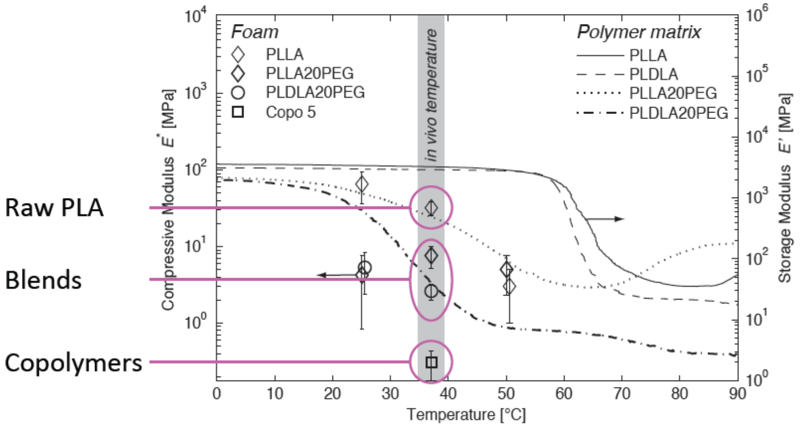
Building up from µm scale : 5-200 µm

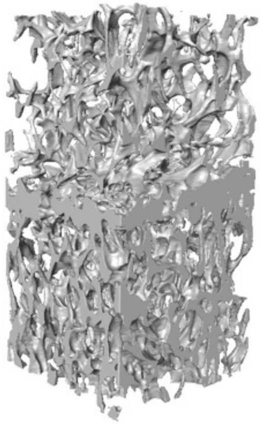
1. **3D deposition for main scaffold**
2. **Impregnation with bioactive hydrogel**
3. **Post processing (crosslinking, …)**



LTC-LBO SNSF project

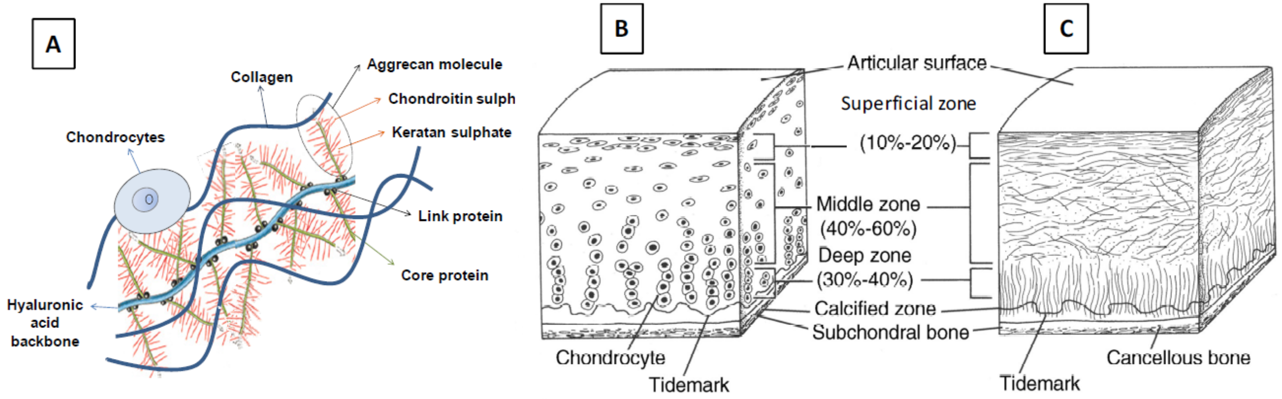
- **Processing with single fibres**
  - **not only at yarn level**
  - **control fibre properties during processing of implant**
- **Processing 3D biocomposite**
  - **be hybrid, anisotropic and bioactive**



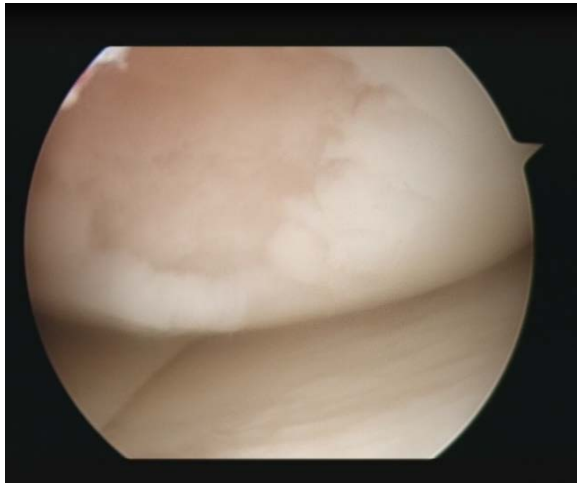


Cartilage

Bone

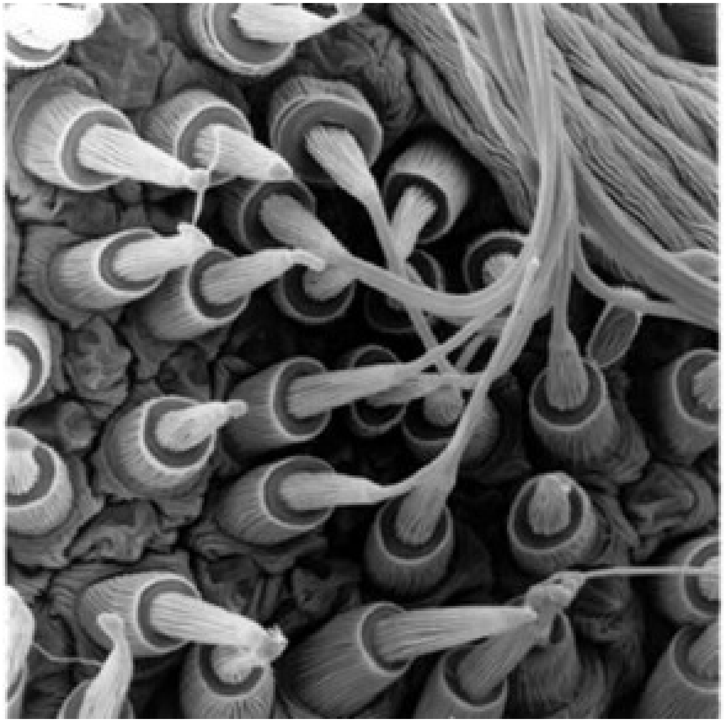


J.Izadifar *et al*, Funct. Biomater. 2012, 3 799



mykneecartilage

FDM



MicroAngela

AM: from Biomaterials to Regenerative Medicine

- **Swiss Society of Biomaterials and Regenerative Medicine**
- **20th Anniversary in 2015**
- **Conference at EPFL, June 9th and 10th 2015**
- **Biomaterials, Biofabrication, Tissue Engineering**

London museum of science

Merci

- EPFL-LTC
- EPFL-LBO, EPFL-LAPD
- CHUV
- SNSF, CTI, FP7
- Eric Boillat
- YOU