INTRODUCTION TO THE PROCESSING OF THERMOPLASTIC COMPOSITES

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YOUR HOSTS

Casey Keulen, Ph.D, P.Eng.
Assistant Professor of Teaching, University of British Columbia
Co-Director of Advanced Materials Manufacturing MEL Program, UBC
Director of Knowledge in Practice Centre, CKN

- Ph.D. and M.A.Sc. in Composite Materials Engineering
- Over 15 years experience in industry and academia working on polymer matrix composites in aerospace, automotive, marine, energy, recreation and others
- Experience working with over 150 companies from SME to major international corporations
- Expertise in liquid composite moulding and thermal management

YOUR HOSTS

Pascal Hubert, Ph.D, P.Eng.
Professor, McGill University
Director, Research Centre for High Performance Polymer and Composite Systems

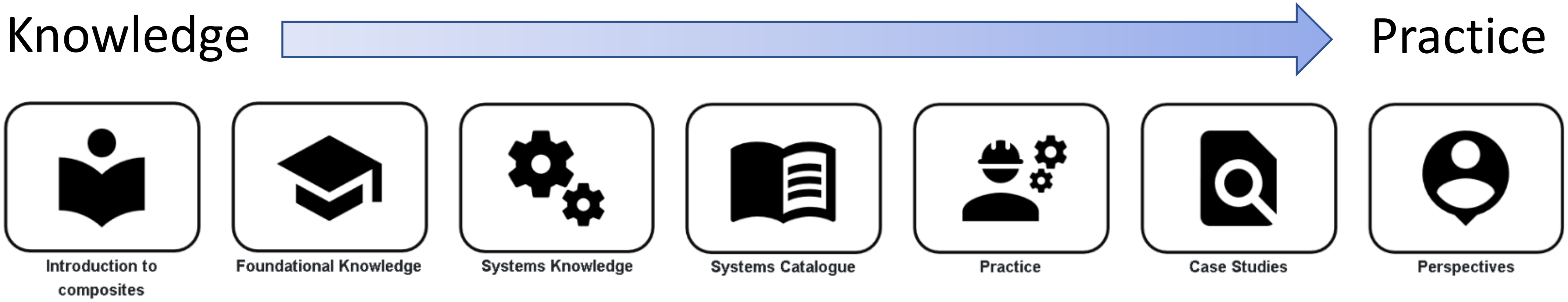
- Ph.D. and M.A.Sc. in Composite Materials Engineering
- Over 30 years experience in processing, testing and analysis of polymer matrix composite materials
- Conducted fundamental and applied research with aerospace and transportation companies on thermoset and thermoplastic composite manufacturing
- Developed courses in processing of composite materials

KNOWLEDGE IN PRACTICE CENTRE (KPC)

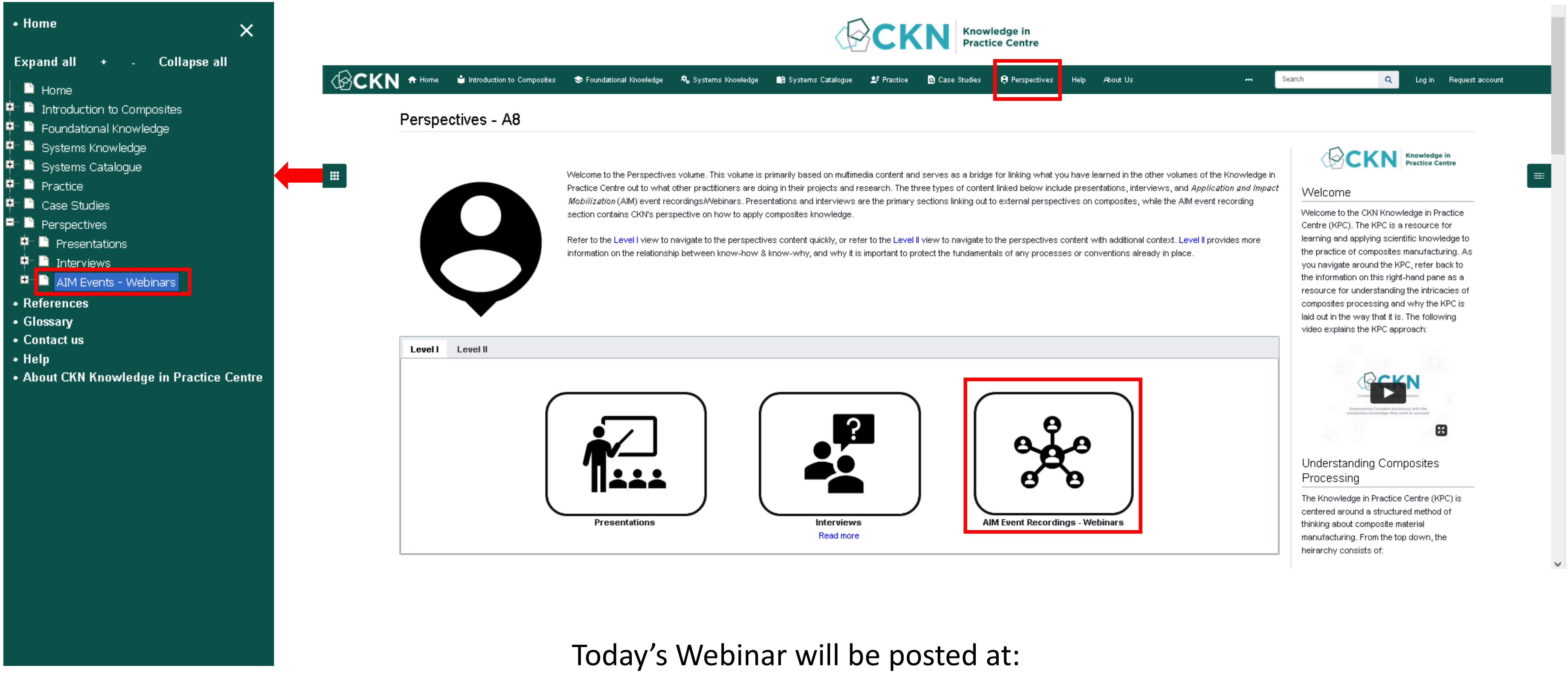
- A freely available online resource for composite materials engineering:

compositeskn.org/KPC

- Focus on practice, guided by foundational knowledge and a systems-based approach to thinking about composites manufacturing



PAST WEBINAR RECORDINGS AVAILABLE



Today's Webinar will be posted at:

https://compositeskn.org/KPC/A322

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TODAY'S TOPIC:

Introduction to the Processing of Thermoplastic Composites

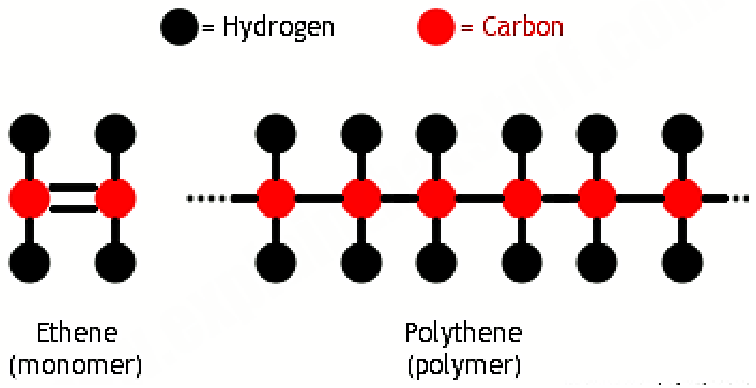
OUTLINE

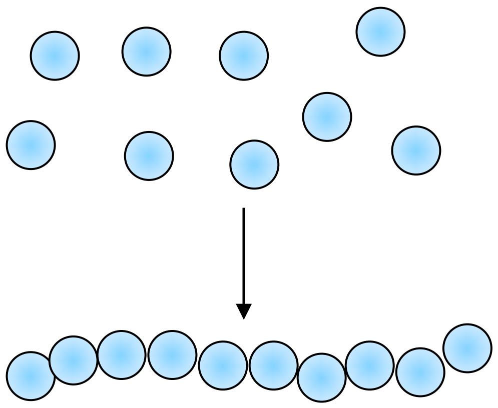
- What are thermoplastic polymers?
- What are the different forms of thermoplastic composites?
- How thermoplastic composites are made?
- How thermoplastic composite parts are made?
- How to define the process cycle for thermoplastic composites?

Learning outcomes

- ✓ Identify main classes of thermoplastic composites
- ✓ Describe thermoplastic composite material forms
- ✓ Describe main processing methods for thermoplastic composites
- ✓ Identify main thermal properties of thermoplastic composites
- ✓ Describe thermoplastic composite consolidation process

What are polymers





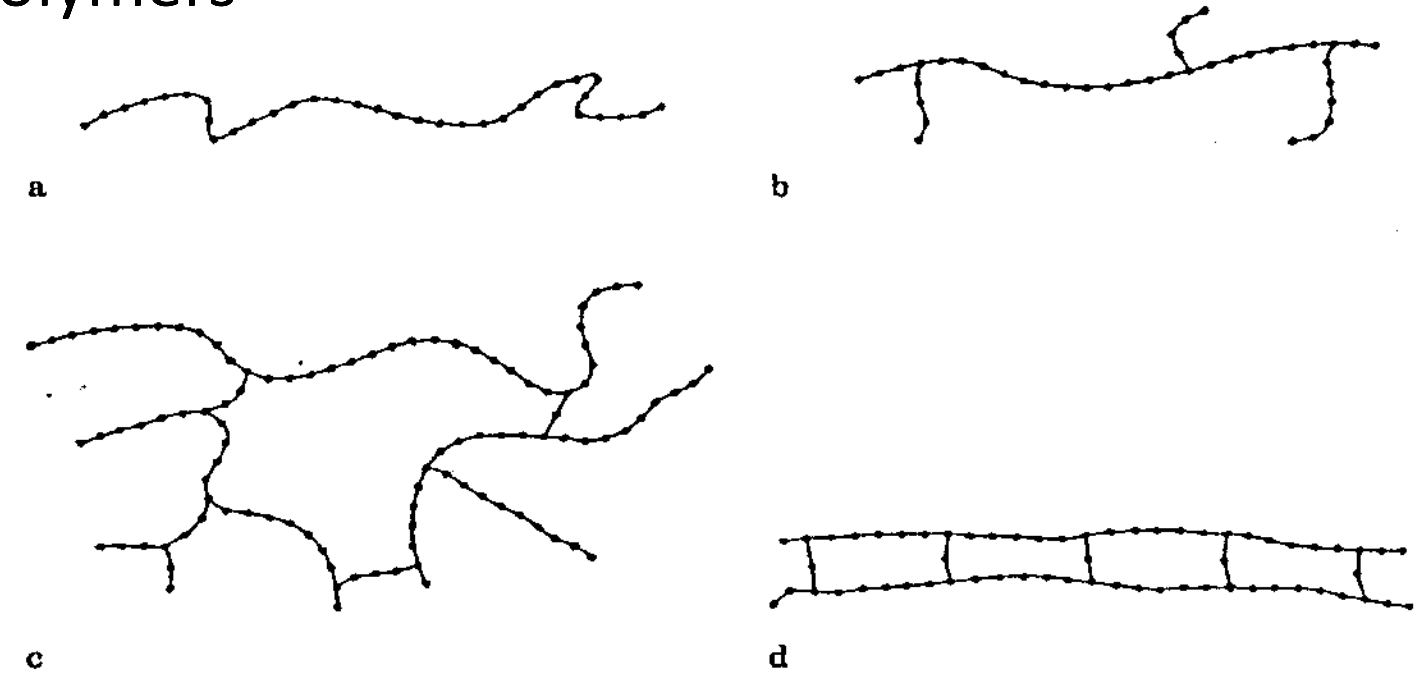
Structure of Polymers

- Giant chain-like molecules with covalently bonded carbon atoms as the backbone of the chain
- Formed by joining many monomers – ***polymerization***

www.explainthatstuff.com

Polymer chain configuration types

a. Linear polymers (soften or melt on heating)
b. Branched polymers
c. Crosslinked polymers (high thermal stability)
d. Ladder polymers



Types of polymer matrix

Thermosets	Thermoplastics	Elastomers
• Solidify via chemical reaction that causes polymer to cross-link • Do not flow once cured due to 3-D cross-linking	• Have the ability to remelt after solidification • No chemical reactions during fabrication	• T_g below room temperature • Low degree of cross-linking • Do not flow because of chemical cross-linking

Thermoplastic polymers

- Soften and melt on heating
- No chemical reactions during fabrication
- Fast processing times
- Generally have high melt viscosities
- Have an indefinite shelf life
- Are ductile (high strain to failure)
- Good environmental resistance
- Exhibit high toughness
- Are potentially recyclable
- Are repairable

Types of thermoplastic

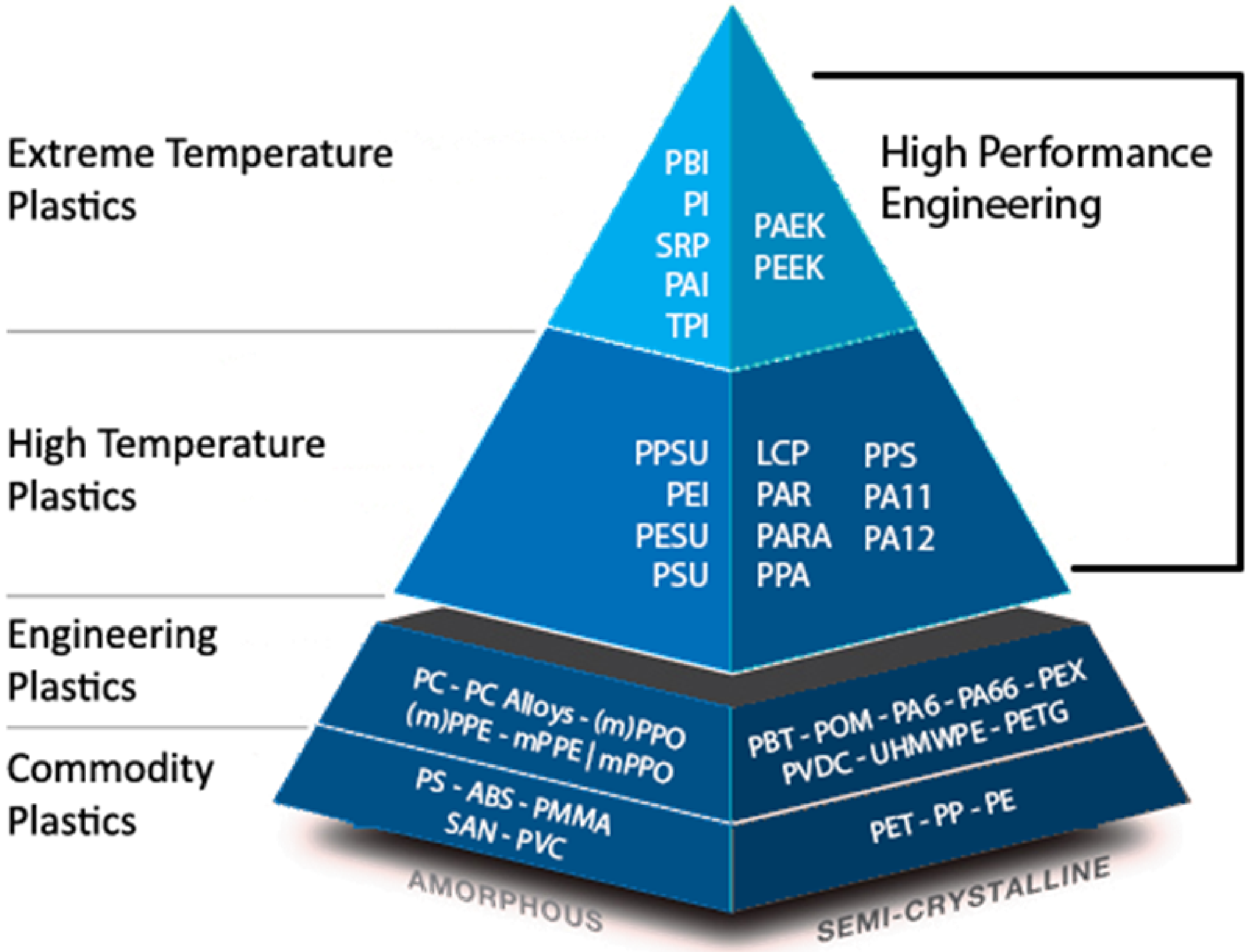
Semi-crystalline

Align with their neighbours forming with a 3-D order

Amorphous

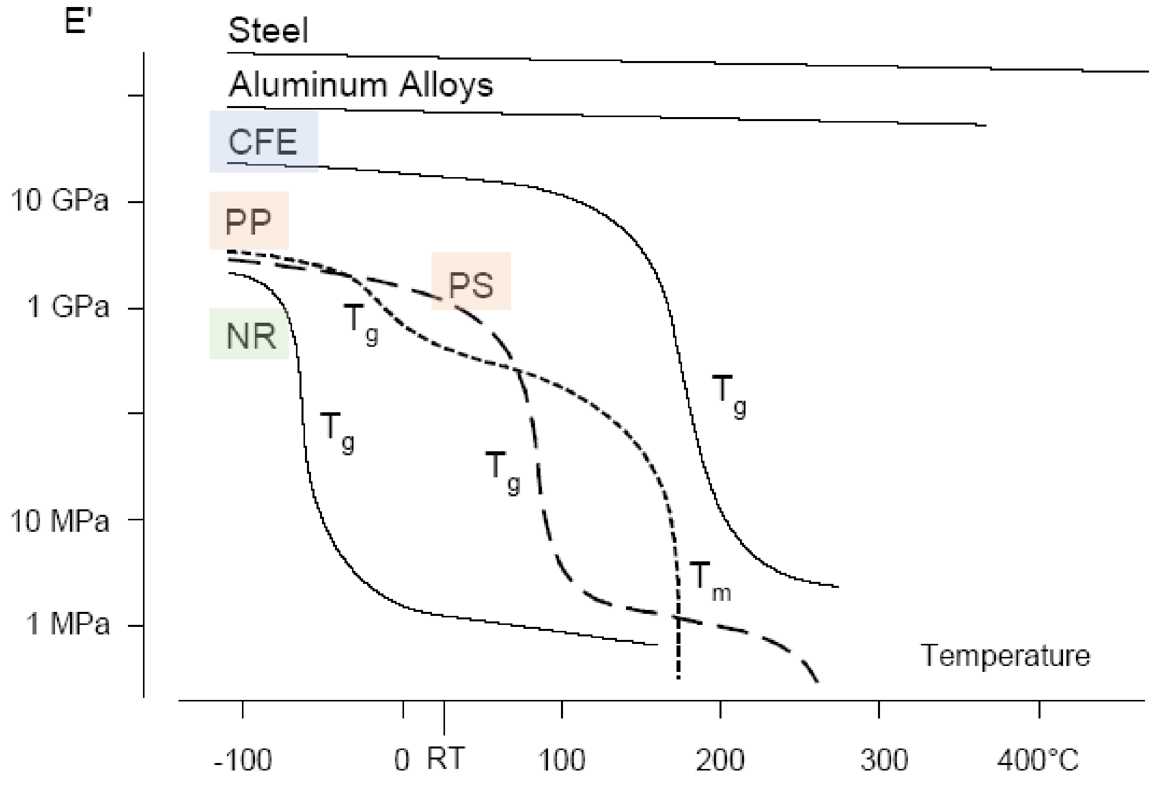
Molecules in random arrangement like a bowl of spaghetti

Thermoplastics



polymers.com.au

Transitions of polymers



T_g: glass transition temperature

T_m: melting temperature

CFE (Carbon reinforced epoxy resin): Thermoset

PP (Polypropylene) : Thermoplastics

PS (Polystyrene): Thermoplastics

NR (Natural Rubber) : Elastomer

Widmann, *Interpreting DMA curves, Usercom11, 2003*

Glass transition

- Reversible change in an amorphous polymer between a viscous condition and a hard, relatively brittle condition
- Crystalline polymers also contains amorphous regions. There is no 100% crystallinity
- What affects T_g?
  - Molecular structure and weight
  - Branches, cross-links
- How to measure T_g?
  - Change in specific volume, modulus, heat capacity
  - Thermal analysis, mechanical and dielectrical measurements

Melting and crystallization

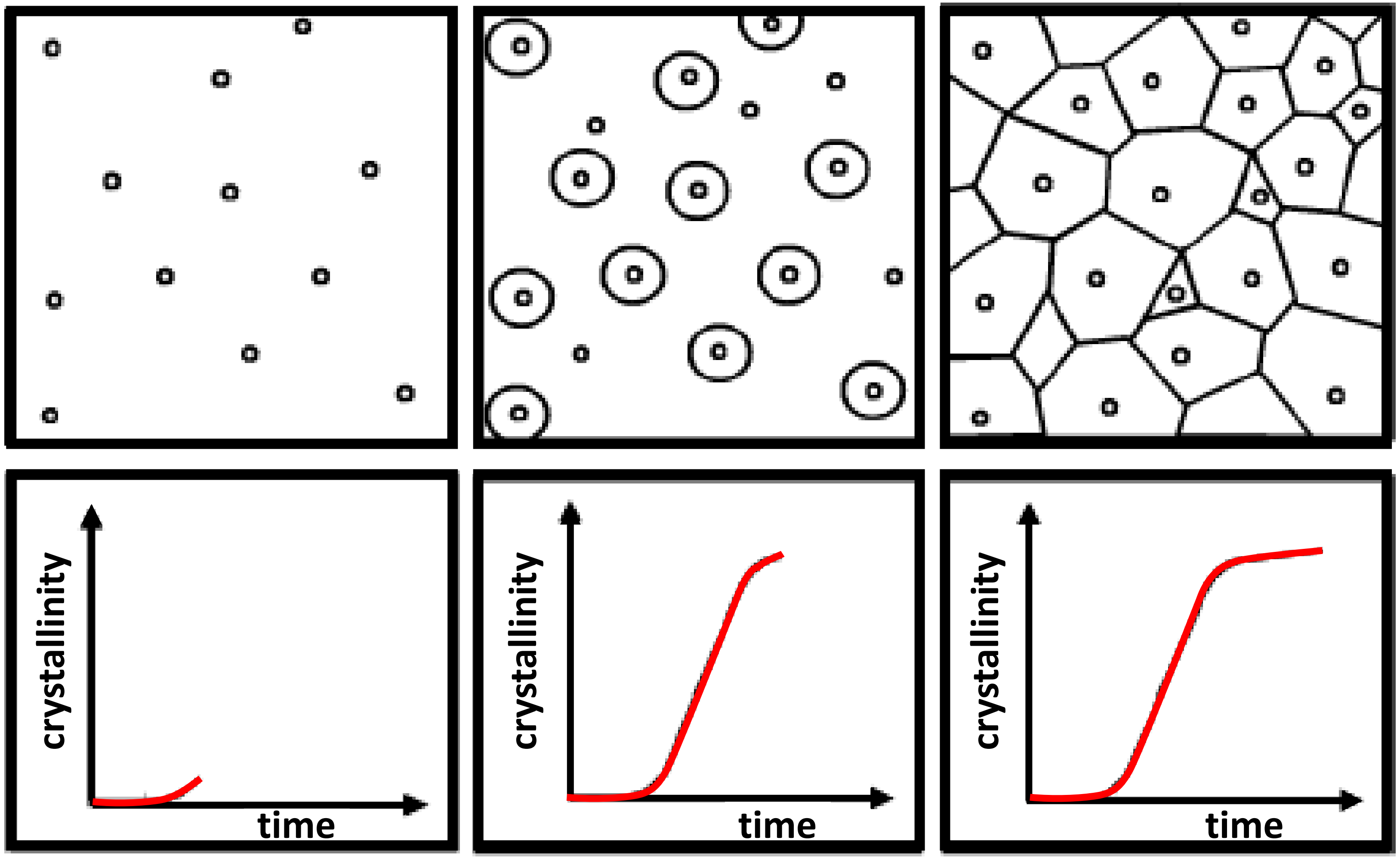
Melting: Transition from a solid to liquid state of crystalline polymer

- Melting is a characteristic of crystalline polymer
- The chains that melt are not the chains that undergo the glass transition.
- When a crystalline polymer melts:
  - It absorbs heat
  - Undergoes a change in heat capacity

Crystallization: The atoms in a molecular structure are arranged in an orderly, three-dimensional pattern.

- It releases heat
- Undergoes a change in heat capacity

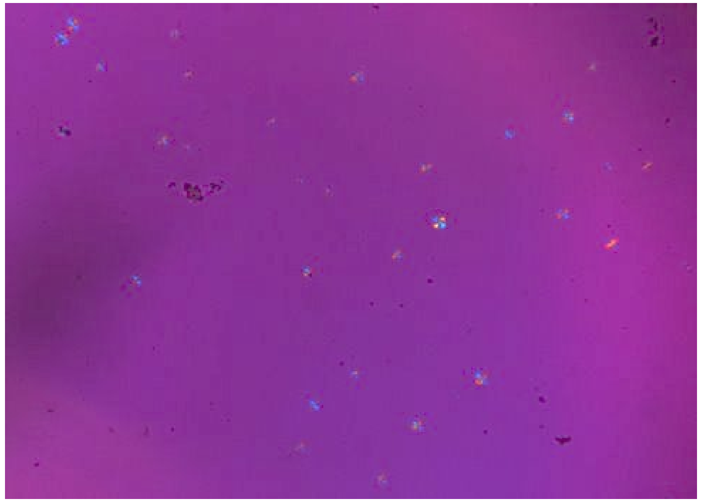
Crystallization

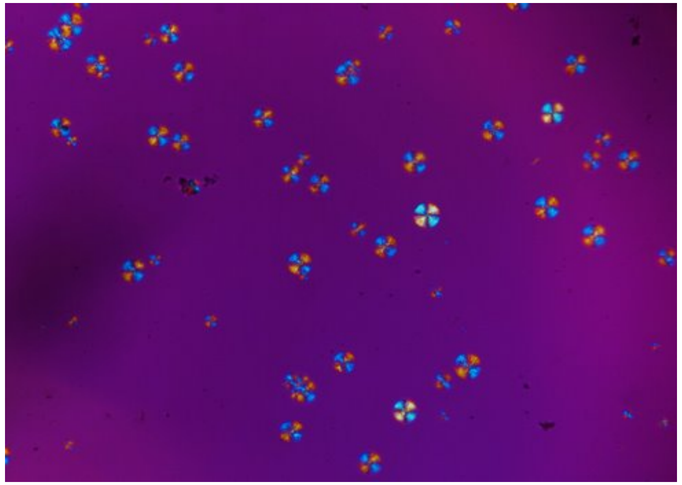


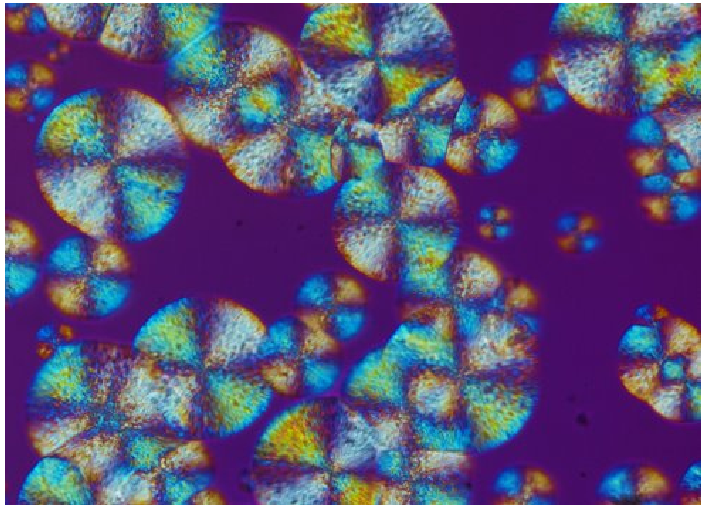
Nucleation   Crystal growth   Secondary crystallization

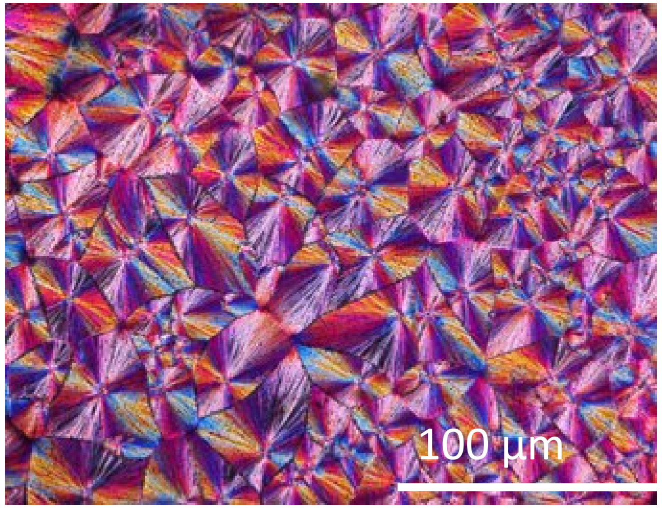
A. Loos

Crystallization of PLA





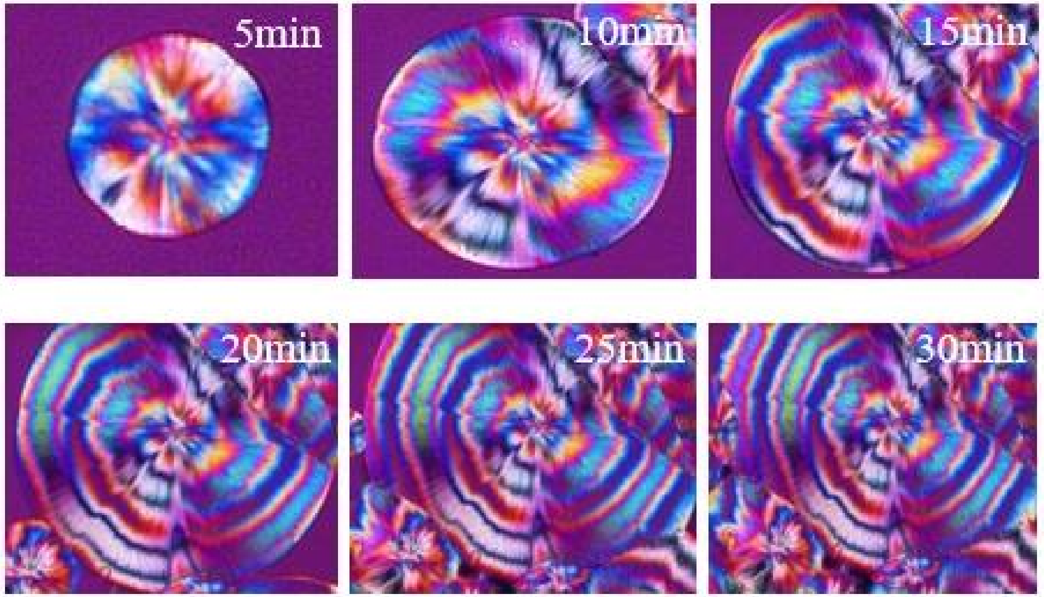




S. Singh

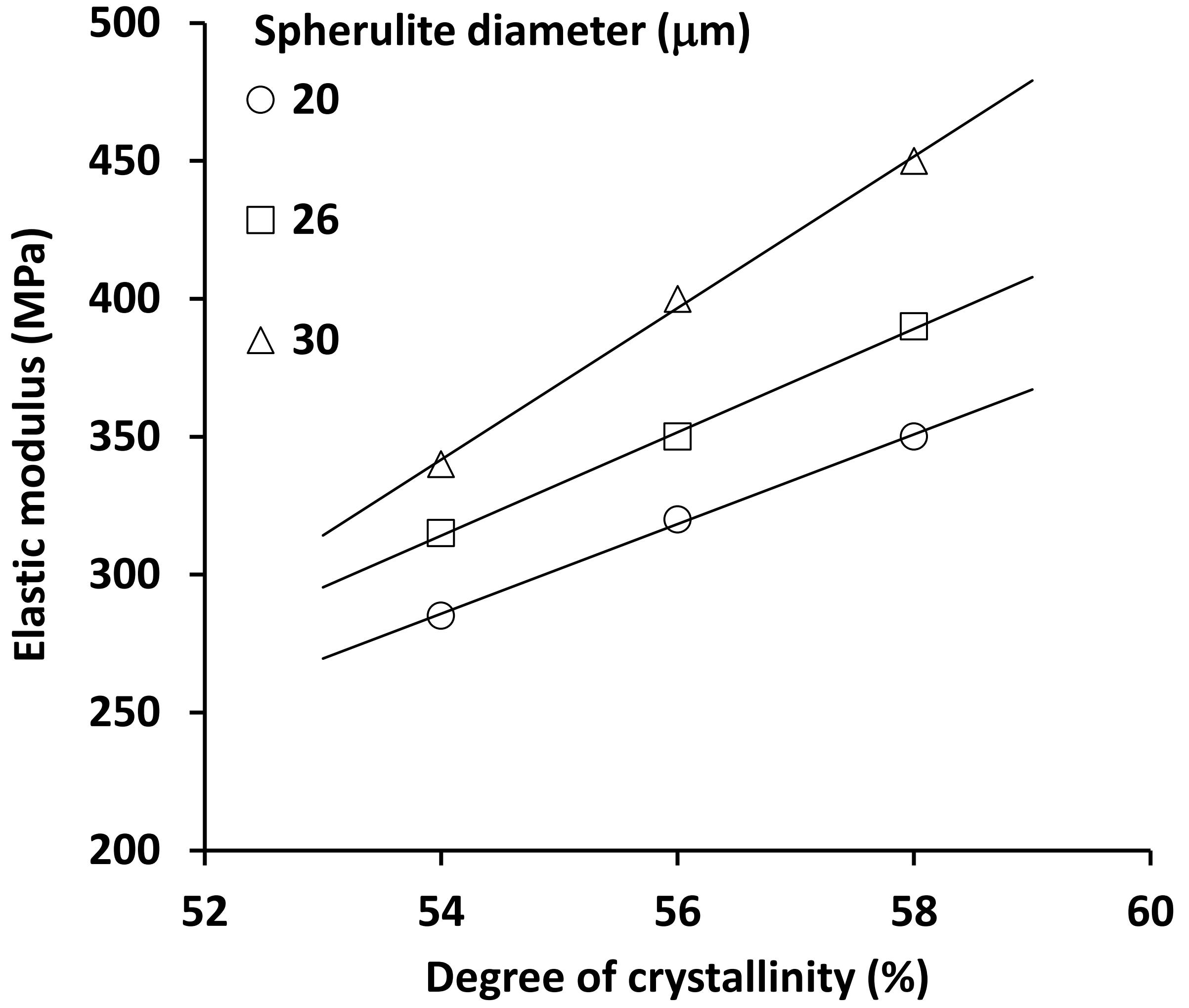
Microstructure of semicrystalline polymers

- Spherulites – crystalline portions of polymer
- Crystal growth begins at nucleation points and grow radially outward
- Size 10 – 100 x 10^{-6} m ~ 1 x 10^{-3} m in diameter



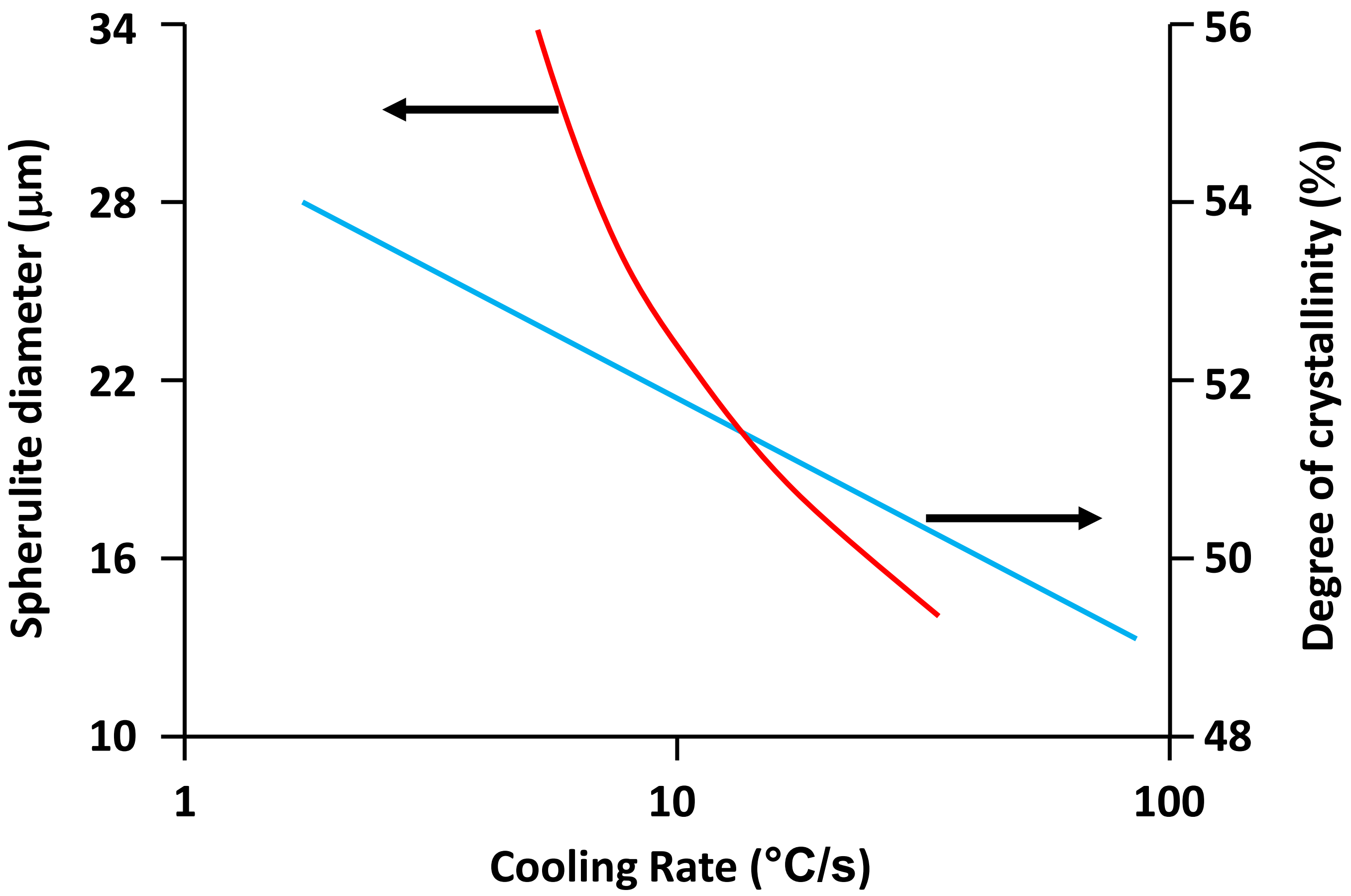
S. Singh

Effect of crystallinity



A. Loos

Effect of cooling rate

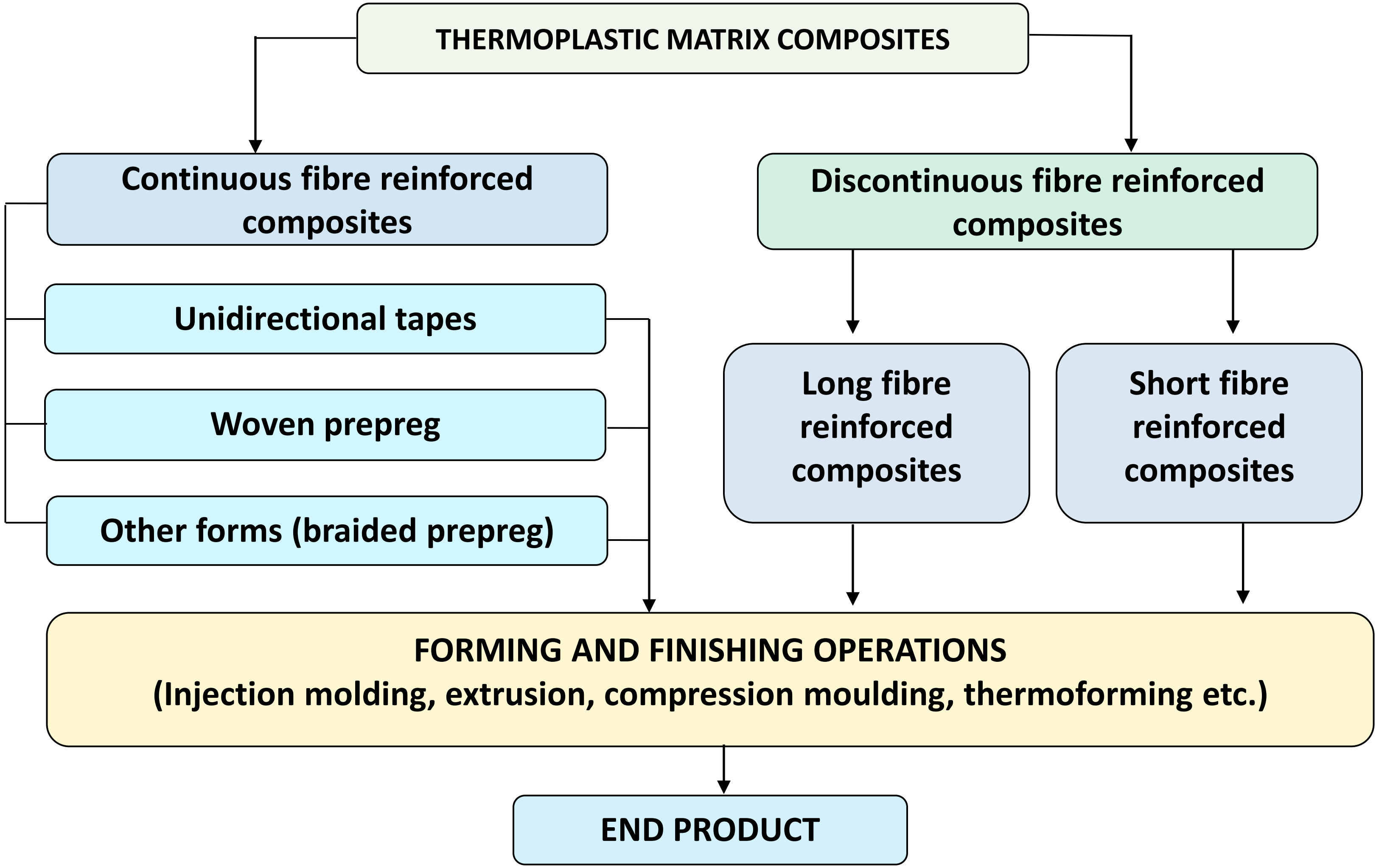


A. Loos

Melting and glass transition

Polymer	T_g (°C)	T_m (°C)
Amorphous		
Acrylonitrile-butadiene-styrene (ABS)	< -50	
Polyvinylchloride (PVC)	80	
Polystyrene (PS)	80 - 100	
Polymethylmethacrylate (PMMA)	105 - 110	
Polycarbonate (PC)	140 - 150	
Polyethersulphone (PES)	217 – 230	
Semicrystalline		
Polyethylene (PE)	< -100	105 - 135
Polypropylene (PP)	-10	160 - 165
Polyamide (PA)	65 - 75	220 - 225
Polyphenylensulfide (PET)	69	245
Polyphenylensulfide (PPS)	93	228
Polyetheretherketone (PEEK)	143	334

Thermoplastics composites material forms



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Impregnation techniques

PREPREG MATERIALS

Pre-impregnated forms (melt or solution impregnation)

- Random fibre prepreg sheets
- Unidirectional tape or tow prepregs
- Fabric prepregs

→ CONSOLIDATION DURING SHAPING

Semi-impregnated forms (fibre and matrix separated)

- Fibre commingling/co-weaving
- Powder coating
- Film stacking

→ FINAL IMPREGNATION AND CONSOLIDATION DURING SHAPING

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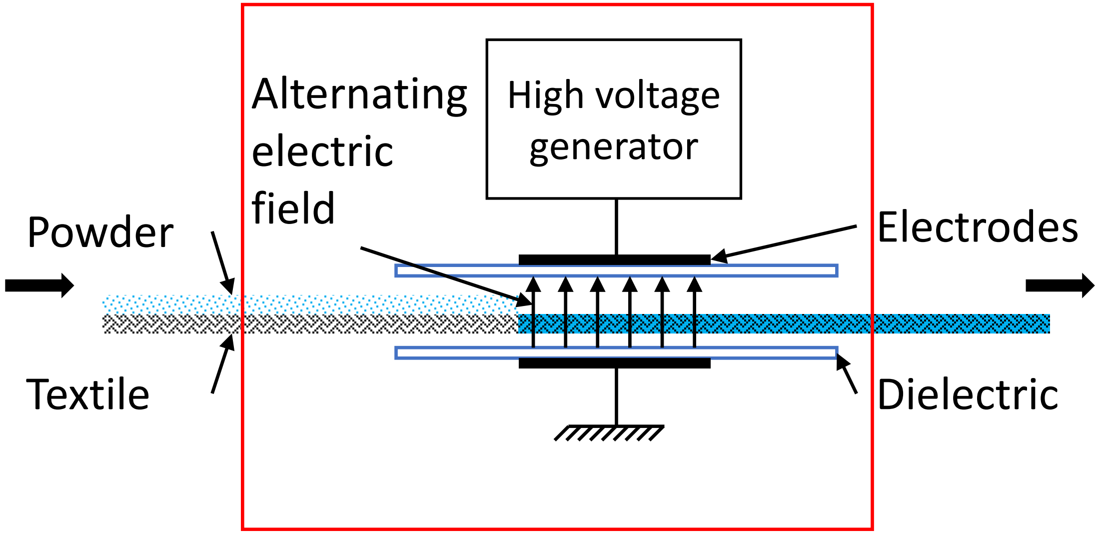
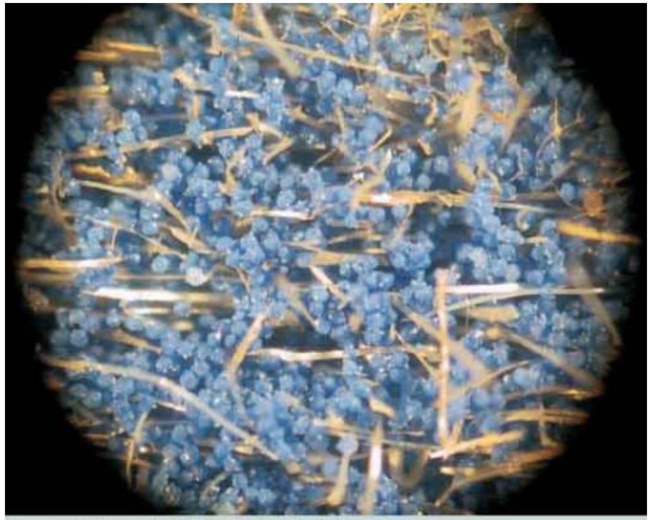
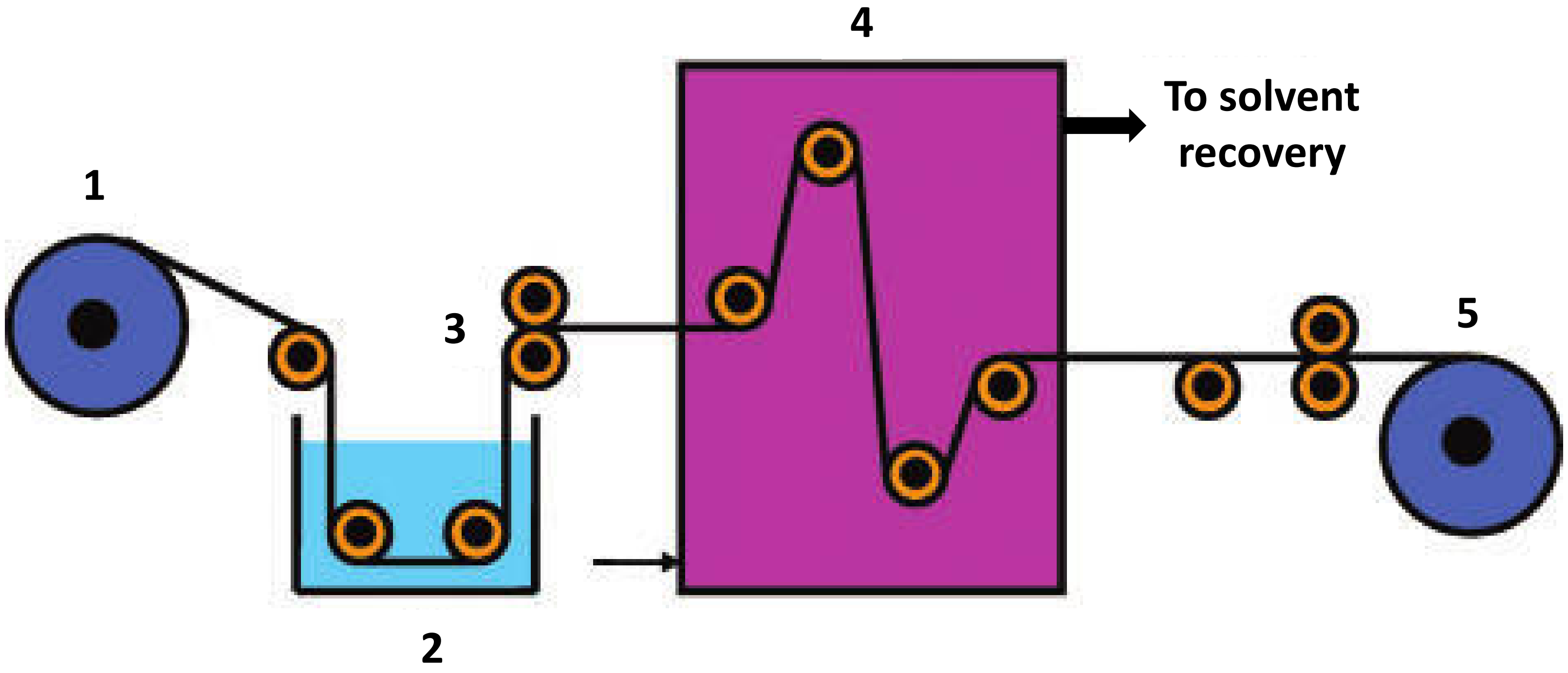
Powder impregnation




Thermoplastic powder distributed in natural fibre felts.

http://www.jeccomposites.com

Solution impregnation



1: fabric supply
2: polymer solution
3: calendering rollers
4: solvent evaporation unit
5: batch collection

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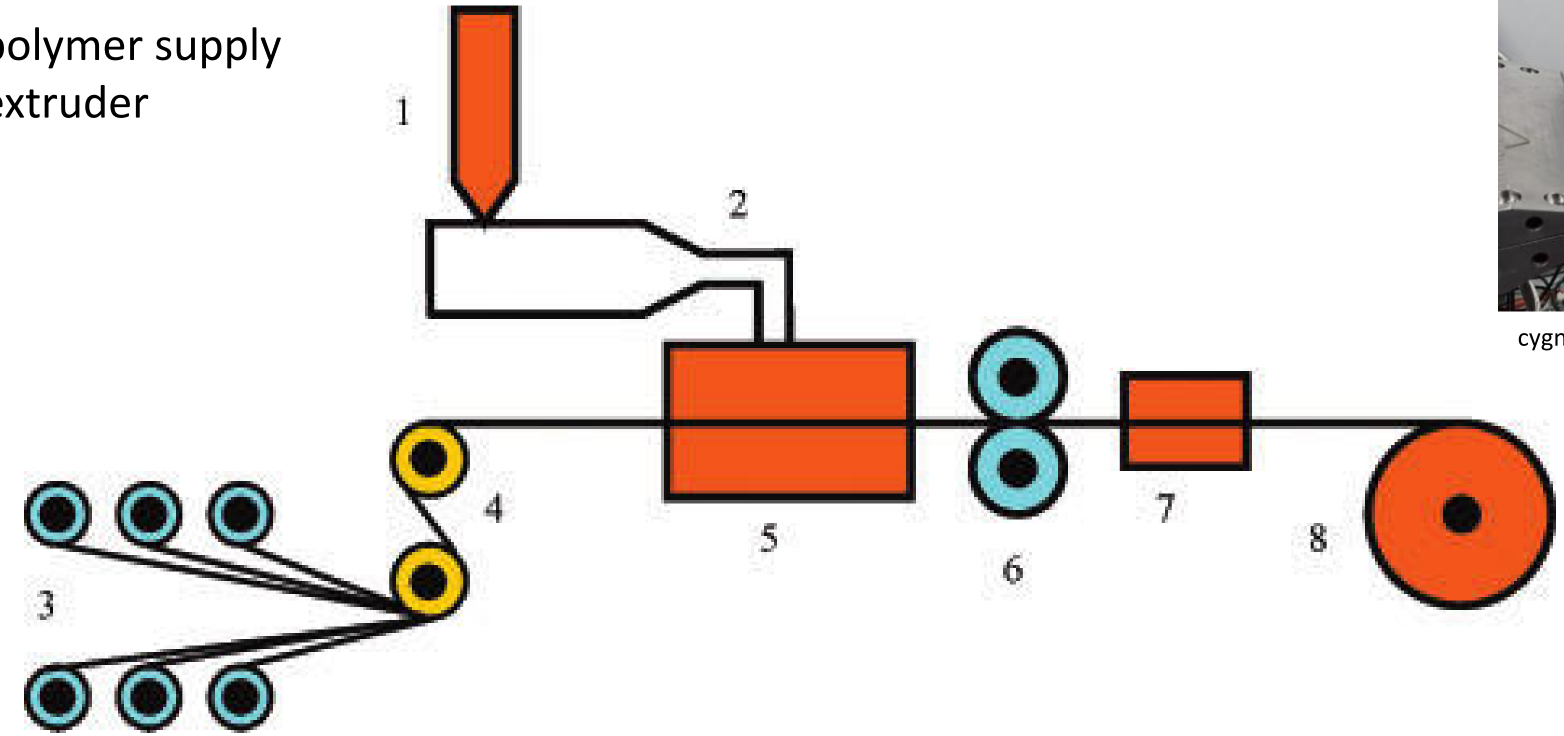
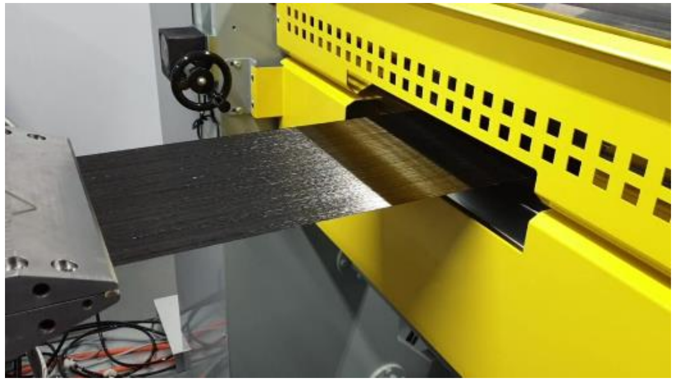
Melt impregnation

1: polymer supply
2: extruder





cygnet-texkimp.com

3: fibre creels 4: tension control 5: impregnator 6: calendering rollers 7: cold zone 8: batch collection

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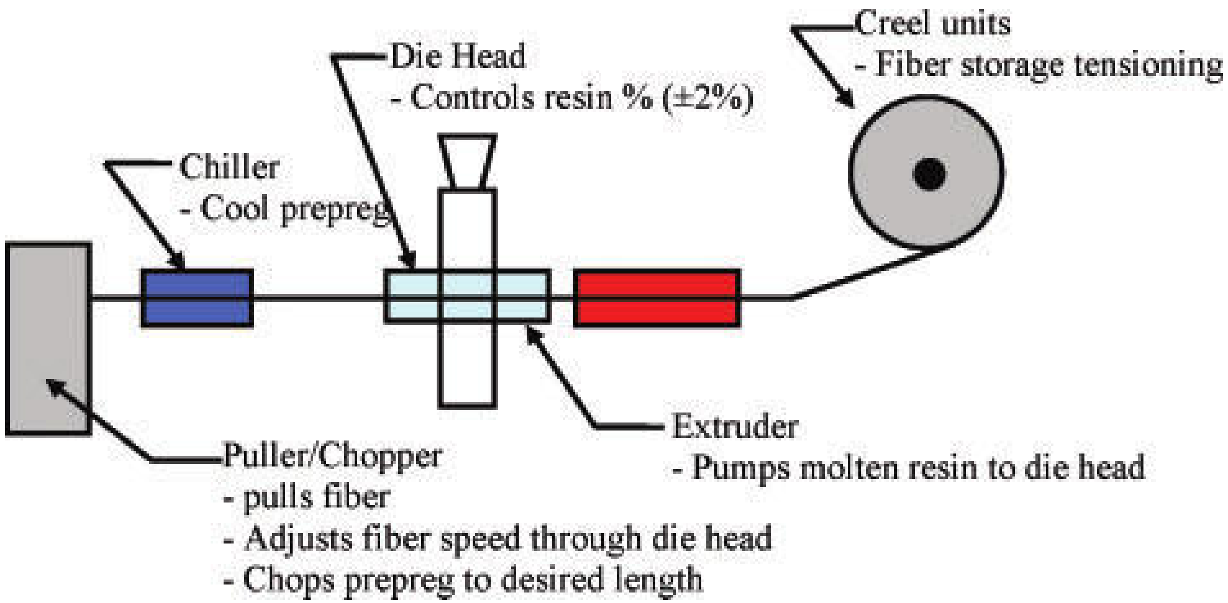
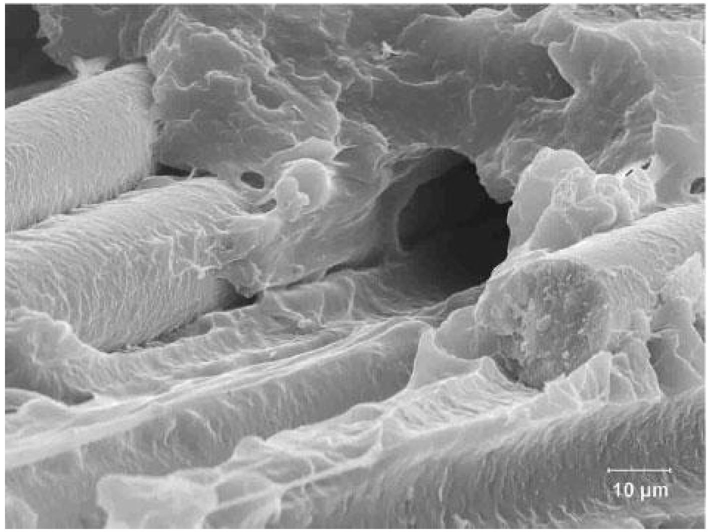
Direct reinforcement fabrication technology (DRIFT)





Impregnation of tapes with thermoplastic polymer

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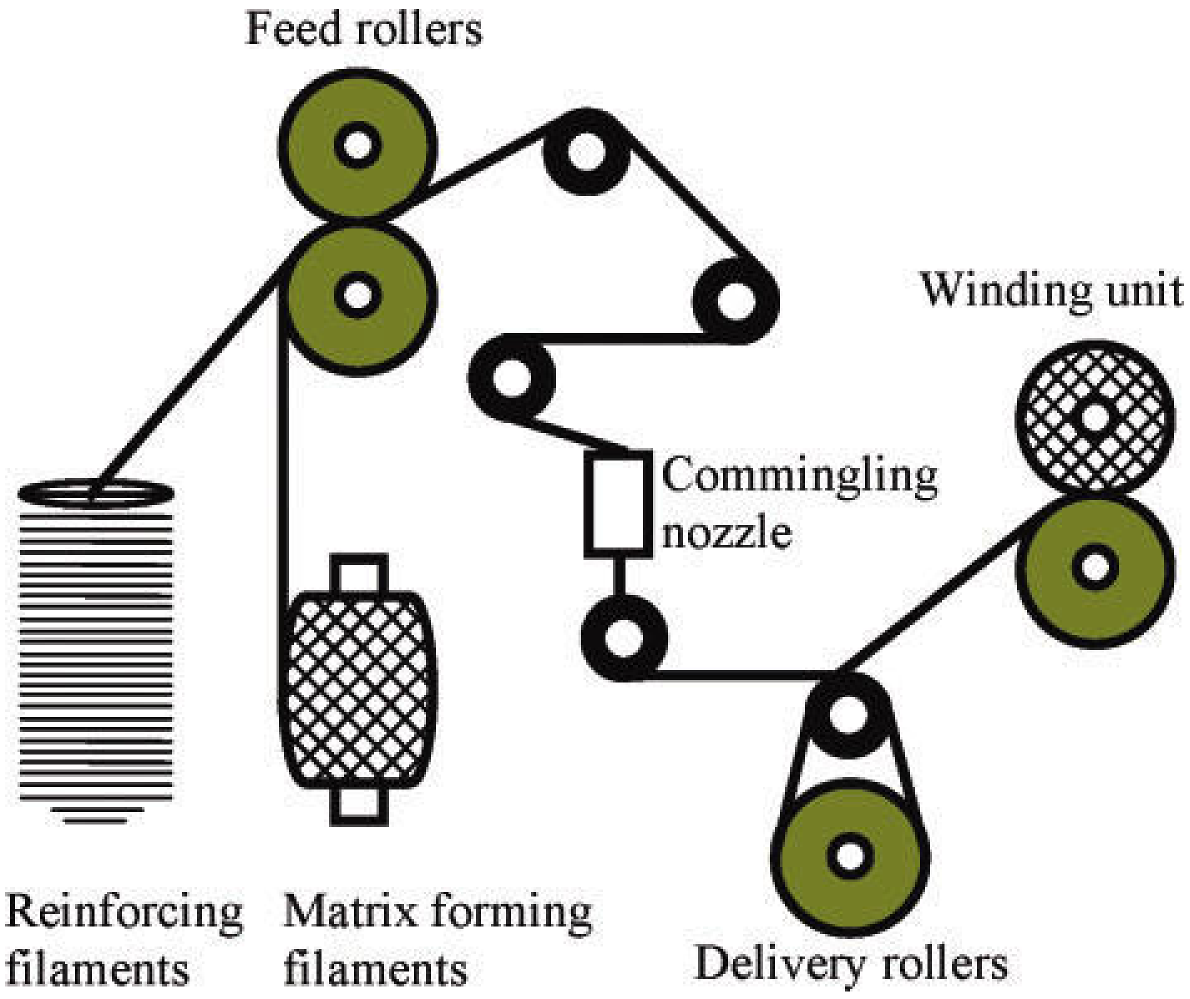
Commingling



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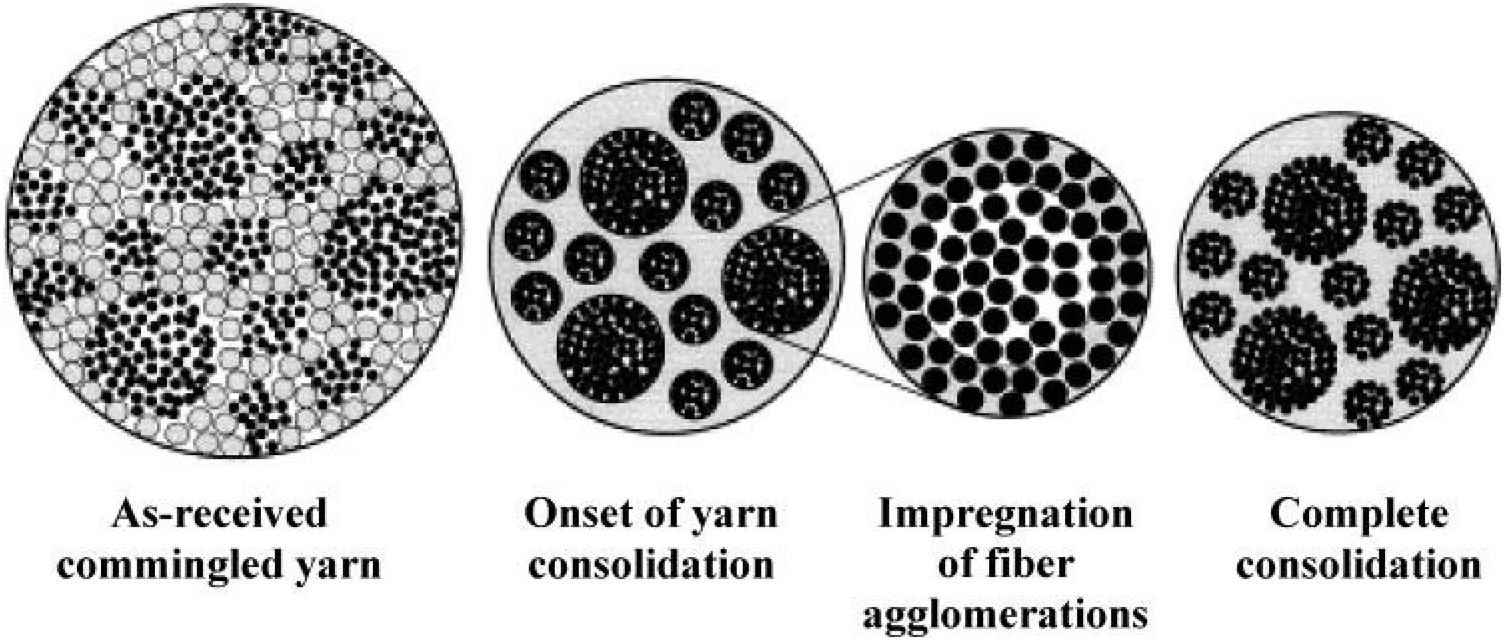
TWINTEX® Technical Fabric from Owens Corning

Commingling consolidation



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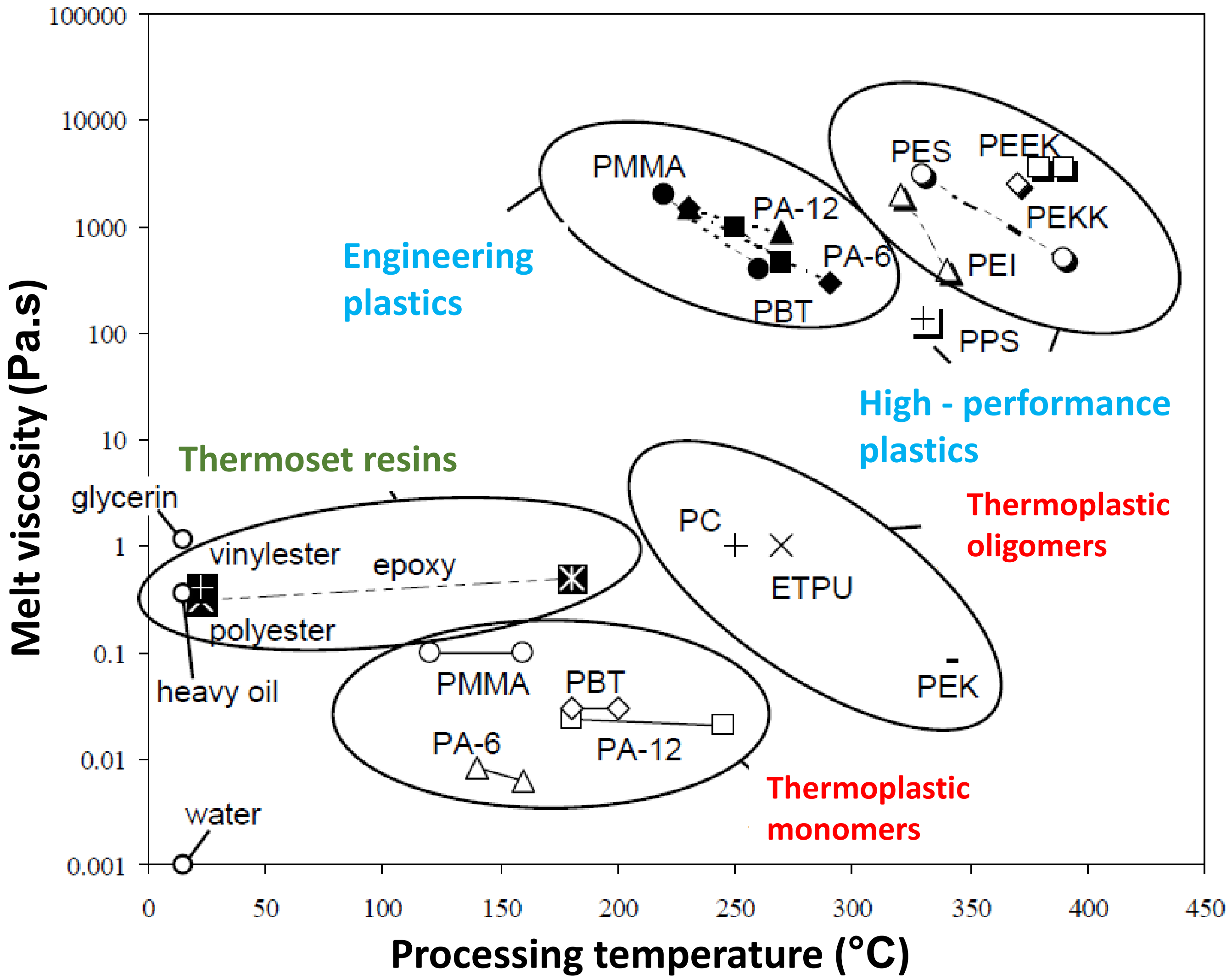
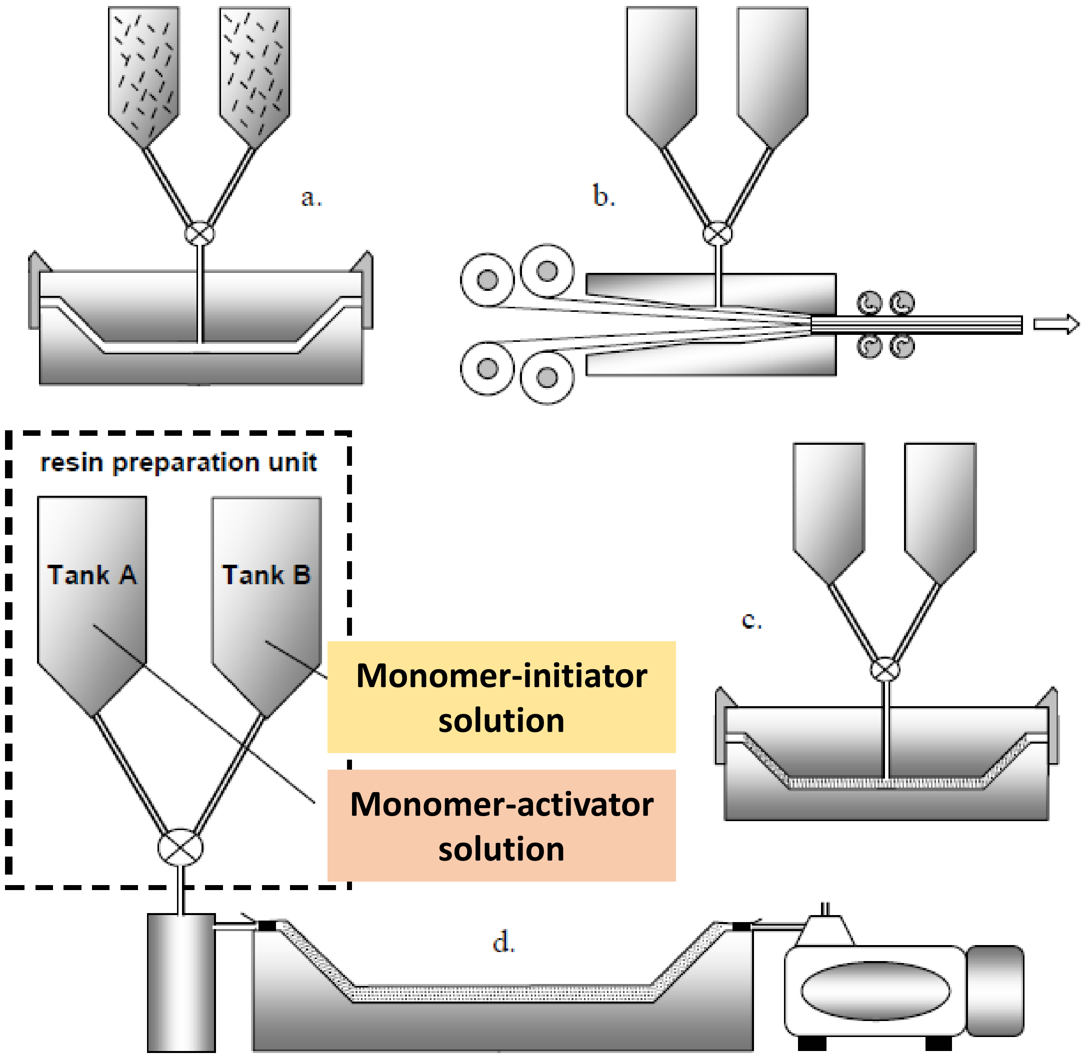
Melt viscosity of thermoplastics



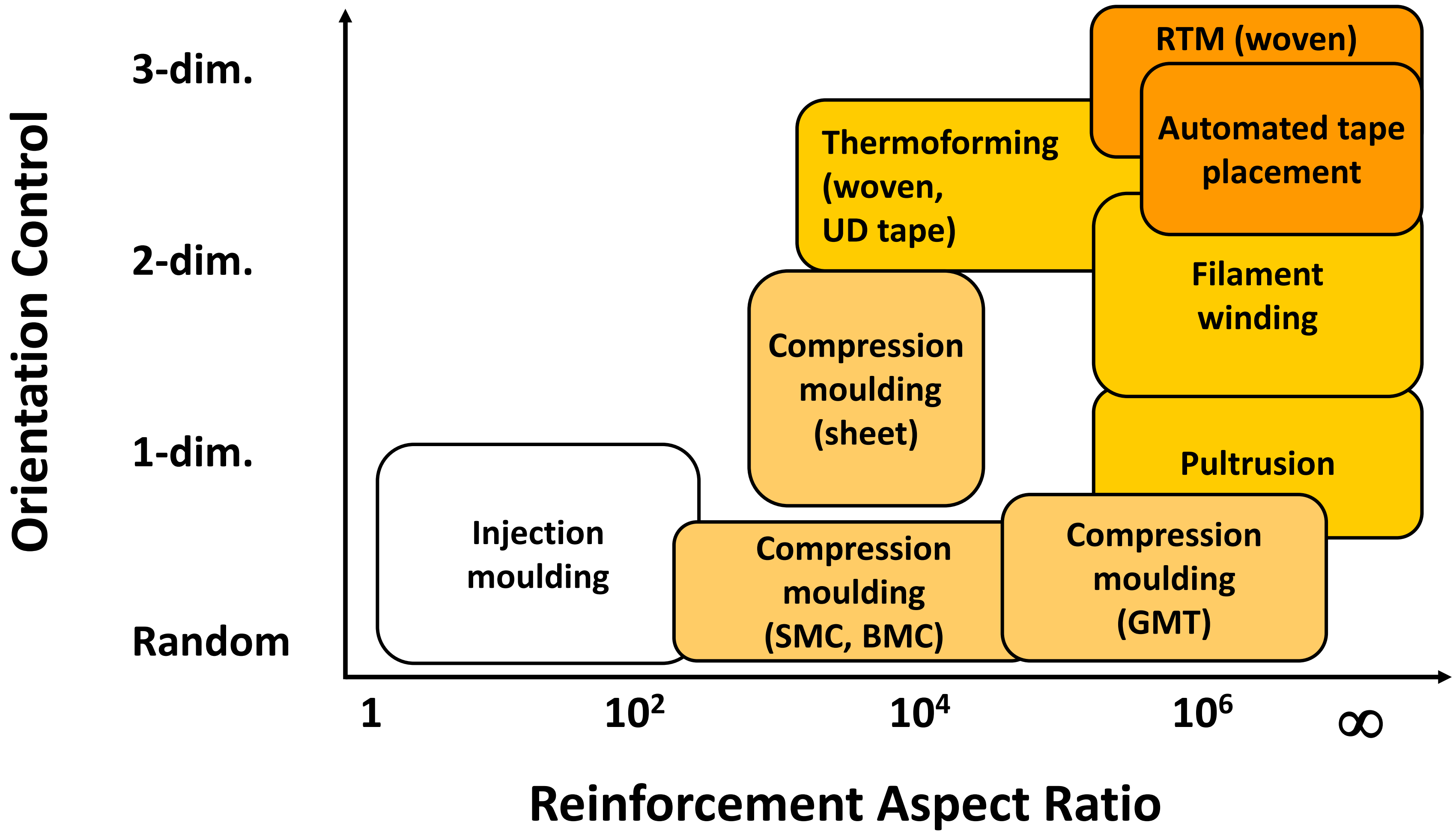
Kjelt VAN RIJSWIJK, 2007

In-situ polymerization processes



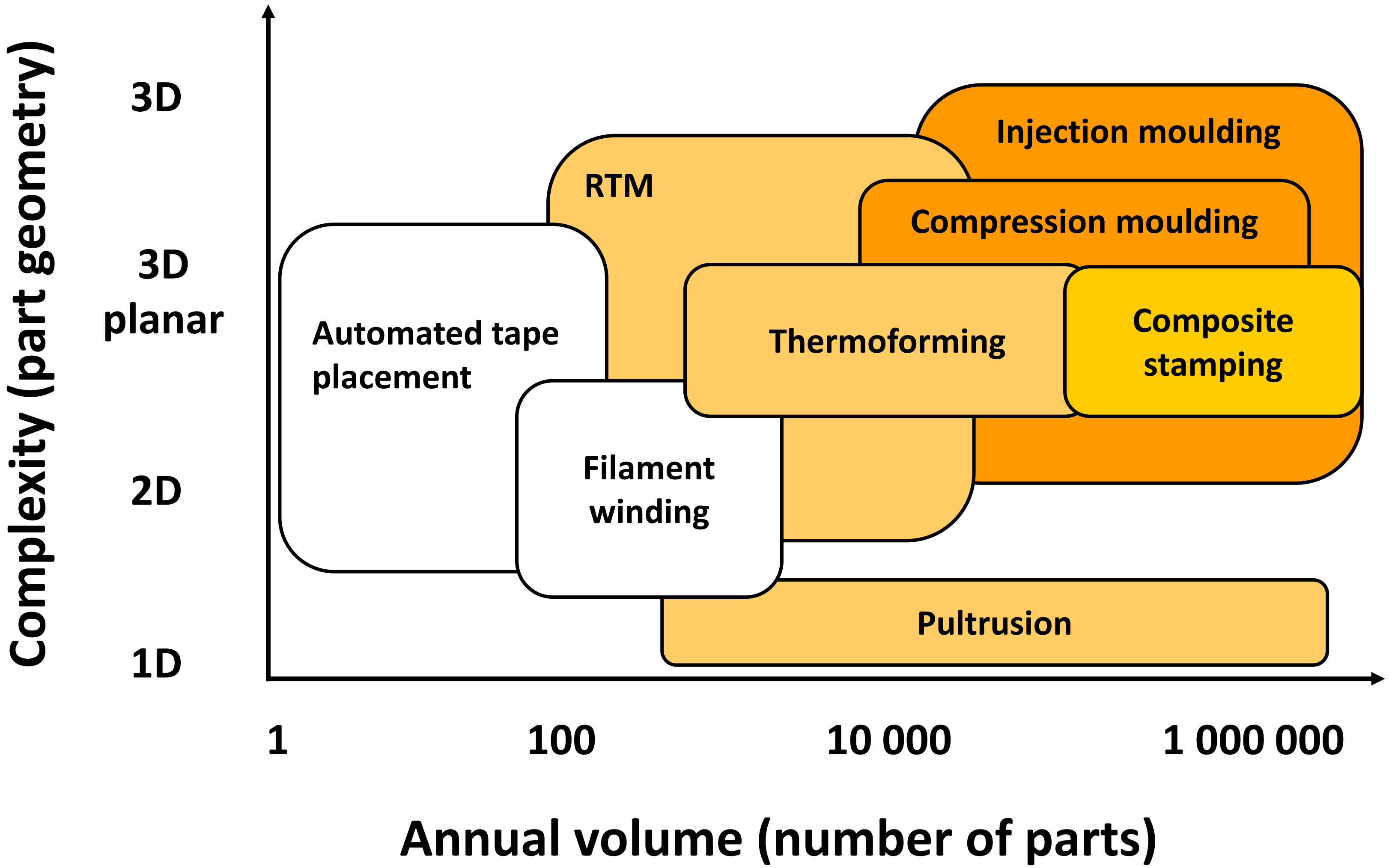
Kjelt VAN RIJSWIJK, 2007

Anisotropy and reinforcement



Comprehensive Composite Materials 2-16 Composite Processing and Manufacturing - An Overview

Geometric complexity



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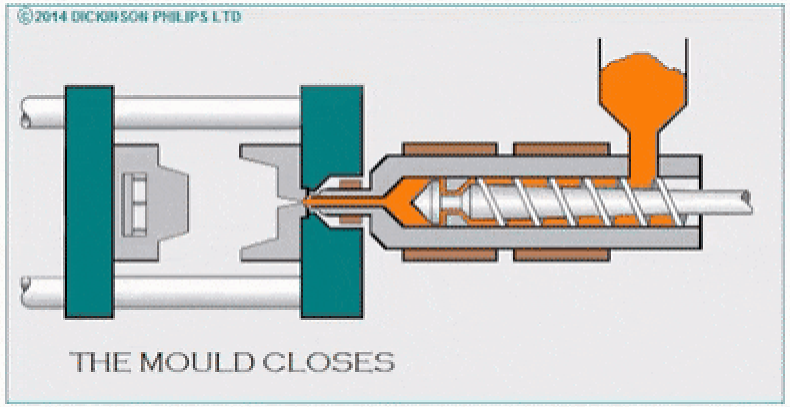
Injection moulding



$

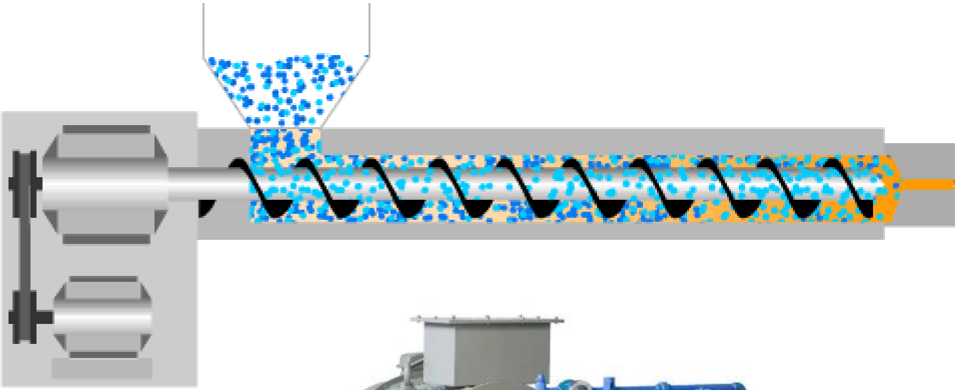
fast

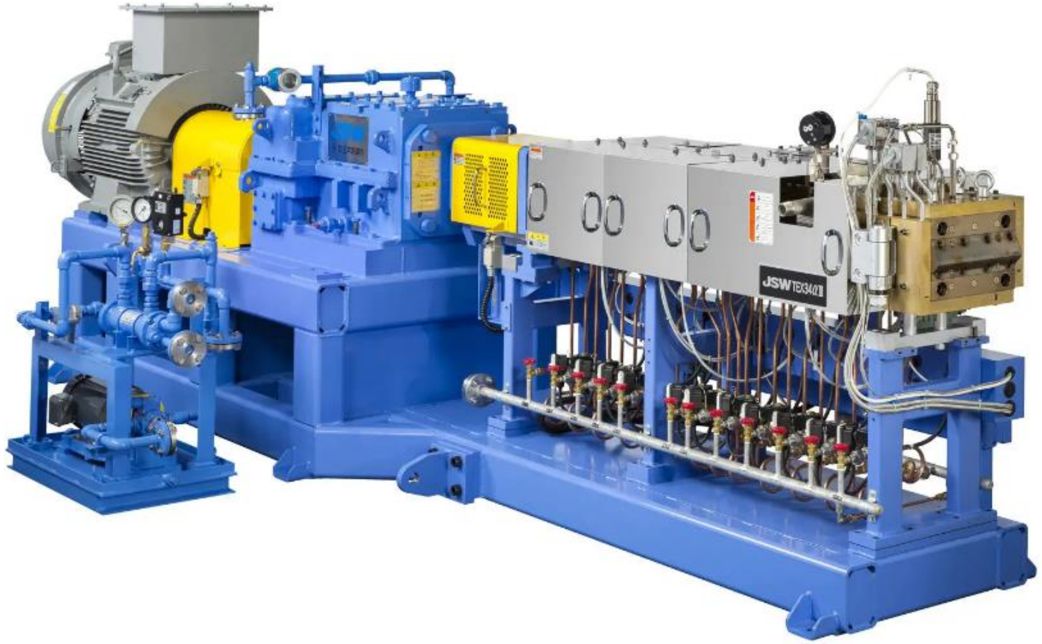
small

low - medium

Polyplastics Co., Ltd.

Extrusion





$

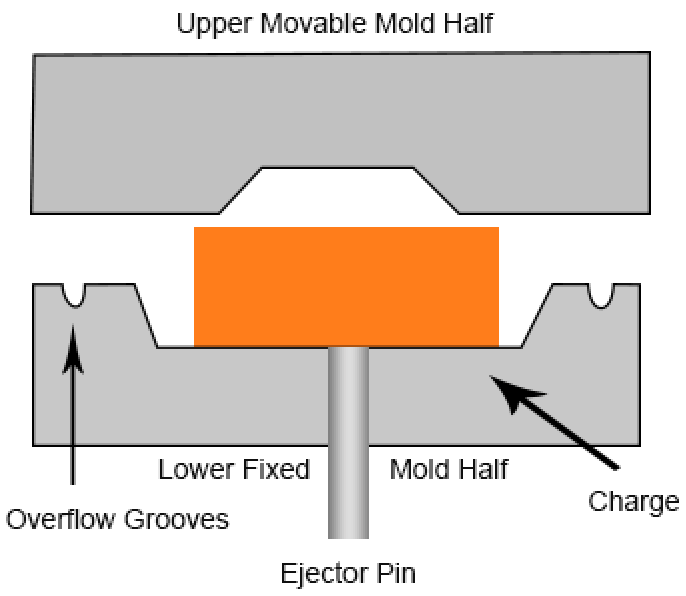
fast

small - medium

low - medium

www.directindustry.com

Compression moulding



$

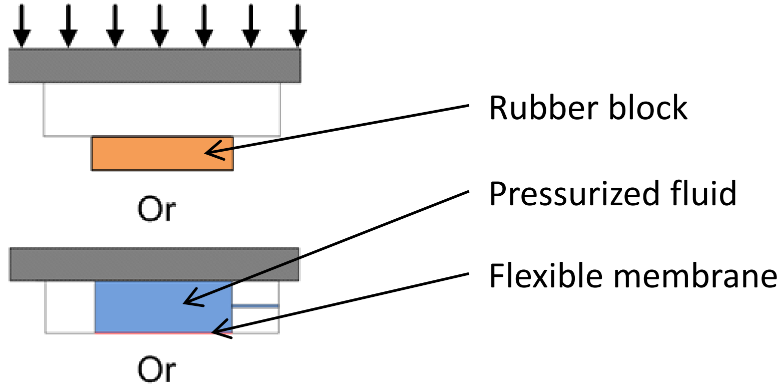
fast

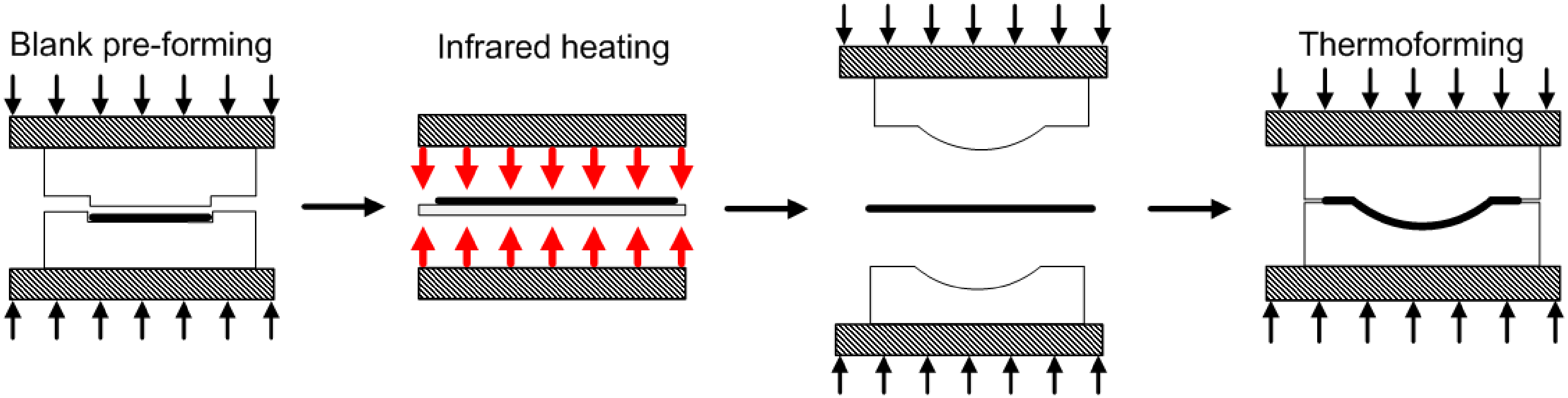
small - medium

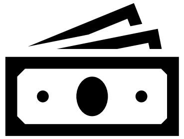
medium

icomold.com/compression-molding/

Thermoforming







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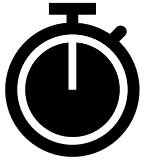
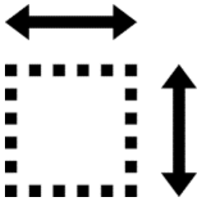


fast

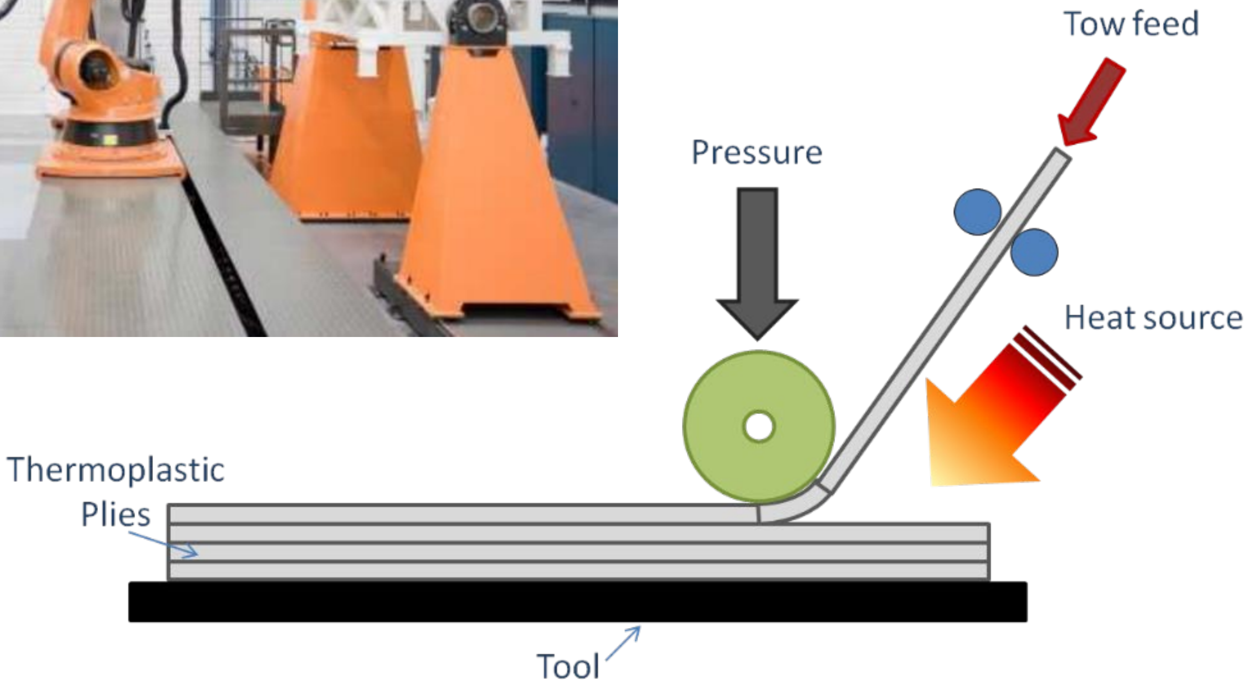


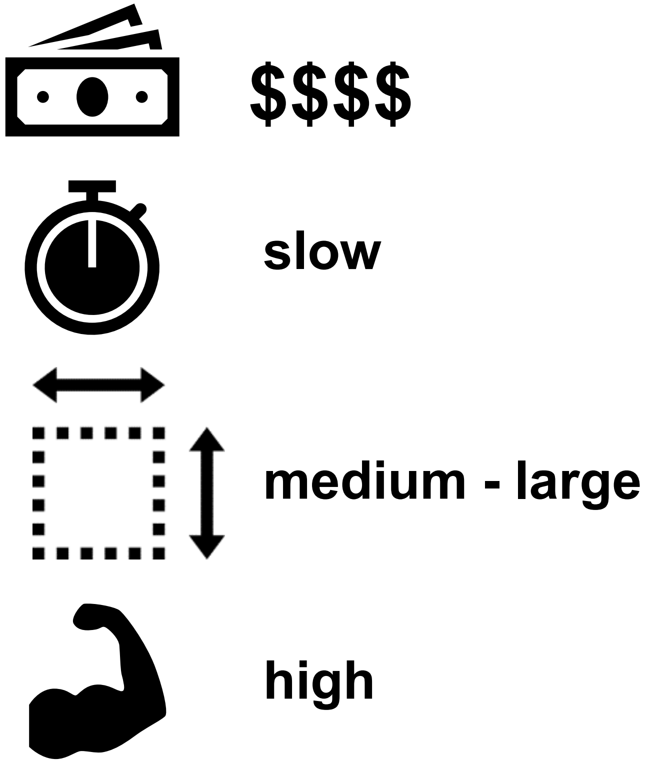
medium

medium

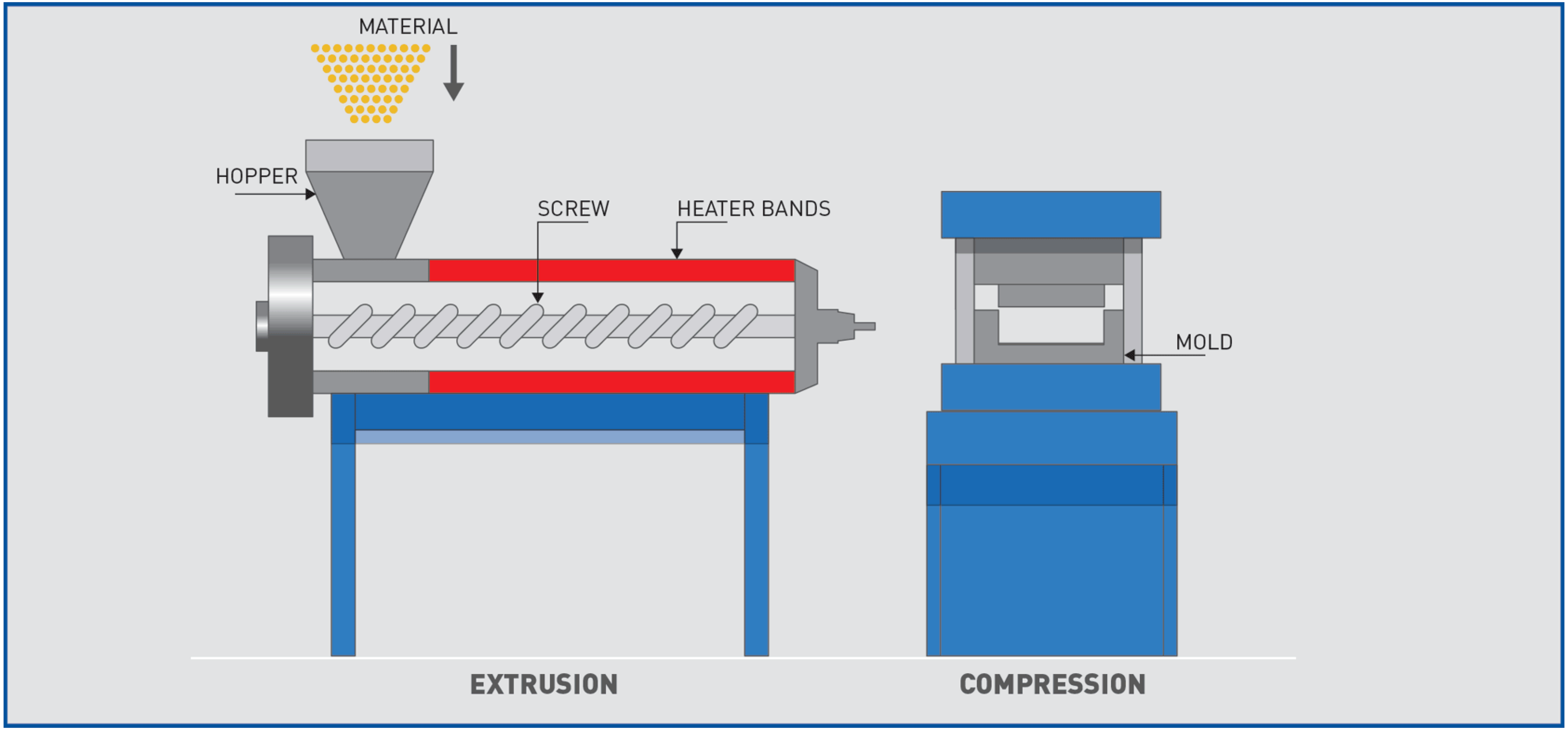
www.fostoriaprocessequipment.com

Automated tape placement (ATP)

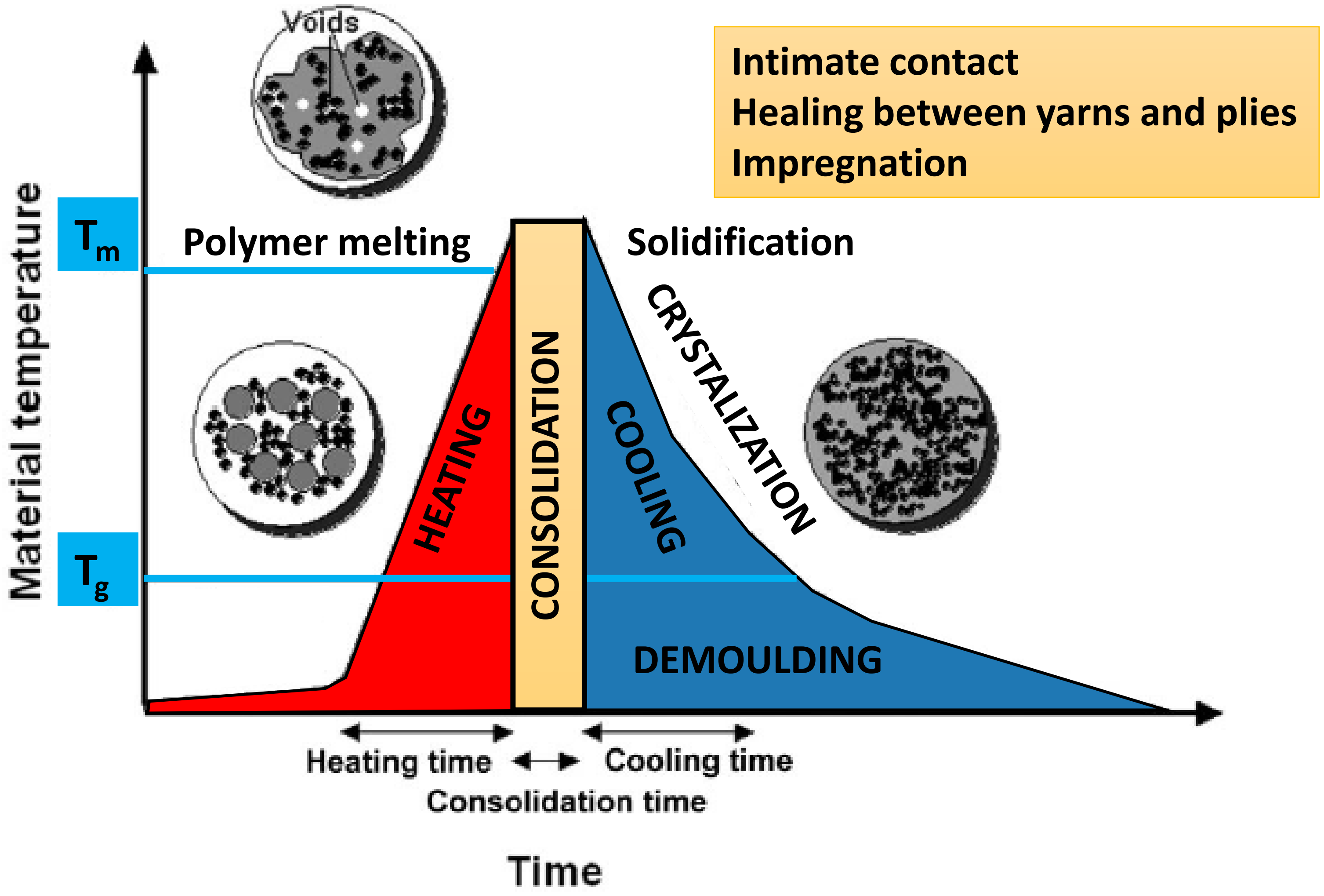




Extrusion compression moulding

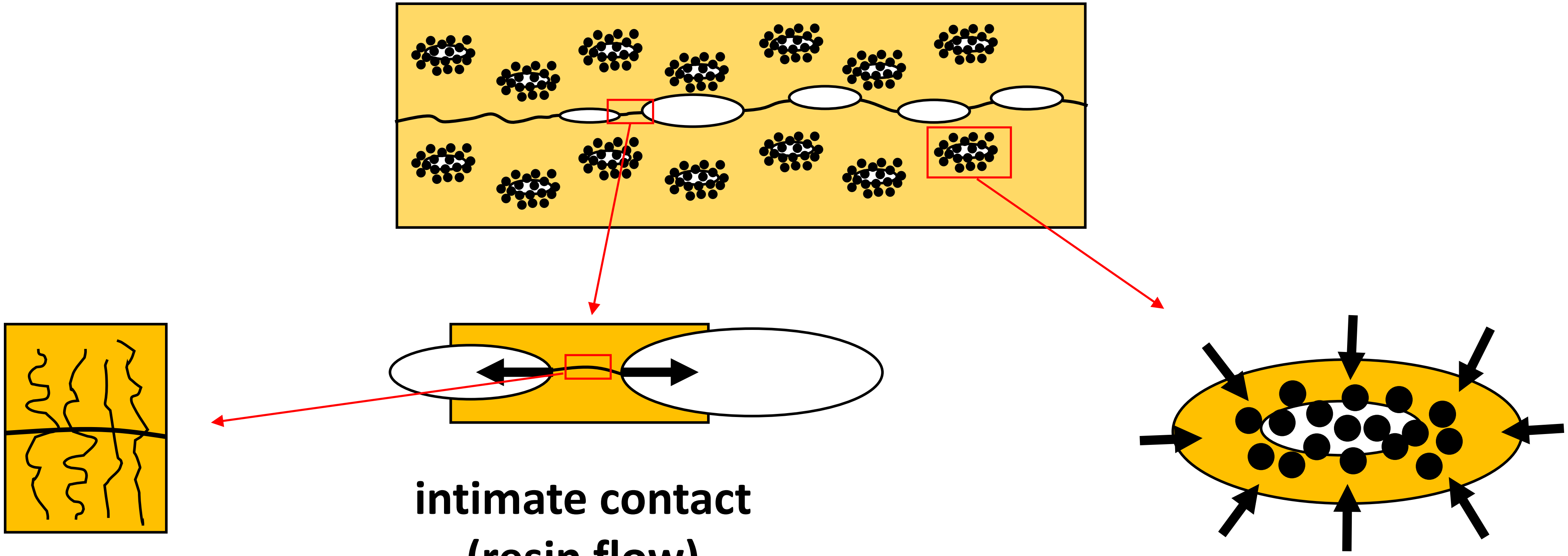


Thermoplastic transformations



Comprehensive Composite Materials 2-16 Composite Processing and Manufacturing - An Overview

Consolidation steps



intimate contact
(resin flow)

autohesion

fibre impregnation

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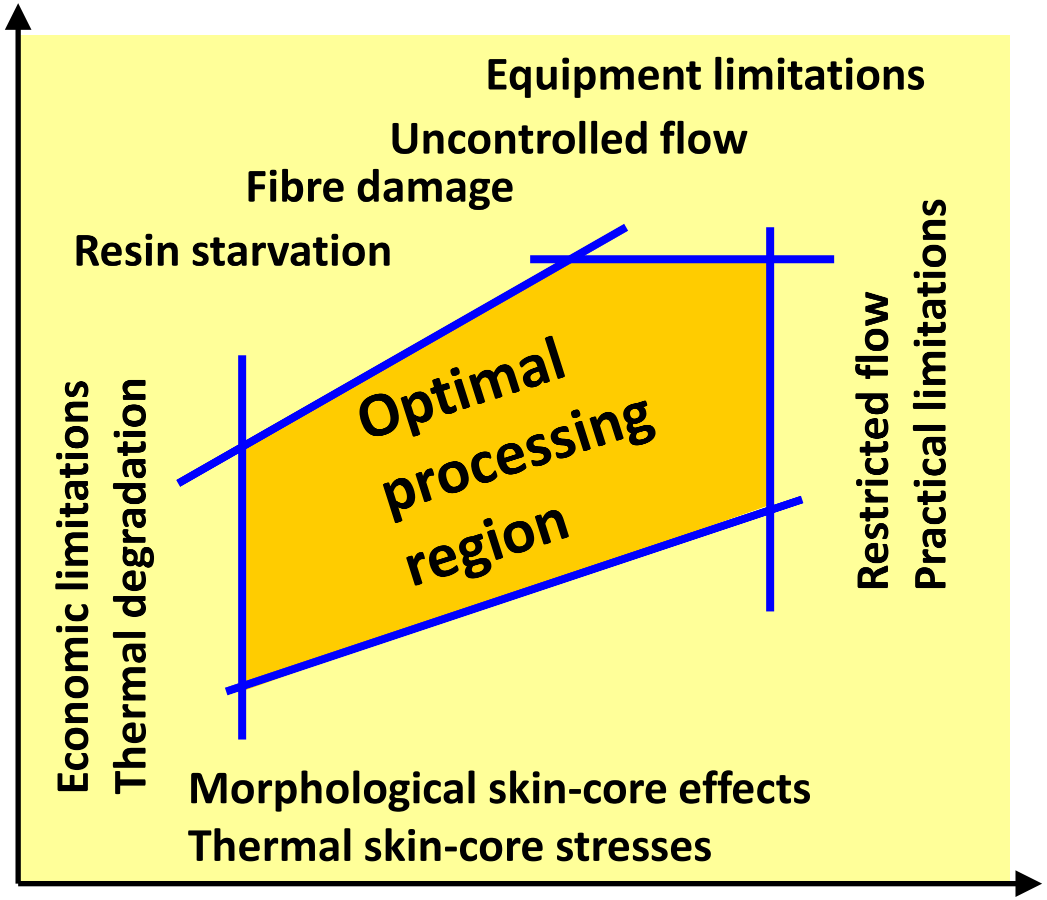
Processing window

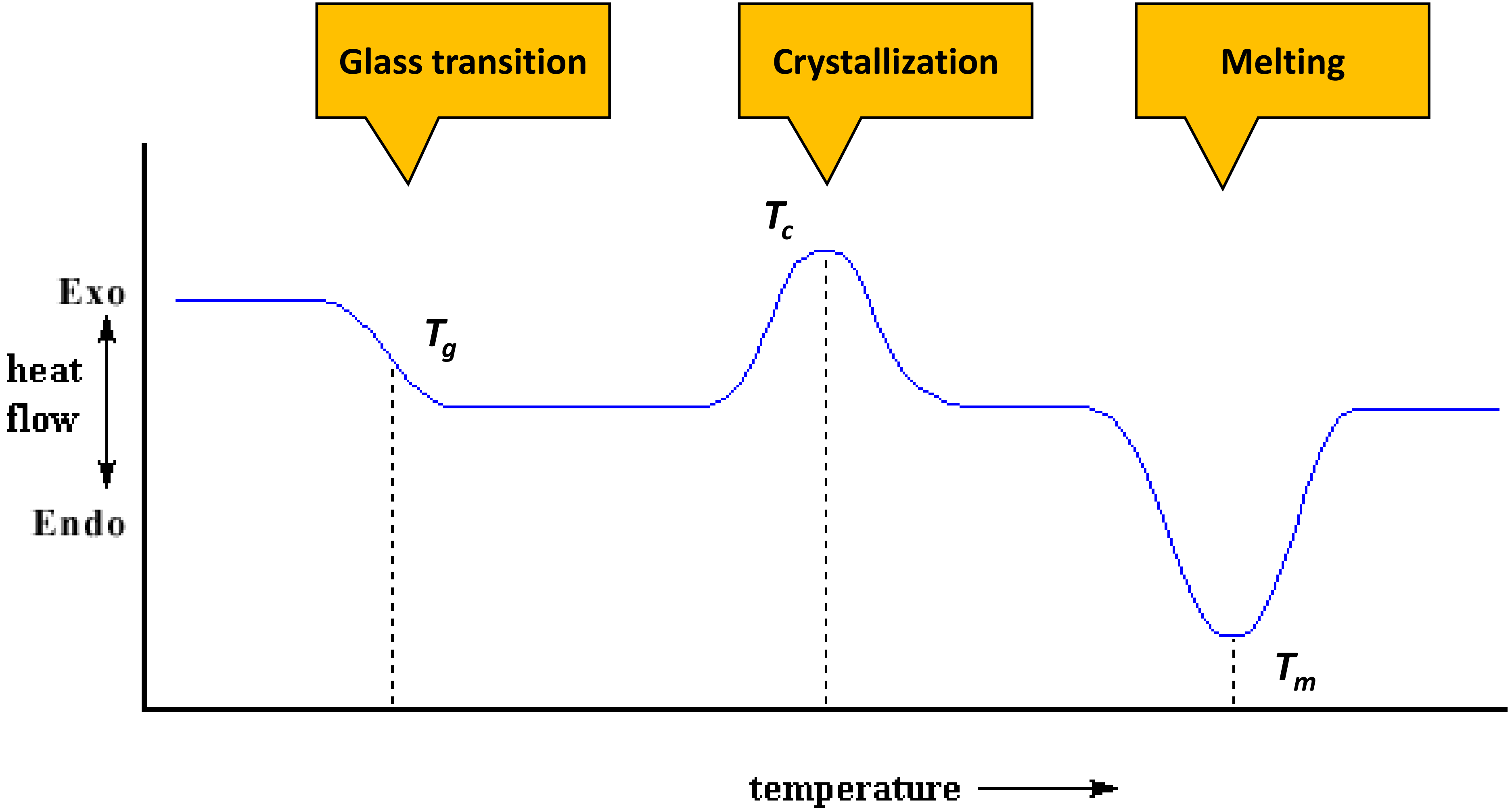


Comprehensive Composite Materials 2-16 Composite Processing and Manufacturing - An Overview

Thermoplastics characterization procedures

- **Thermal stability** (TGA)
  - **Crystallinity** (DSC)
    - **Volumetric change Shrinkage** (TMA)
  - **Rheological** (Rheometer)
    - **Modulus** (DMA)
  - **Glass transition** (DSC, DMA, TMA)
    - **Volumetric change CTE** (TMA)

Differential scanning calorimetry



Questions in ATP manufacturing

- What is the temperature of the material during processing?
- What are the heating and cooling rates?
- How does the processing affect the polymer crystallinity?

Material systems

- Semi-crystalline thermoplastic polymer
  - Poly-ether-ether-ketone (Cytec-PEEK)
  - Poly-ether-ketone-ketone (Cytec-PEKK)
- Carbon fibre reinforcement/thermoplastic matrix tape
  - Cytec-APC2/PEEK
  - Cytec-APC/PEKK

	T_g [°C]	T_m [°C]	$T_{Processing}$ [°C]
PEEK	143	343	380-400
PEKK	154	308	340-370

Crystallinity characterization method

- Using a DSC:
  - Melt film to 380°C at heating rate of 10°C/min
  - Hold for 5 minutes
  - Cool at desired cooling rate (0.5-30°C/min) to 20°C

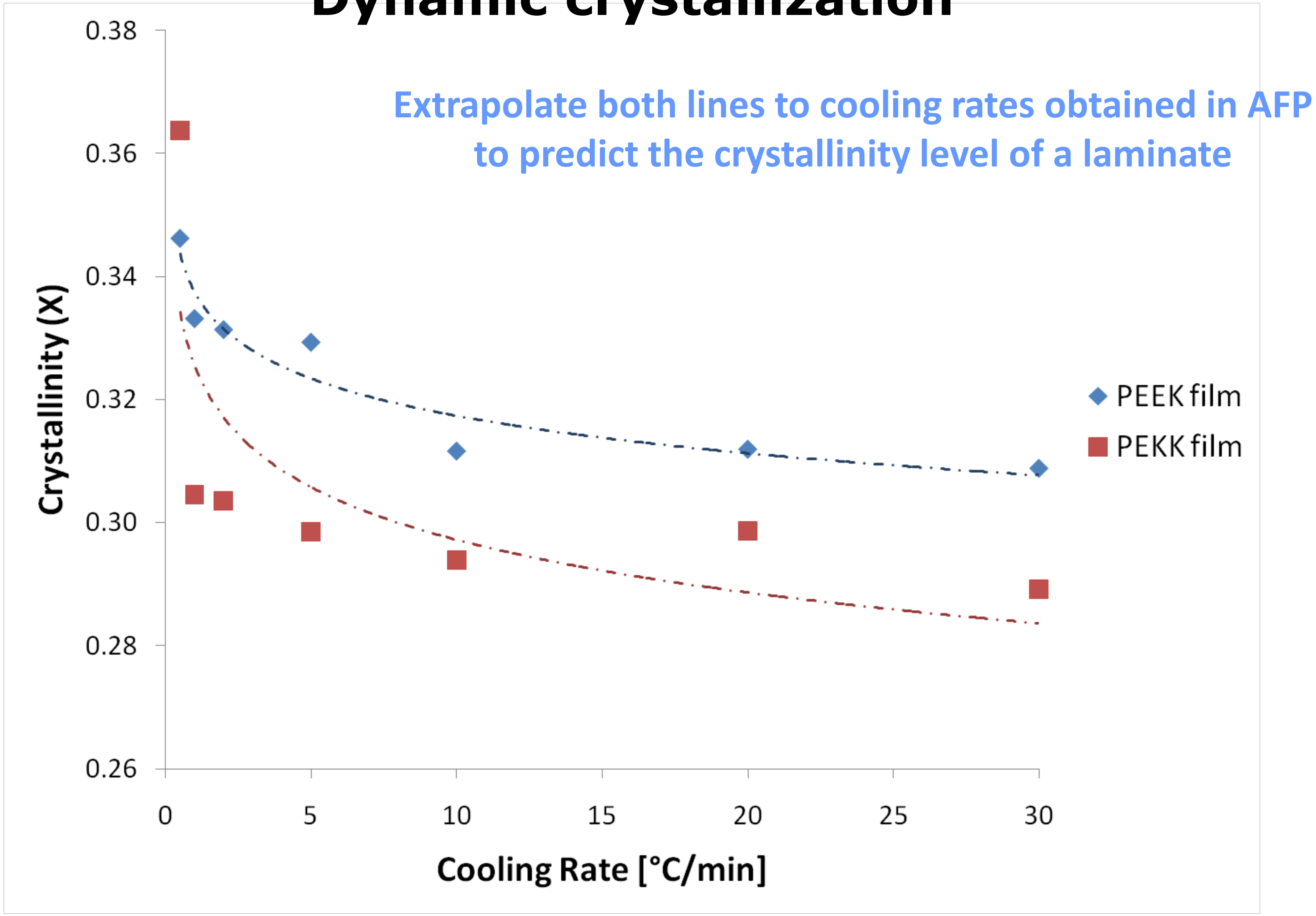
crystallinity

heat of crystallisation

$$X = \frac{H_c}{H_u}$$

Ultimate heat of crystallization for PEEK and PEKK: H_u=130J/g

Dynamic crystallization



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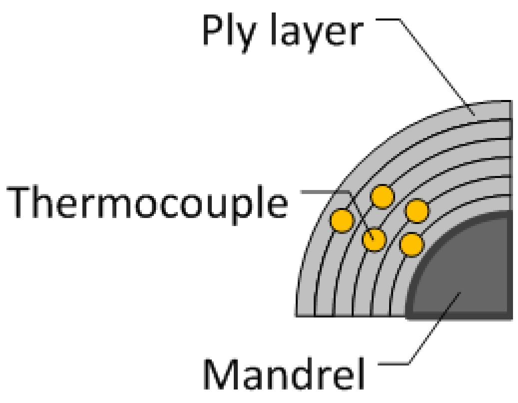
Experimental plan



Manufacture rings 80 layers thick on 15 cm diameter mandrel

↓

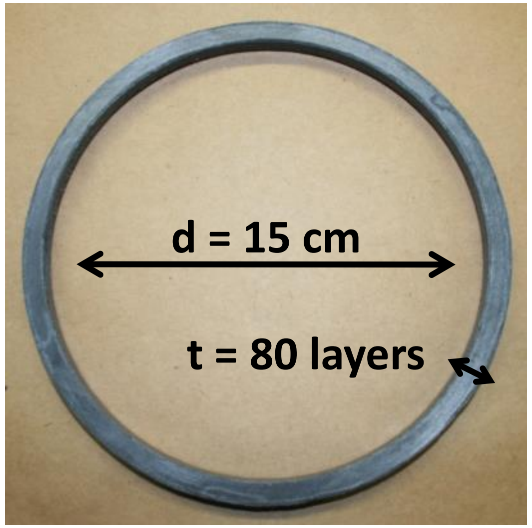
Insert thermocouples between every 10 plies during processing

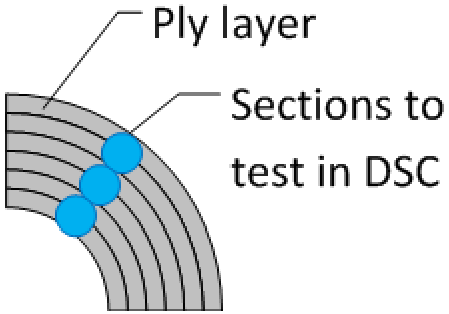
↓

Allow the ring to cool completely post processing

↓

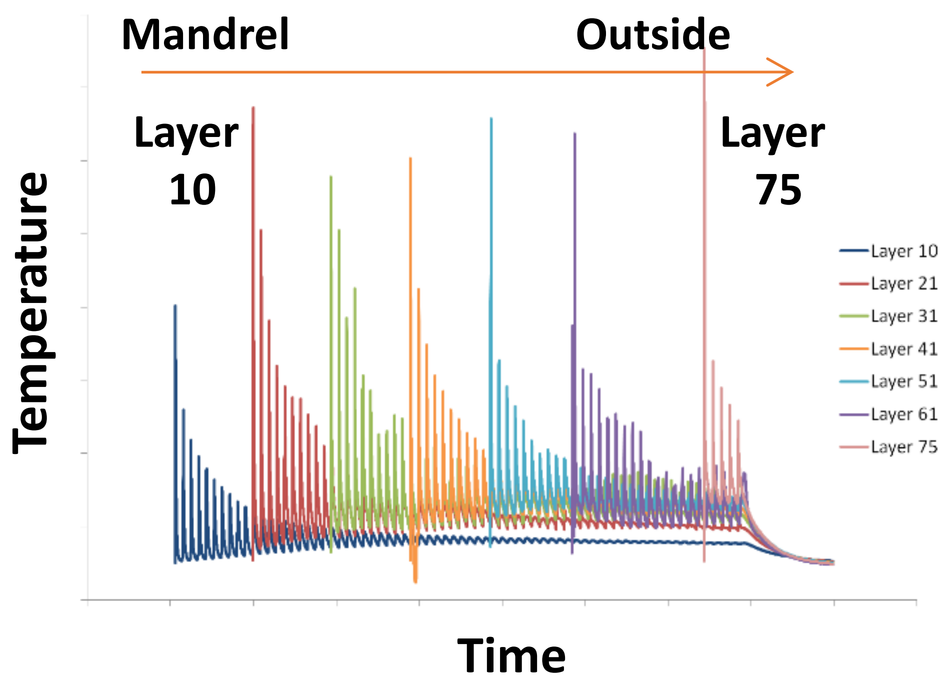
Measure crystallinity level through the thickness by DSC



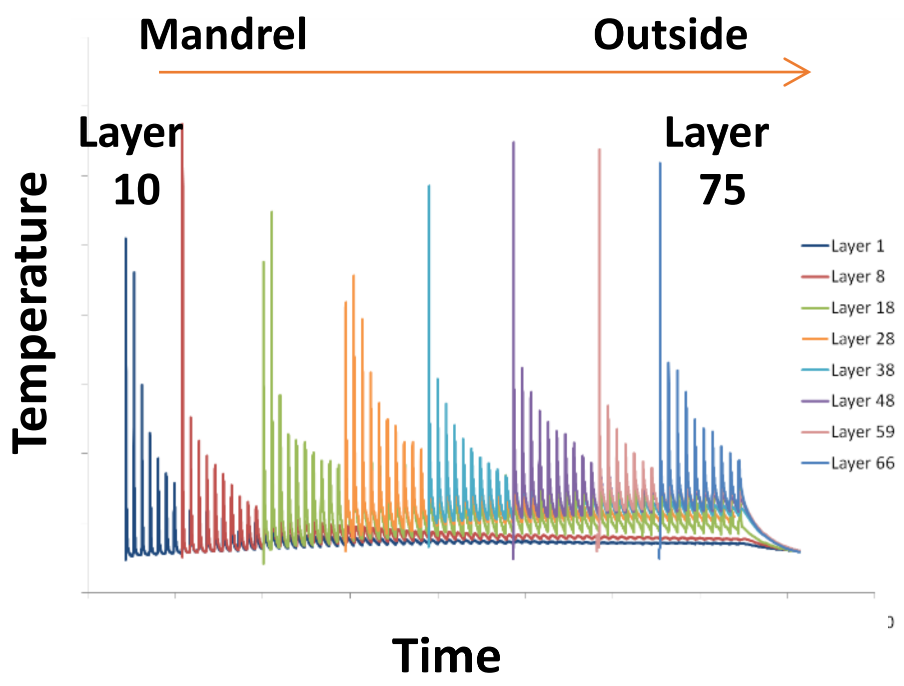


Temperatures during AFP

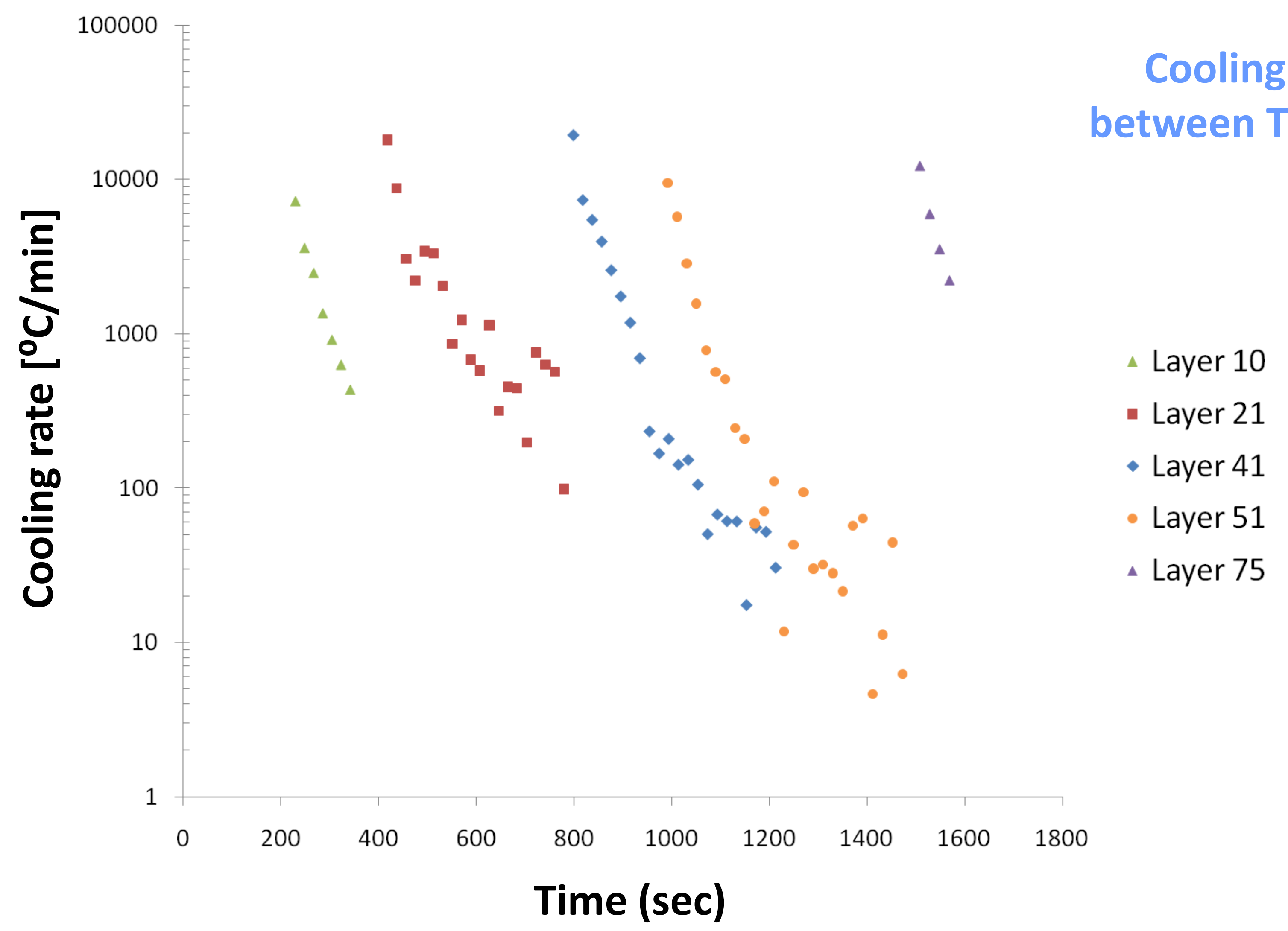
PEEK Ring



PEKK Ring

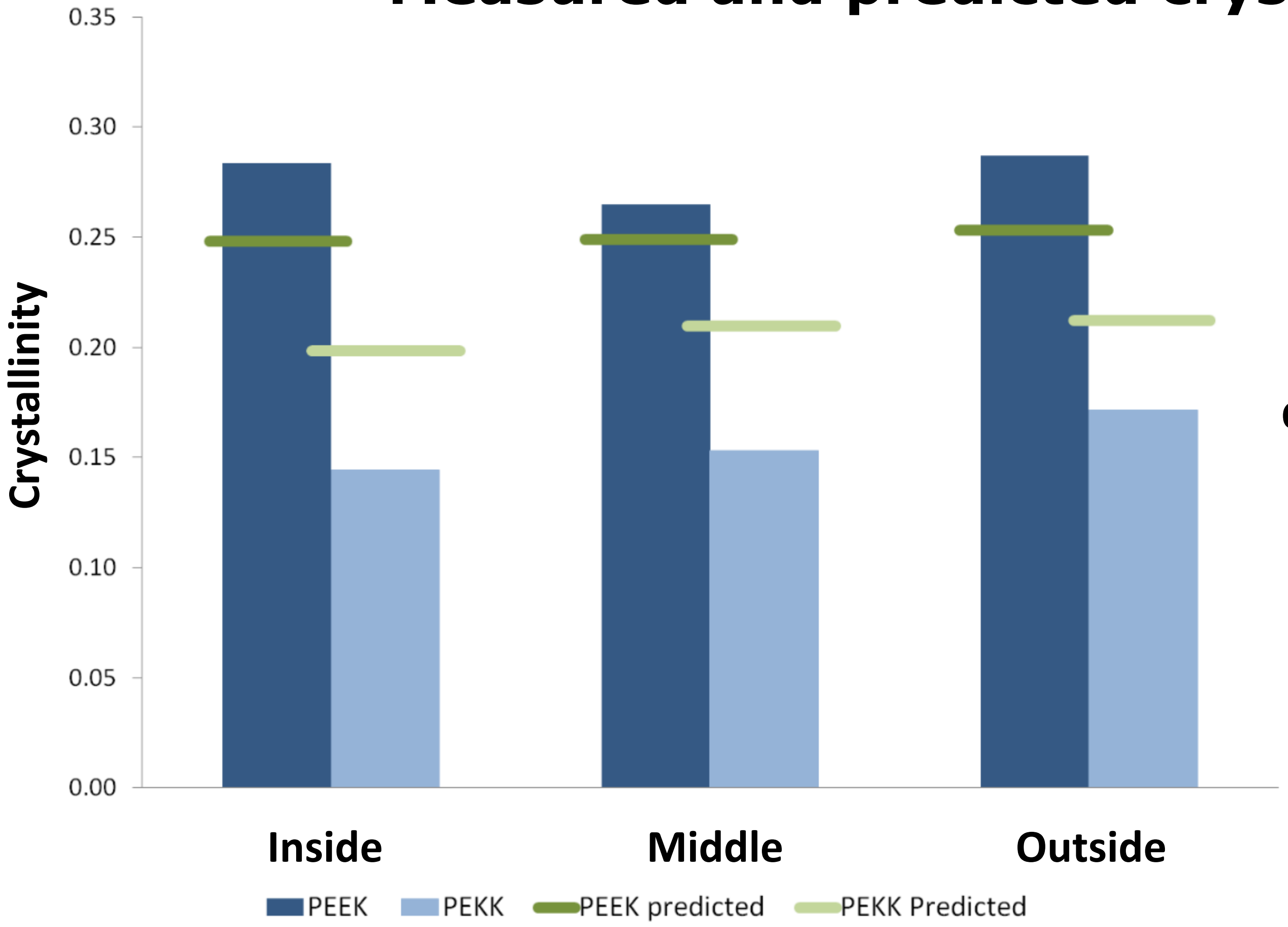


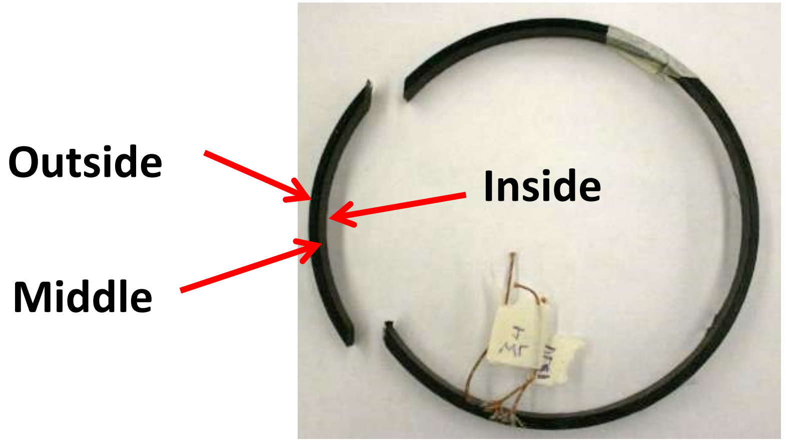
Process cooling rates of PEEK ring



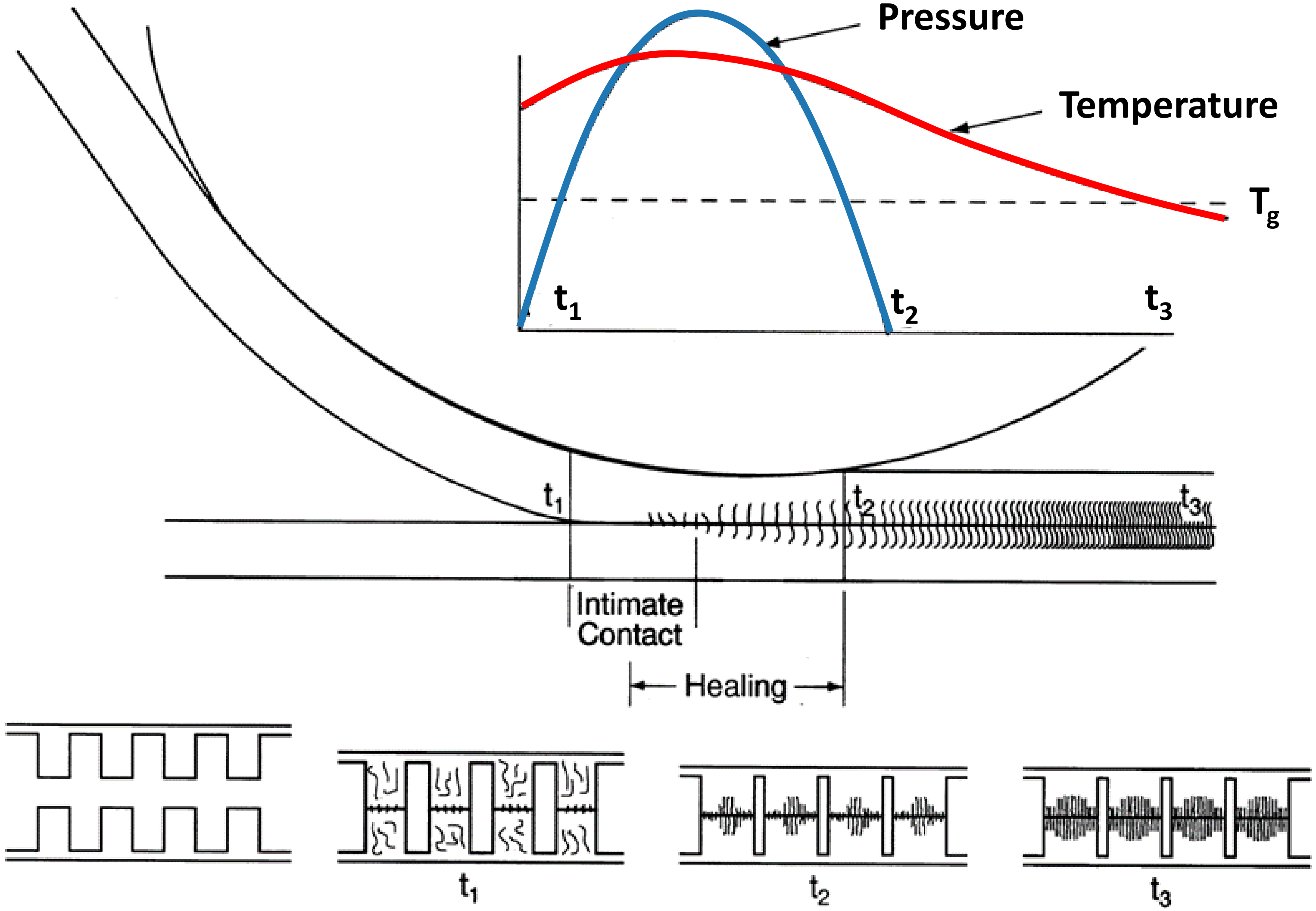
Cooling rate between T_m and T_g

Measured and predicted crystallinity





ATP processing window



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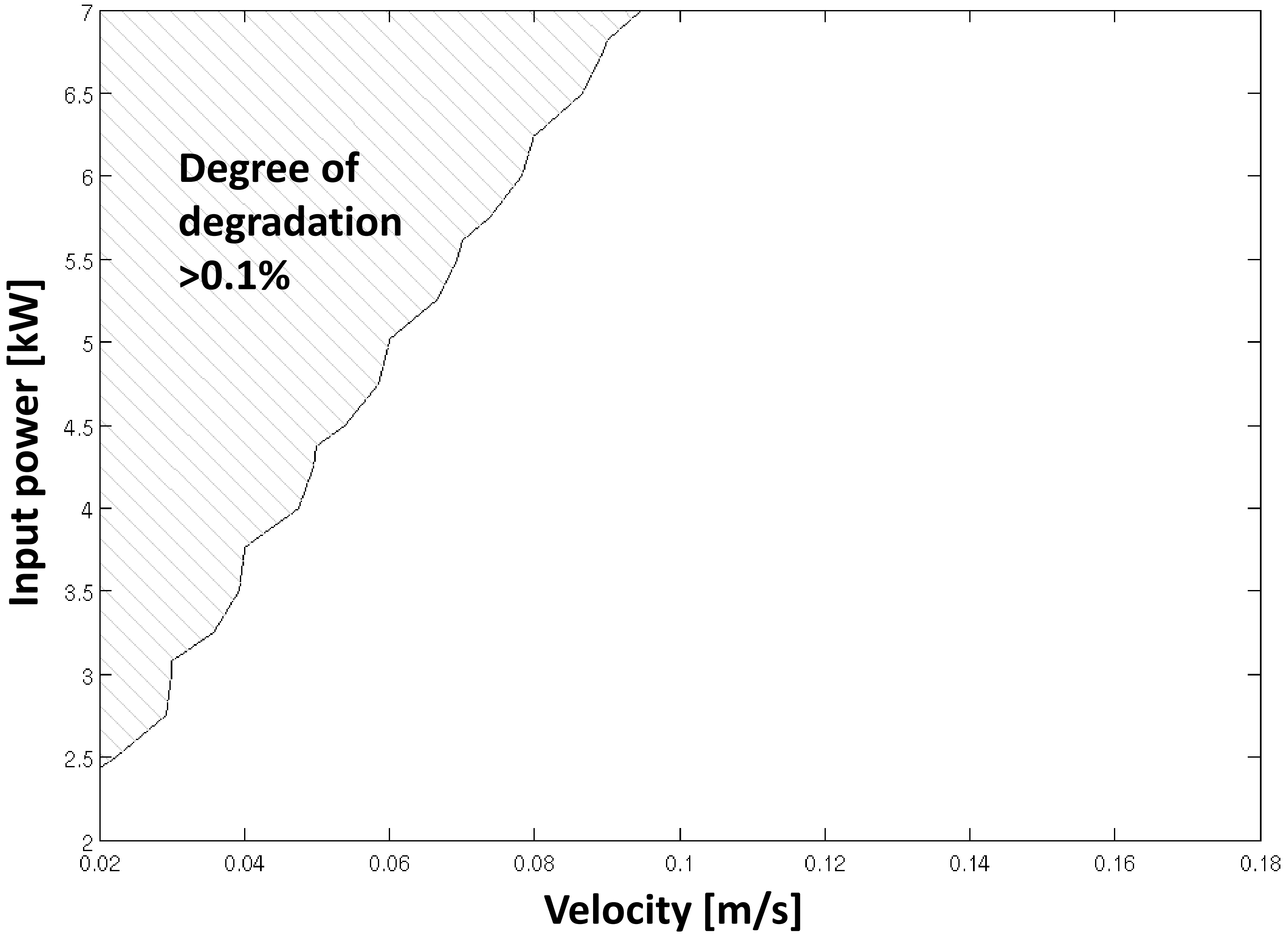
Degradation



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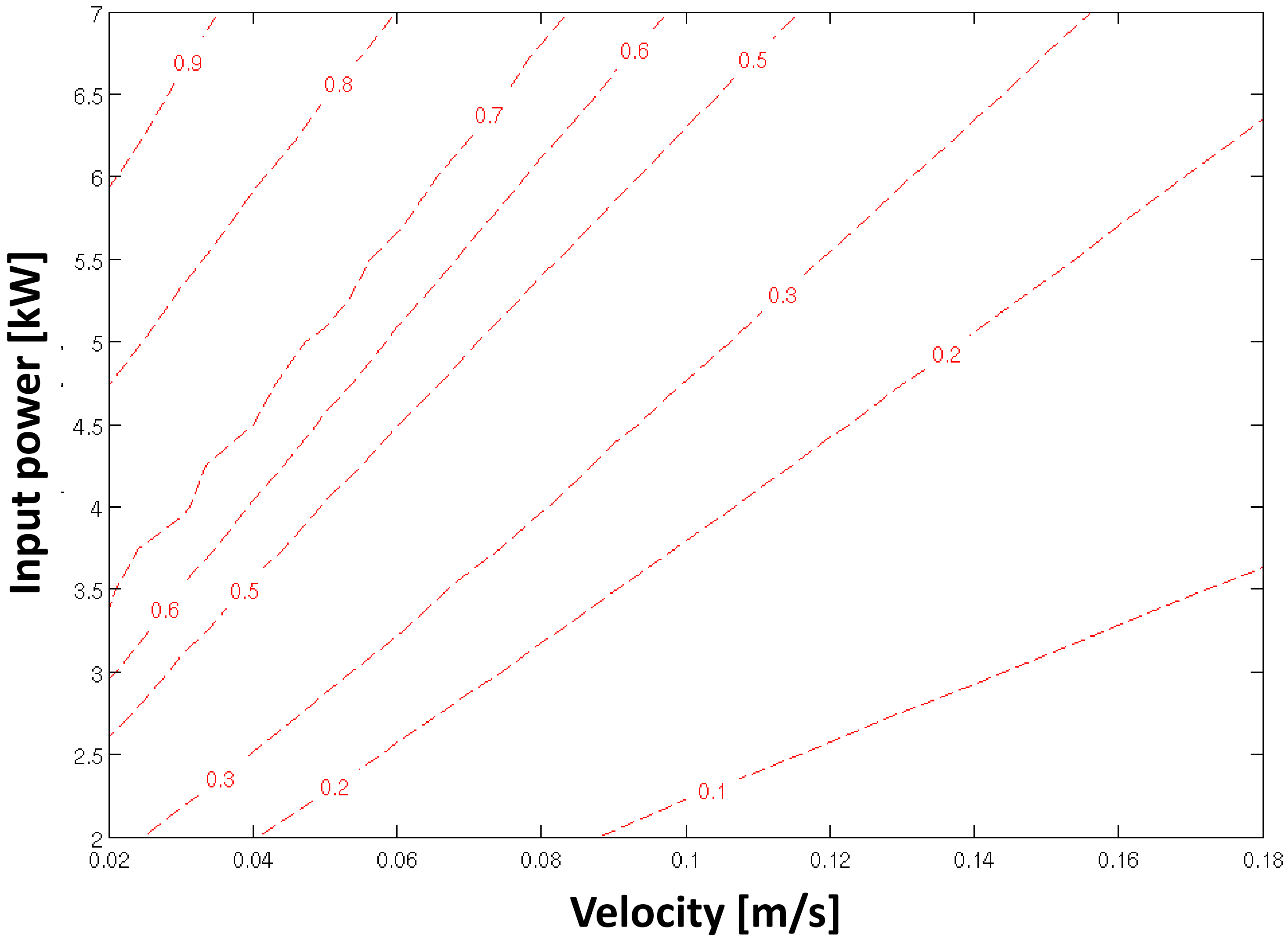
Levy, A., et al. (2012). Simulation And Optimization Of The Thermoplastic Automated Tape Placement (ATP) Process. SAMPE - Baltimore.

Minimum bonding



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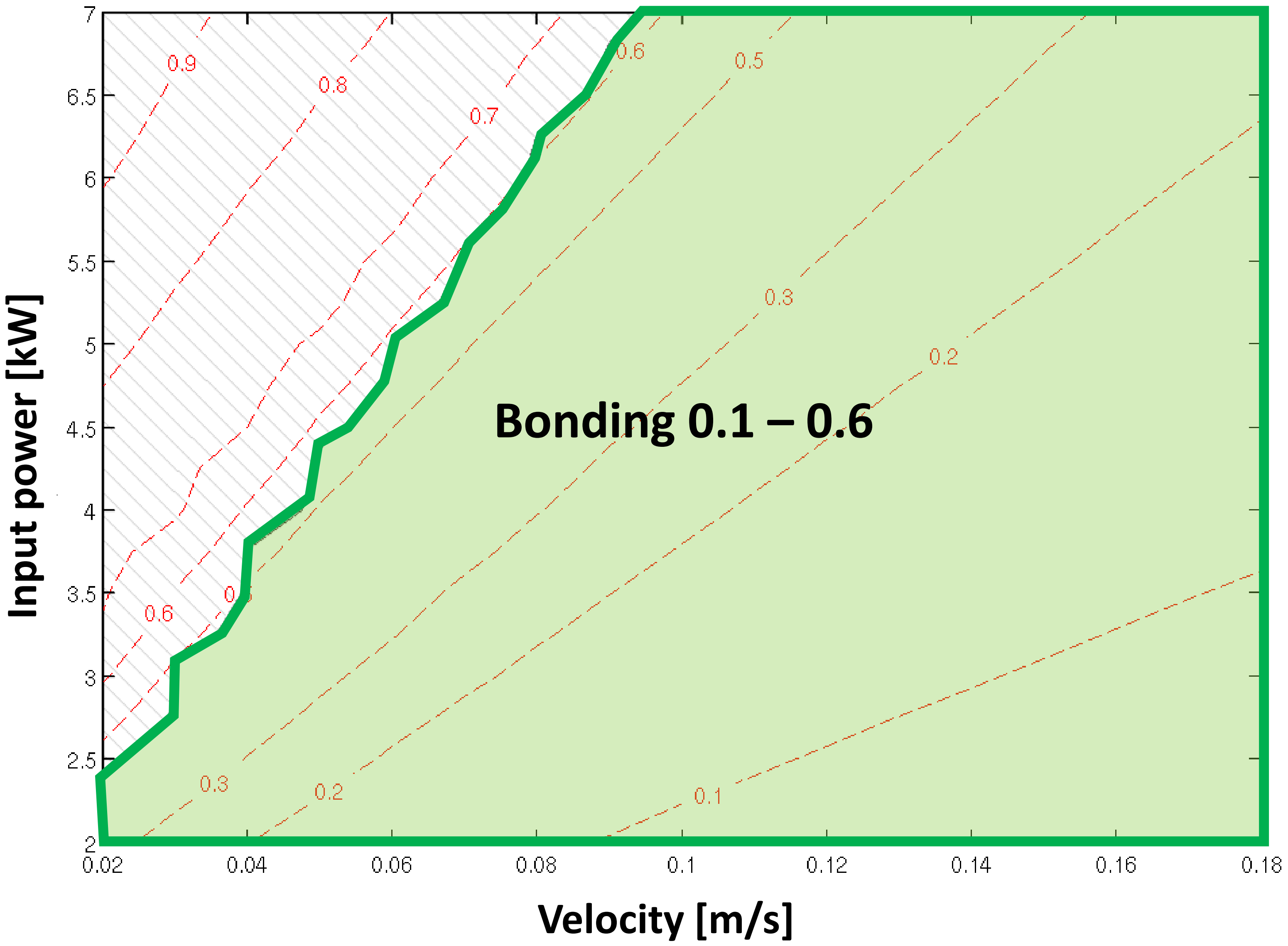
Levy, A., et al. (2012). Simulation And Optimization Of The Thermoplastic Automated Tape Placement (ATP) Process. SAMPE - Baltimore.

Degradation and bonding



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Summary

Pros

- Good toughness and damage resistance
- Low moisture uptake
- Fire retardancy
- Low void content
- Short cycle time
- Infinite shelf life
- Ability to re-form parts

Cons

- Higher processing temperatures
- High initial raw material cost over thermosets
- High tooling cost
- Traditional part maker unfamiliarity with current thermoplastic composite processing options

References

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Thank you for joining us!

Keep an eye out for upcoming AIM events:

Introduction to the welding of thermoplastic composites
Hosted by Dr. Martine Dube, École de Technologie Supérieure
June 22, 2022

Case Study: Optimizing a Press Moulding Process
Dr. Casey Keulen, July 27, 2022

And don't forget to visit the KPC for more information:

https://compositeskn.org/KPC

Today's Webinar will be posted at:
https://compositeskn.org/KPC/A322