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**INSA**



# Chemical Disassembly and Recycling of Electronic Devices Manufactured with Biosourced Polymers

**C. Goument**<sup>1,2</sup>, T. Gerges<sup>1</sup>, F. Da Cruz-Boisson<sup>2</sup>, A. Crepet<sup>2</sup>, B. Allard<sup>1</sup>,  
J.-Y. Charmeau<sup>2</sup>, M. Cabrera<sup>1</sup>

<sup>1</sup>Univ Lyon, INSA Lyon, Université Claude Bernard Lyon 1, Ecole Centrale de Lyon, CNRS, Ampère, UMR 5005, 69621 Villeurbanne, France

<sup>2</sup>Univ Lyon, INSA Lyon, Université Claude Bernard Lyon 1, CNRS, IMP, UMR 5223, 69621 Villeurbanne, France

## Contacts:

[caroline.goument@insa-lyon.fr](mailto:caroline.goument@insa-lyon.fr)

[michel.cabrera@insa-lyon.fr](mailto:michel.cabrera@insa-lyon.fr)

[jean-yves.charmeau@insa-lyon.fr](mailto:jean-yves.charmeau@insa-lyon.fr)



# BIOANTENNA project

PhD work  
at the INSA Lyon labs

Project partners



3D Plastronics lab (AMPERE), Villeurbanne  
Plastics processing site (IMP), Bellignat  
Polymers characterization (IMP), Villeurbanne



Antennas development  
and characterization



3D Plastronics



Polymer materials processing,  
characterization and recycling



Funding from AURA Region

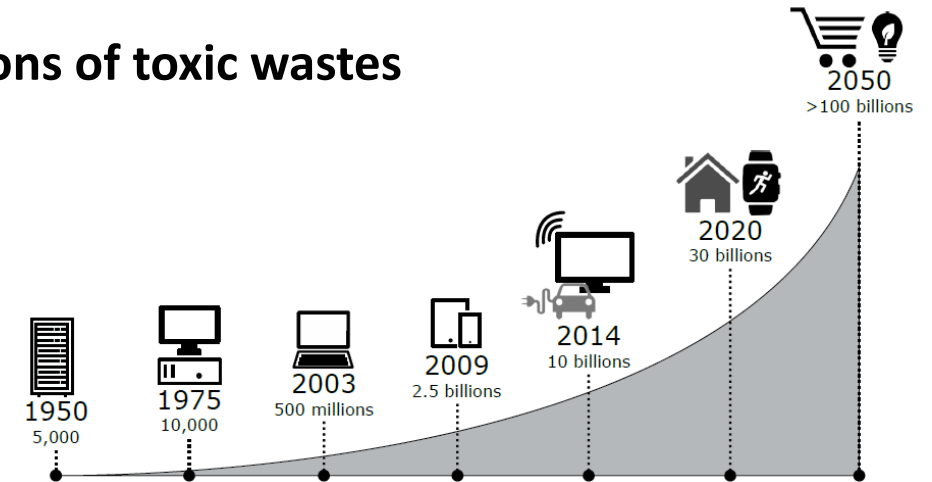
1. Context and objectives of the BIOANTENNA project
2. Polymer materials and IME technology
3. Scientific challenges
4. Experimental results
  - IME manufacturing
  - Polymer recycling
5. Conclusion

- IoT (Internet of Things) revolution towards direct interaction between objects thanks to an internet network
  - 30 billions IoT worldwide in 2020<sup>1</sup>
- **Why plastronic IoT antennas for energy storage and harvesting ?**



2019, France: 1,5 billion batteries  $\approx$  **32 500 tons of toxic wastes**

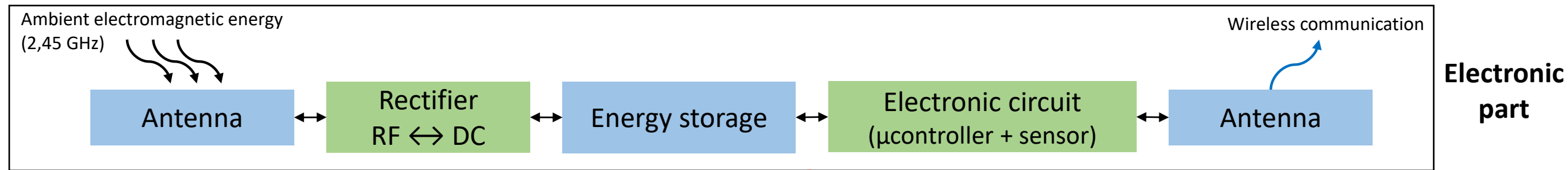
Less than **50% collected**  
**35% recycled**  
**30% thrown** in domestic wastes  
 → increasing environmental pollution



[1] Agence de la transition écologique (ADEME), *Piles et Accumulateurs – Rapport annuel 2020– Données 2019*, accessed 13/05/2021

[2] Maurizio CAPRA et al., *Edge Computing: A Survey On the Hardware Requirements in the Internet of Things World*, Department of Electrical, Electronics and Telecommunication Engineering, Politecnico di Torino, 10129 Torino TO, Italy, accessed 13/05/2021

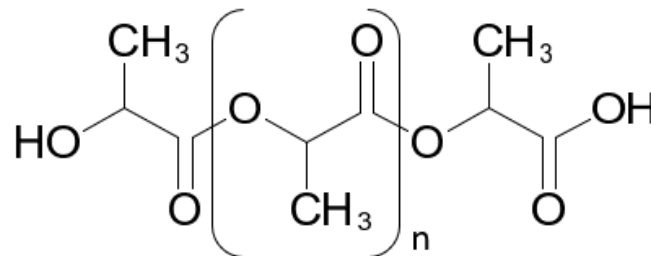
- Replacing small batteries with energy harvesting device integrated in 3D plastronic object



## In-Mold Electronics (IME) on Poly(lactic acid) (PLA)

Manufacturing discussed here

- Why PLA ?
  - Biosourced (corn starch) and biodegradable (industrial compost)
  - Very high rigidity
  - Great chemical reactivity

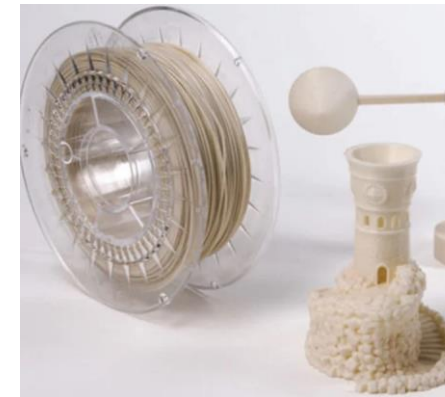


- Two thermoplastic polymers:
  - **Poly(Lactic Acid) (PLA)**, sustainable alternative for the environment
  - **PolyCarbonate (PC)**, reference material in IME

- PLA already used for:

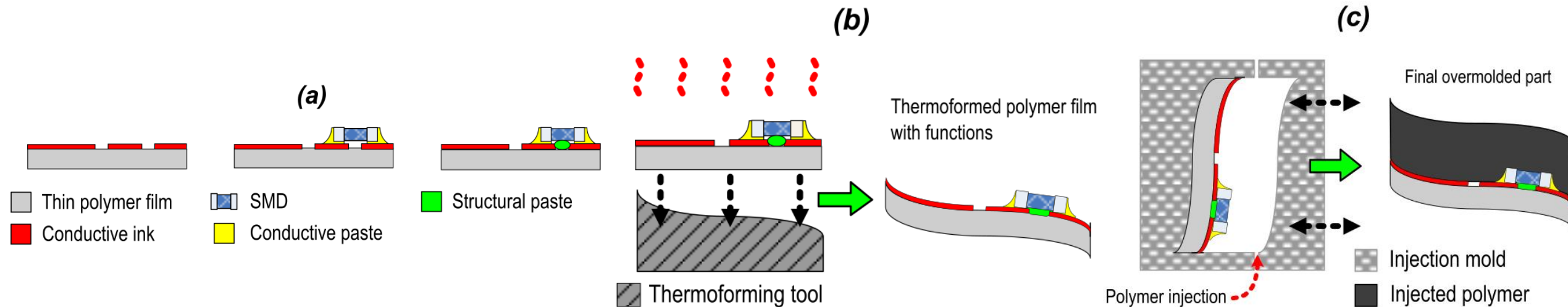
- Extrusion
- 3D printing
- Injection molding

→ Interesting choice for IME



- Main objective: determine the compatibility of PLA at each step of the IME process
- Secondary objective: determine the recycling capability of plastronic devices made of PLA

- Used to give a 3D shape to the device which enables better integration of the desired electronic functions to the object
- Main steps of the process: screen printing, thermoforming and injection molding



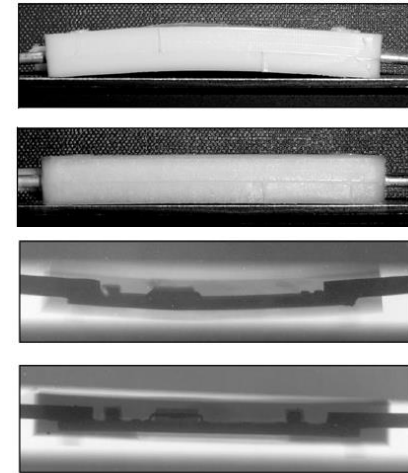
- Process in late-stage development with amorphous PC
- Not studied with semi-crystalline PLA



- MANUFACTURING

- Compatibility of inks with PLA films (adhesion, low Tg of PLA → During curing after inking?)
- Adhesion “polymer/ink+electronic components” during thermoforming?
- Adhesion “polymer/polymer” and “circuit/polymer” during injection molding?
- Thermoformability of PLA with screen printed inks and glued components (cracks, delamination of inks on PLA)?
- Injection molding: thermal shrinkage inducing warping, early deterioration, ink delamination or component shearing?

*Example of warping after injection molding<sup>3</sup>*



- DISASSEMBLY and RECYCLING

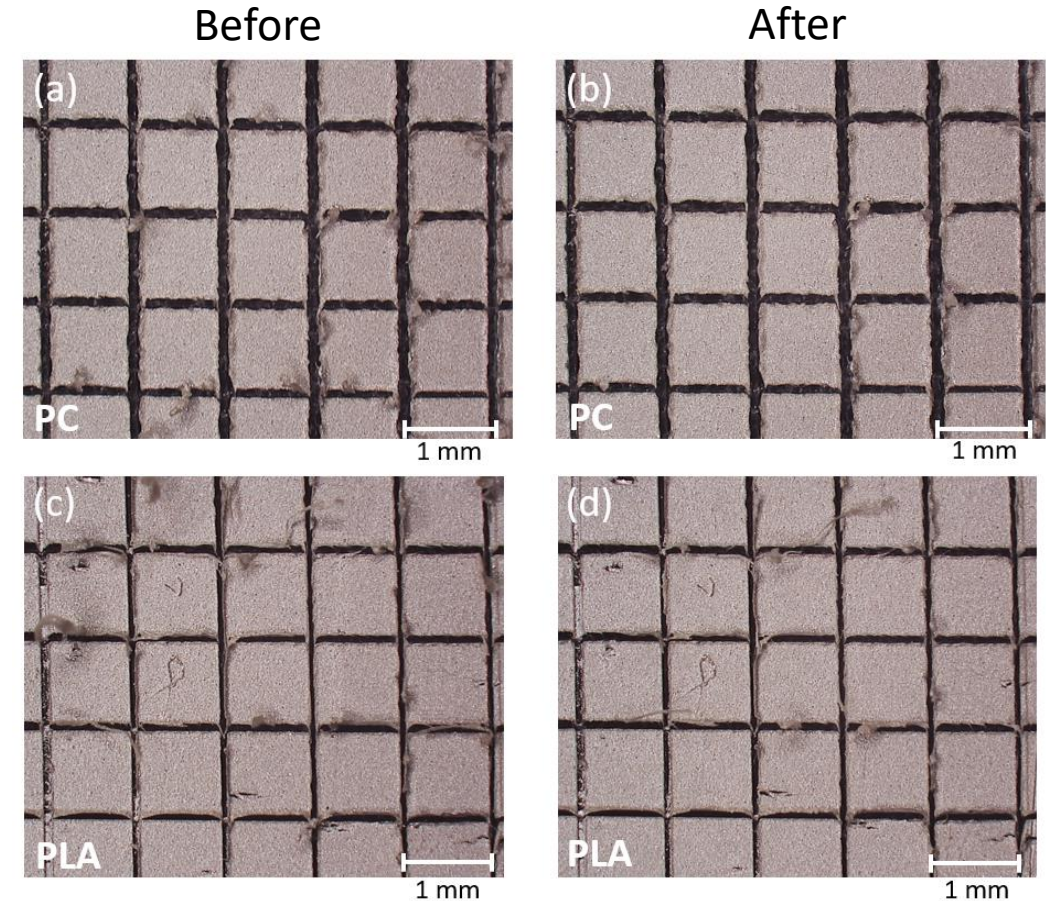
- Which method ? Mechanical, chemical, both?
- What kind of value-added products do we want?
  - Solvents, reactants?

[3] N. J. Teh et al., “Statistical optimisation of thermoplastic injection moulding process for the encapsulation of electronic subassembly,” *J. Electron. Manuf.*, Sep. 2000

# The IME process steps

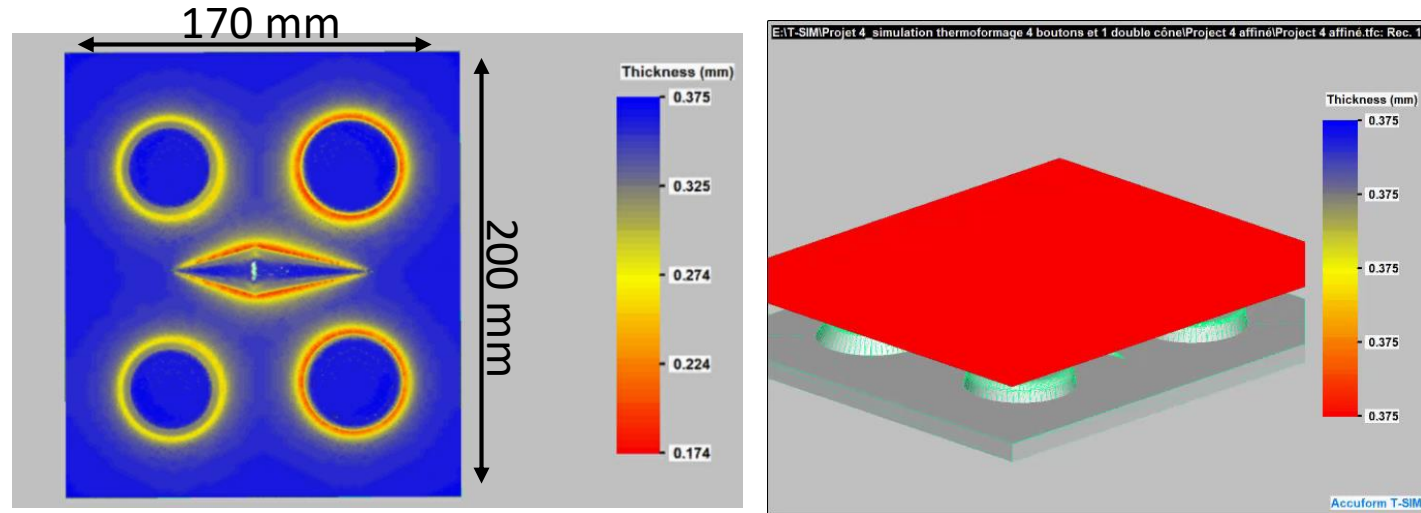
Experimental work for manufacturing

- Conductive ink (silver particles)
- Drying on PC1: 120°C – 20 min
- Drying on PLA1: 55°C – 2h30
- Standardized cross-cut test ISO 2409
  - 6-blade cutter
  - Adhesive tape
- Very good adhesion
  - Category 0 in classification
    - Edges of the cuts smooth
    - No square of the lattice detached



- 10 mm-high molds:
  - Cylinder-shaped
    - Fillet radius: 0,5 mm or 1 mm
    - Draft angle: 10° or 30°
- 15 mm-high double cone-shaped mold

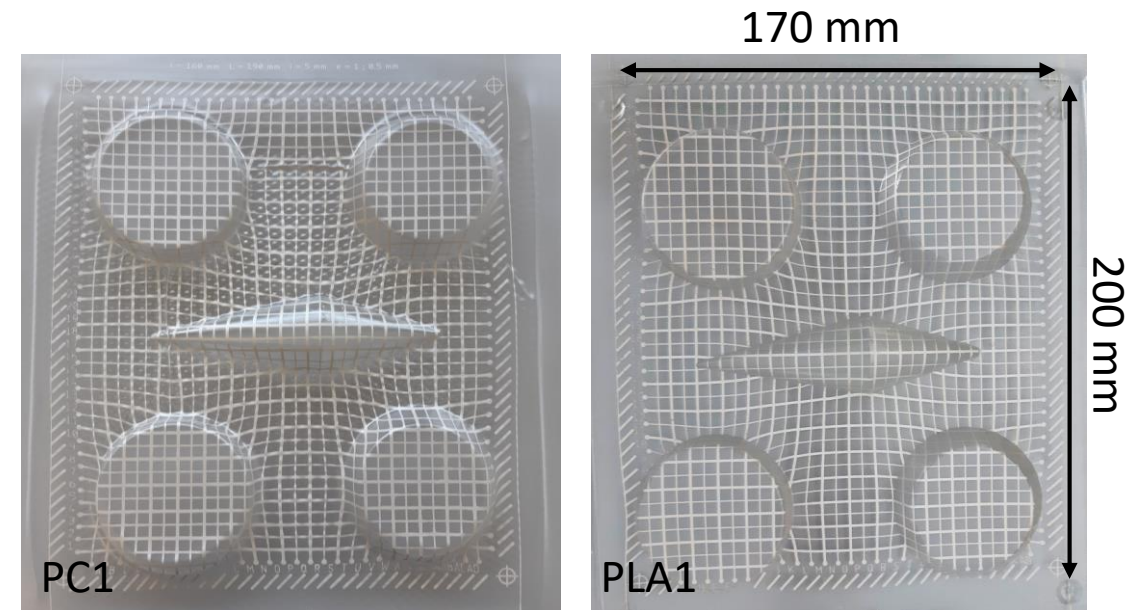
- Simulation:



Thermoforming simulation with 375 μm thick PC film (T-SIM software)

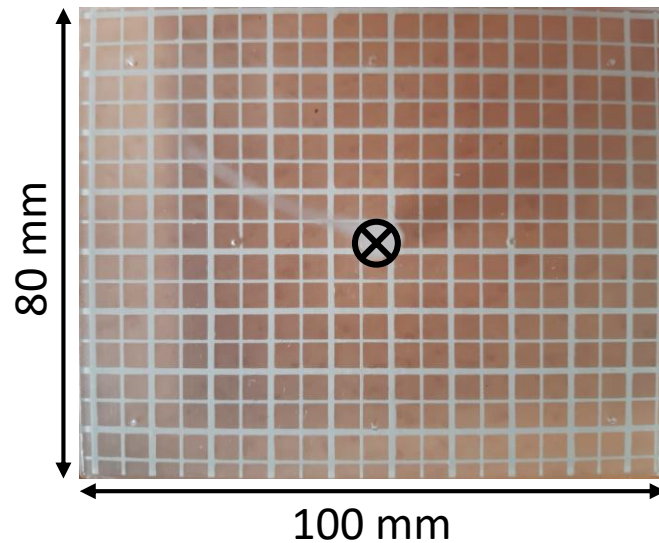
## Effect of geometrical parameters on film stretching

- Reduction in thickness to 174 μm
- Experimental:
  - PLA film well thermoformed: no cracks or holes
  - Ink slightly cracked in areas of greater deformations (→ smaller draft angle)



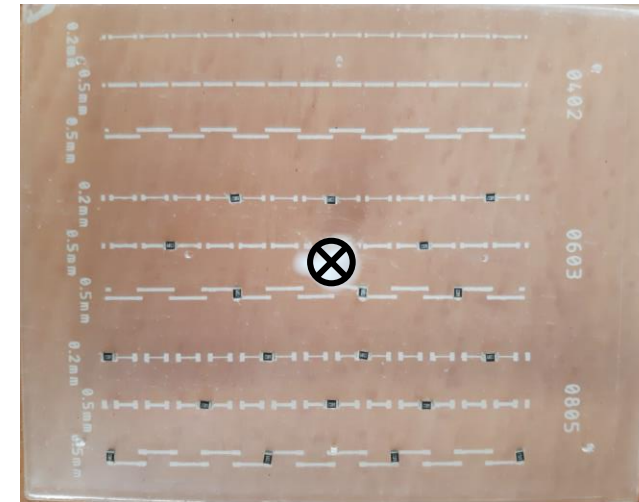
- Laboratory-scale injection molding of PLA2
  - Injection mold: 3-mm-thick plate, central injection point
  - Polymer melt temperature: 195°C
  - Injection mold at room temperature
  - Screw speed: 60 mm/s
- PLA1 screen printed films overmolded with PLA2

ME603 grid pattern



Central injection point

ME603 with electronic components

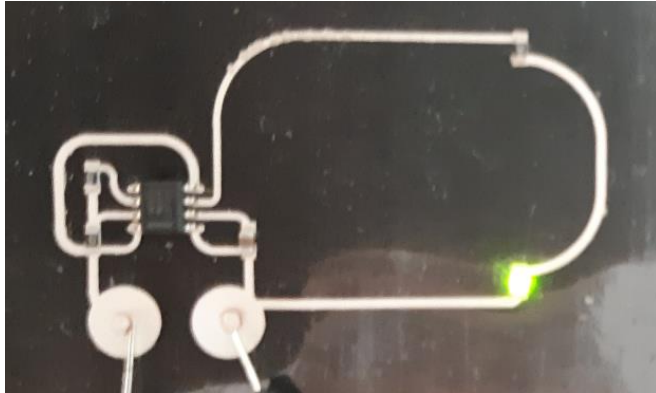


➤ No wash-out of conductive ink, even close to the injection point

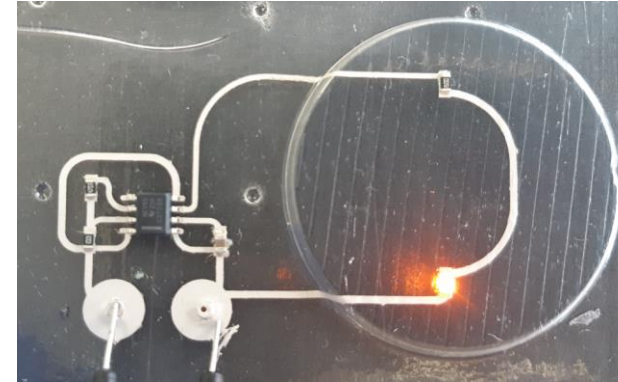
➤ No wash-out, SMDs perfectly in place in plate mold area

# Proof of concept

- Electronic circuit on PLA1, conductive ink dried at 55°C – LED on

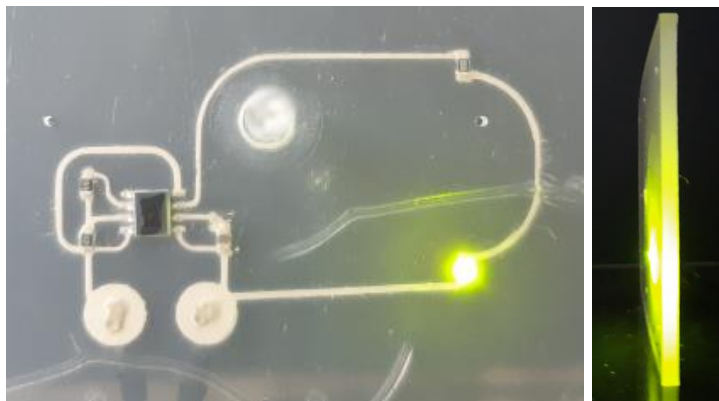


After screen printing + SMDs pasting

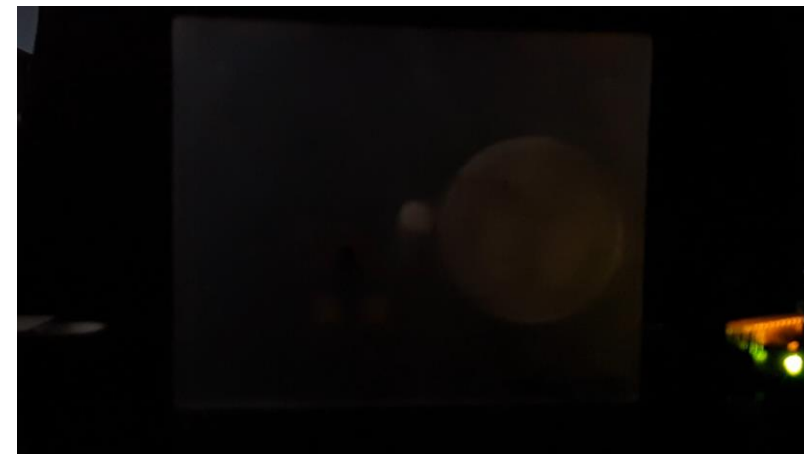


After thermoforming

Plate mold: 100 x 80 x 3 mm, central injection point



After overmolding



- Electronic circuit well encapsulated

# Disassembly and recycling

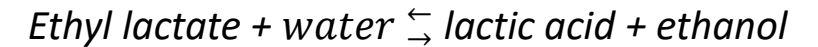
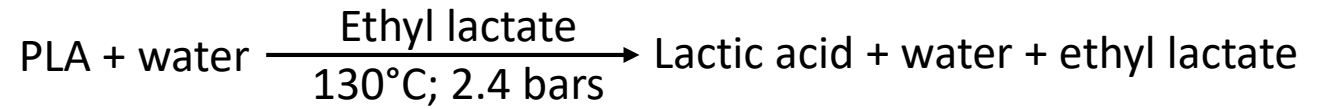
By chemical means

- Independent works of interest published:

- P. Coszach, J-C Bogaert, J. Willocq (2010, patent in French) → Chemical recycling of PLA by hydrolysis

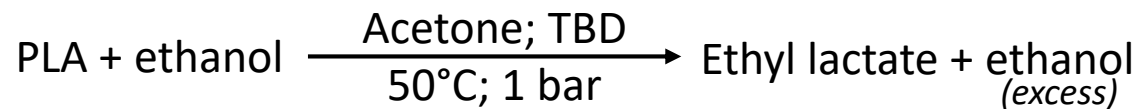
Four steps :

- Grinding of PLA wastes
- Dissolution of PLA in solvent
- Chemical recycling in mild conditions to avoid PLA degradation
- Purification of lactic acid

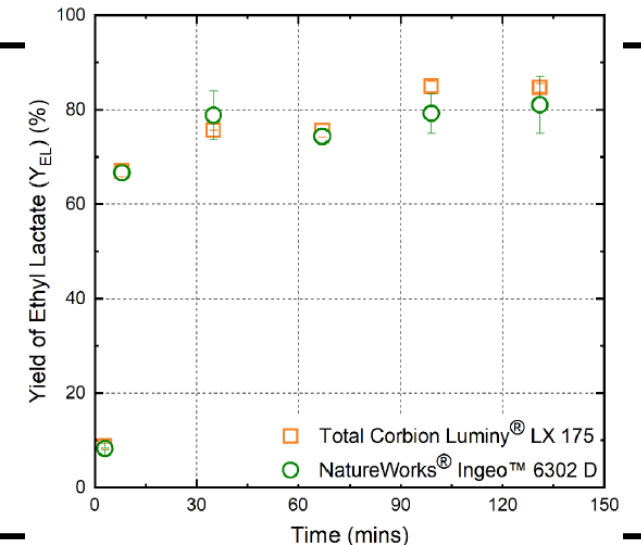


- Leibfarth et al. (2012), *Transforming Polylactide into value-added materials* → study of 14 nucleophiles for the depolymerization of PLA by transesterification

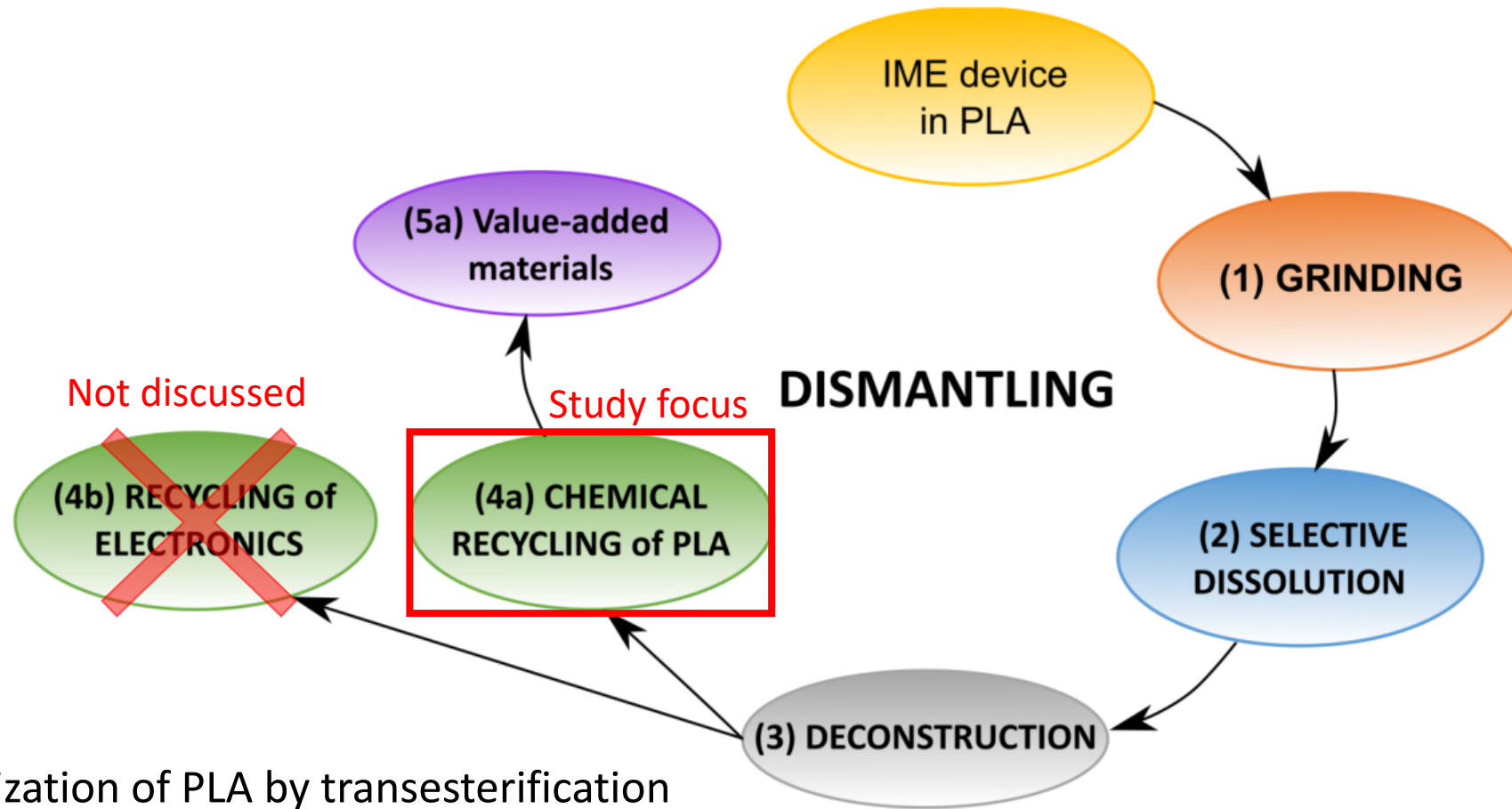
- Majgaonkar et al. (2021) → Chemical recycling of PLA by alcoholysis



- Yield in ethyl lactate between 60% and 80% in 150 min of reaction



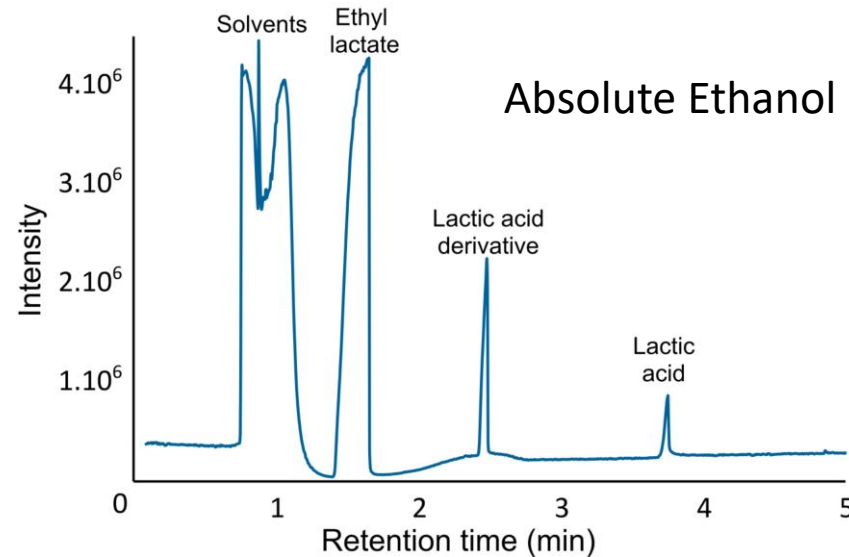
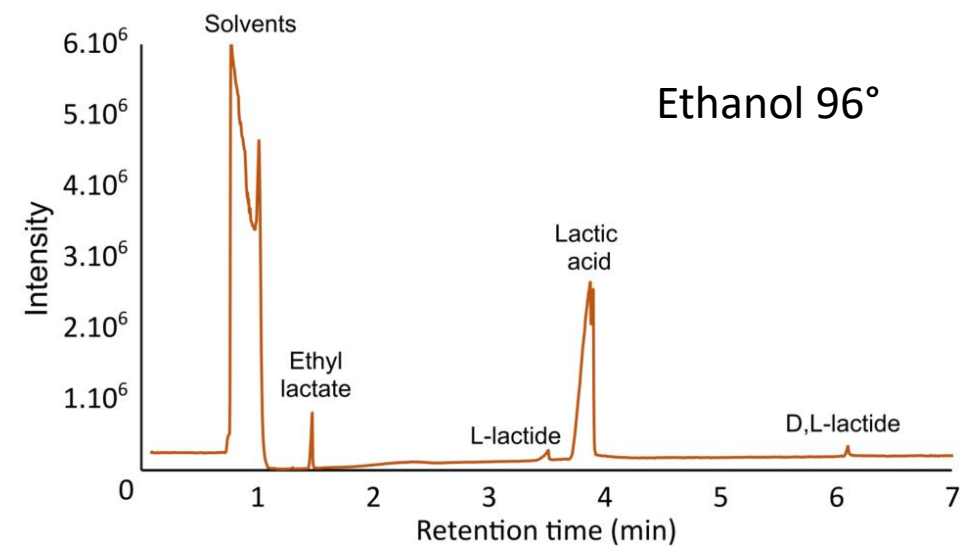




Depolymerization of PLA by transesterification

- Alcoholysis : ethyl lactate as main product
- Hydrolysis : lactic acid as main product

- Reaction at 60°C for 120 min ; magnetic stirring
- Main difference between the 2 reactions = nucleophile
  - Comparison ethanol 96° and absolute ethanol
- Effect on the production of ethyl lactate and lactic acid after 120 min



Ethyl lactate yield

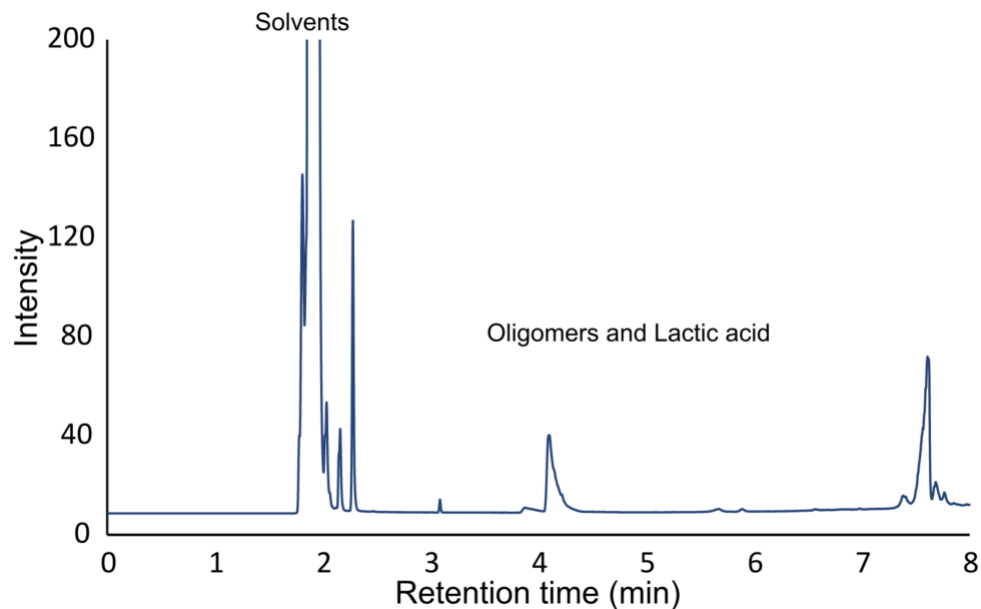
- Ethanol 96° ~ 1%
- Absolute ethanol ~ 60%

Lactic acid yield

- Ethanol 96° ~ 4%
- Absolute ethanol ~ 1%

➤ Hydrolysis seems to predominate over alcoholysis with Ethanol 96°

- In literature: for better hydrolysis reaction, use temperature above 100°C
- Test at 60°C for identical reaction as alcoholysis
  - Nucleophile = deionized water
- Effect on the production of lactic acid (and oligomers) after 240 min



Reaction occurs but very slow  
Lactic acid yield ~ 4%

- Temperature not high enough
  - Necessity to get closer to 100°C
- Kinetic study depending on temperature

- Published article
  - C. Goument *et al.* “In-Mold Electronics on Poly(Lactic Acid): towards a more sustainable mass production of plastronic devices”. *Int J Adv Manuf Technol* (2023).  
<https://doi.org/10.1007/s00170-023-10878-4>
    - For the manufacturing steps of IME devices in PLA
- Recycling of Poly(Lactic Acid) from electronic devices
  - Alcoholysis
    - Optimized for PLA with mild conditions and non-toxic solvents
  - Hydrolysis
    - Study still ongoing with promising results
- Perspective
  - Life Cycle Assessment (LCA) to determine the most interesting method from an environmental point of view

# Thank you for your attention!

## Do you have questions?

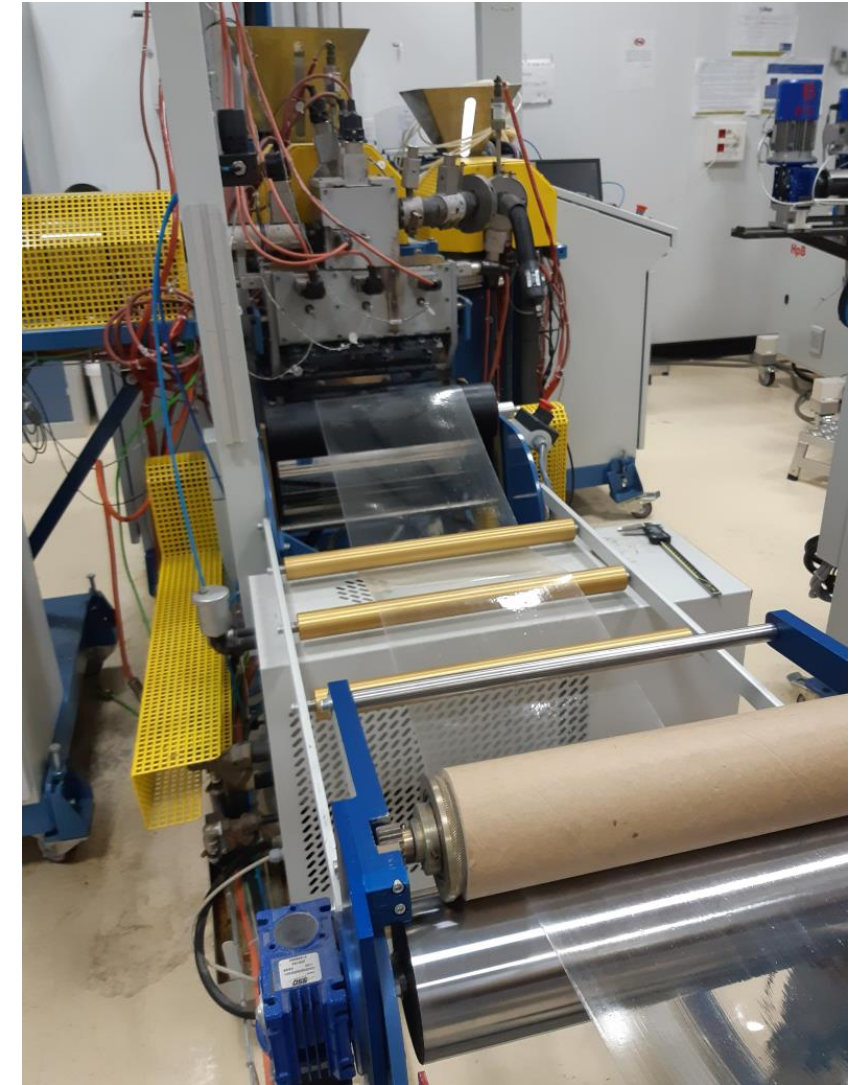


Caroline GOUMENT

[caroline.goument@insa-lyon.fr](mailto:caroline.goument@insa-lyon.fr)

# Appendix 1: PLA extrusion

- Laboratory-scale extrusion of PLA films
  - SCAMEX single-screw extruder
- Profile temperature 160-190-200-210°C from zone 1 to cast film die
- Screw speed 56 rpm
- Chill roll temperature 55°C
- Obtained films about 300  $\mu\text{m}$  thick



*Extrusion of PLA films at IMP Bellignat*

		Film		Injection		
Analyses	Propriété	PLA1	PC1	PLA2	PC2	
Thermal	DSC	Tg (°C)	55	150	59	144
		Tm (°C)	151	/	171	/
	TGA	Td (°C)	310	455	310	455
		Residue (%)	1	25	1	24
Mecanical	Tensile tests	Young Modulus (MPa)	2971	2132	/	/
		Tensile strength at break (N/mm <sup>2</sup> )	59	65	/	/
		Elongation at break (%)	3,9	128,7	/	/
	Charpy	Impact resistance (kJ/m <sup>2</sup> )	/	/	1,7 (notched)	8,9 (notched)
Surface	Wettability	Roughness Sa (µm)	0,37	0,19	/	/
		Surface energy (mN/m)	37,8	45,8	45,7	46,8
		Dispersive (mN/m)	32,4	44,4	39,9	43,6
		Polar (mN/m)	5,4	1,5	5,7	3,2