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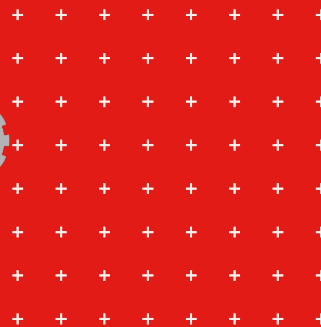
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PHOTONIC CURING FOR IN-MOLD ELECTRONICS

Hugo CAUCHY-CLERC^{1,2}, Tony GERGES², Philippe LOMBARD², Vincent SEMET², Bruno Allard², Jean-Yves CHARMEAU¹, Michel CABRERA²

(1) Université de Lyon, Université Claude Bernard Lyon 1, INSA Lyon, Ecole Centrale de Lyon, CNRS, Ingénierie des Matériaux Polymères IMP, UMR 5223, F-69622 Villeurbanne Cedex, France

(2) Université de Lyon, Université Claude Bernard Lyon 1, INSA Lyon, Ecole Centrale de Lyon, CNRS, AMPERE, UMR 5005, F-69622 Villeurbanne Cedex, France

Projet ANR-22-CE05-0015-03 AMBRE : Antenne Multifonctionnelle Biosourcée pour la récupération d'Énergie

hugo.cauchy-clerc@insa-lyon.fr
michel.cabrera@insa-lyon.fr

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5. PREVIOUS WORK
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3D PLASTRONICS AT AMPERE AND IMP LABORATORIES

- **Positioning and scientific activities → Research and development in Plastronics:**
 - Electrical engineering: advanced packaging of electronic components and systems
 - Materials engineering: polymers and shaping processes
 - Global approach: Feasibility – Design/Simulation – Manufacturing (prototyping) – Characterization
→ Plastronics functionalization of polymers: from sensor to system

- **Our objectives :**
 - New process & Design innovative functions → Understand the physical phenomena involved
 - Starting from an idea, designing and producing a functional prototype and obtaining its multi-physical characteristics
 - Our resources → Dedicated 3D plastronics platform + Plastics processing platform
+ Resources and skills of 2 laboratories specializing in electronics and materials

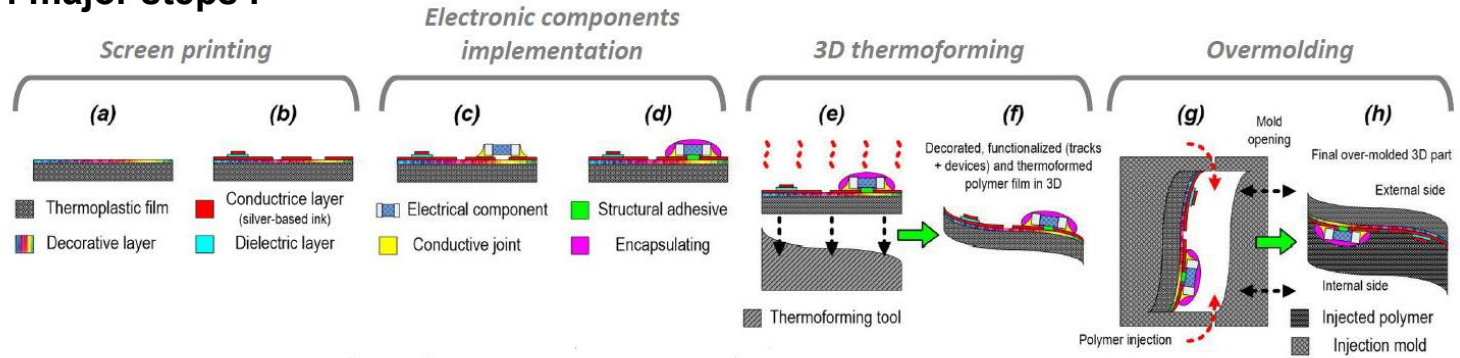
- **Academic activities** → Training offers through research in connection with industry (theoretical and practical training, projects monitoring, internships, etc.)





IN-MOLD ELECTRONICS (IME)

4 major steps :



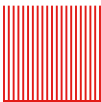
IME examples in Human Machine Interfaces :



Technology demonstrator by Tactotek

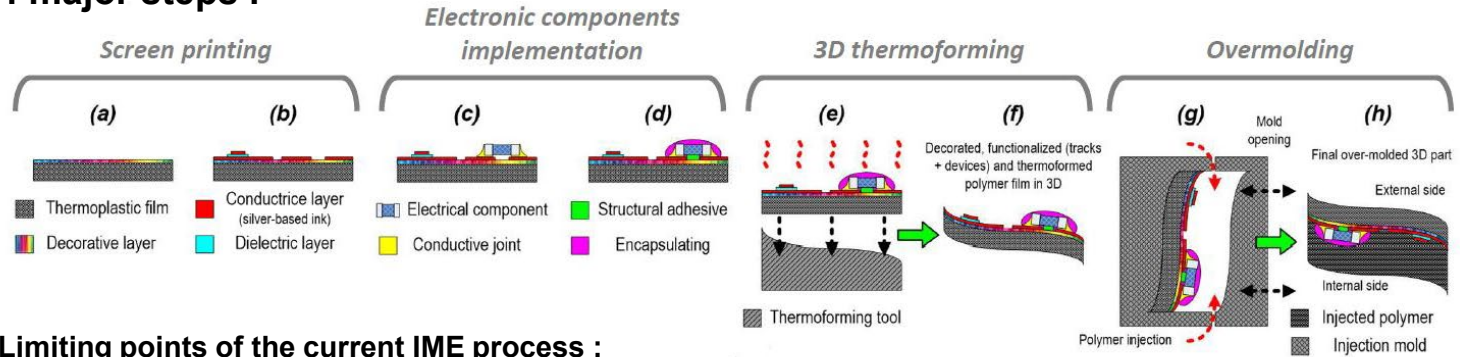


Mercedes Benz concept car



IN-MOLD ELECTRONICS (IME)

4 major steps :

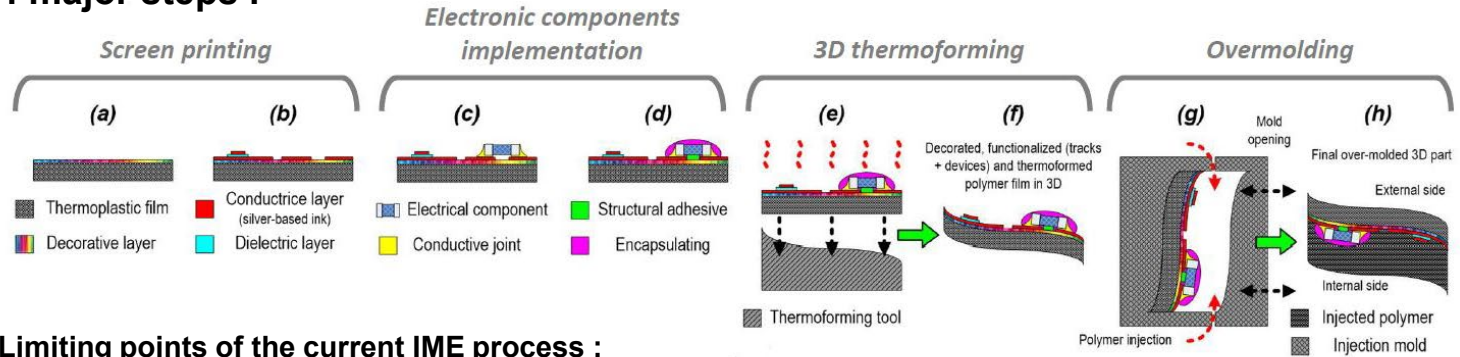


Limiting points of the current IME process :

- Limited height due to stretching of the tracks during thermoforming
- High cost of the silver ink
- High resistivity of the inks compared to the bulk copper on conventional PCB
- High resistivity of the glues compared to conventional soldering
- Mechanically weak bonds between the tracks and components
- Long process time due to the drying of the inks and glues

IN-MOLD ELECTRONICS (IME)

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- High cost of the silver ink
- **High resistivity of the inks compared to the bulk copper on conventional PCB**
- **High resistivity of the glues compared to conventional soldering**
- Mechanically weak bonds between the tracks and components
- **Long process time due to the drying of the inks and glues**

Here we propose a new way to cure the conductive inks and glues in order to minimize the resistivity of inks and glues and the process time using the Photonic Curing technology.



AIM AND MOTIVATIONS

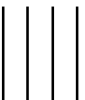
Improve on the current IME process on conventional polymers like **PC** (HDT **145°C**)

Process parts on lower temperature polymers, such as **PLA** (bio-based, $T_g \sim 55^\circ\text{C}$).

More precisely:

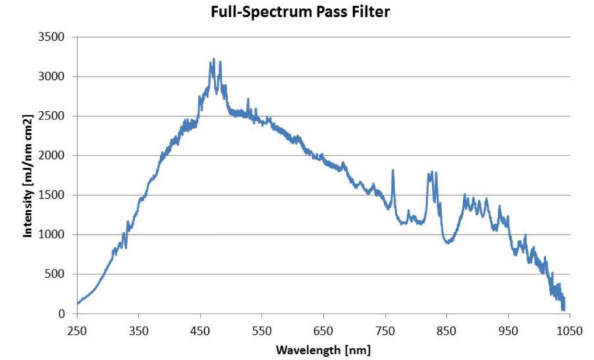
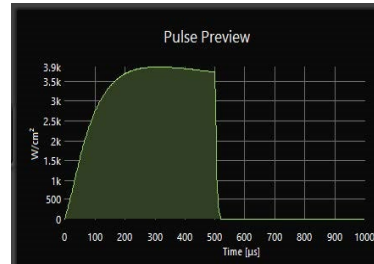
- Improve conductivity of the tracks on conventional materials (PC)
- Connect components to the tracks using conductive glue
- Find whether photonic curing can cure inks on low-temperature substrates (PLA)

Main challenge: the PLA substrate cannot withstand the high temperatures needed for conventional oven ink curing (e.g. **120°C** for Dupont ME603) [1]



PHOTONIC CURING

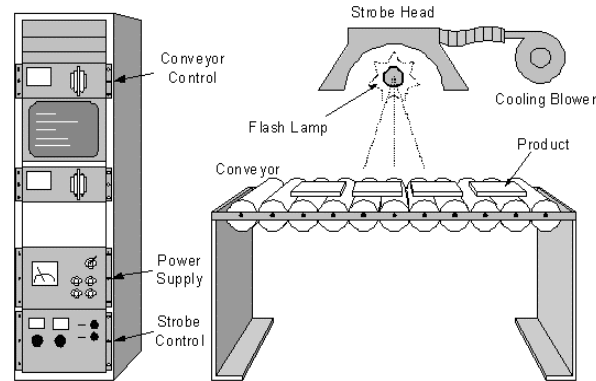
- High-intensity light pulses (Xenon broad spectrum lamp)
- Light is mainly absorbed by the ink/solder paste
- Very short pulses to limit the heating of the polymer substrate (in the millisecond range, 1 μ s increments)
- Depending on the parameters, ink annealing or SMD soldering can be done



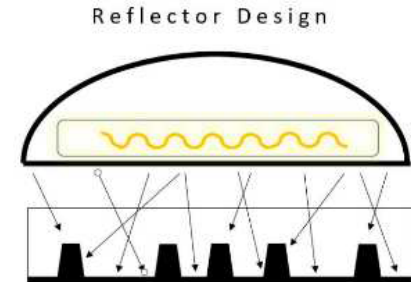
- Adjustable pulse duration
- Configurable frequency and number of repetitions
- Broad spectrum, can be limited by filters



Novacentrix PulseForge Invent
Photonic Curing Machine



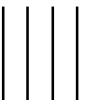
Schroder et. al., NSTI, 2006 [1]





PREVIOUS WORK

- Photonic curing has been introduced as a process to cure silver nanoparticle inks on low temperature films by Schroder et. Al. in 2006 [2]
- In 2014, van den Ende et. Al studied the soldering of SMD components on PI($T_g > 200^\circ\text{C}$) and PET ($T_g \sim 80^\circ\text{C}$) substrates showing the feasibility of the photonic curing [3]
- Das et al studied the process using copper oxide based inks on a paper substrate in 2015, showing that substrates are preserved in the process [4]
- Mu et. al. sintered tracks on 3D printed light-absorbing black polymer substrate with success in 2018 [5]



INK CONDUCTIVITY IMPROVEMENT

Conductive ink = silver particles(~60%) + polymer binder + **solvent**

- **Curing is meant to evaporate the solvent**

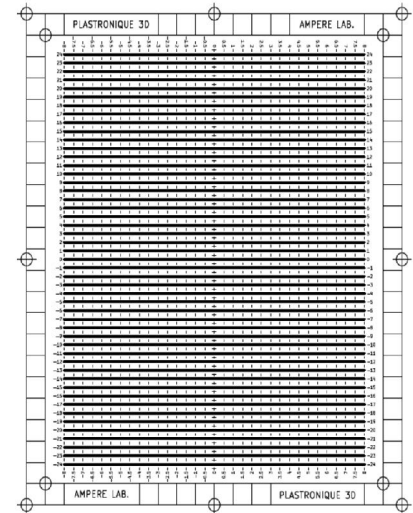
Process parameters :

Oven Curing	Config.	Temperature	Duration	source
	P0 PC	120°C	20 min	Supplier data
	P0 PLA	55°C	2h30	Previous work
Photonic Curing	Config.	Frequency	Pulse duration	nb. pulses
	P1	1 Hz	1000 μ s	20
	P2	1 Hz	1000 μ s	40
	P3	10 Hz	1000 μ s	40
	P4	20 Hz	1000 μ s	40
	P5	30 Hz	1000 μ s	40

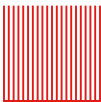
- The pattern was screen printed using a semi-automatic machine with two passes to ensure a good print quality
- The programs shown here are based on preliminary results by our team which served as a basis for this study

Ink used : Dupont ME603

Substrates : Covestro Makrofol DE 1-1 (PC) or NatureWorks Ingeo 2003D (PLA)

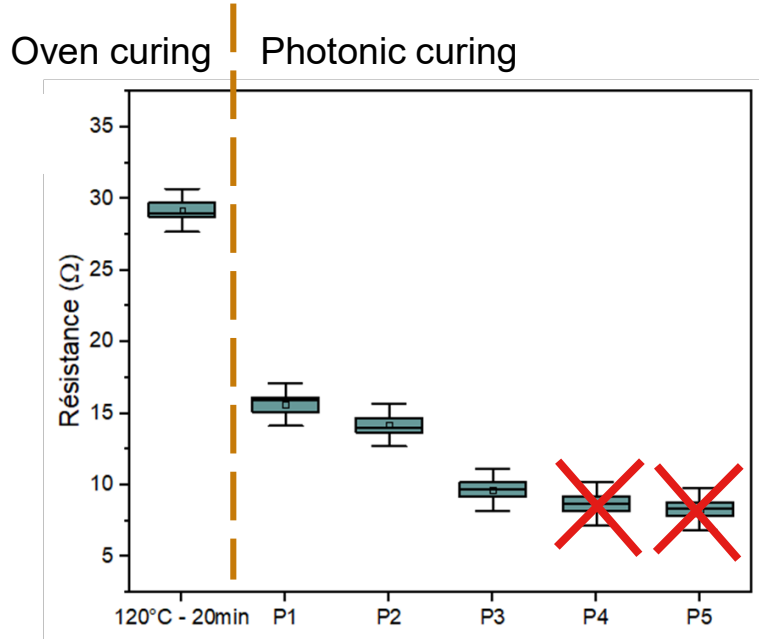


Screen printed pattern for this study:
49 lines, L= 160mm, w = 1 mm



INK CONDUCTIVITY IMPROVEMENT

Effect of Photonic curing on track resistance, PC substrate



Ink used : Dupont ME603

Substrate : Covestro Makrofol DE 1-1 (PC)

Oven Curing	Config.	Temperature	Duration	source
	P0 PC	120°C	20 min	Supplier data
Photonic Curing	Config.	Frequency	Pulse duration	nb. pulses
	P1	1 Hz	1000 μs	20
	P2	1 Hz	1000 μs	40
	P3	10 Hz	1000 μs	40
	P4	20 Hz	1000 μs	40
P5	30 Hz	1000 μs	40	

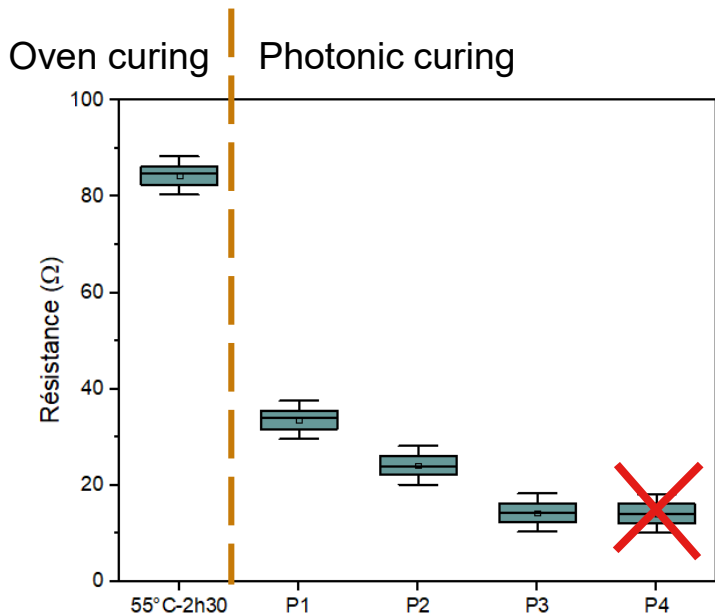
Here we compare various settings of photonic curing to find an optimum. Programs P4 and P5 damage the substrate.

Conductivity of the ink is 3 times better on PC using photonic curing than with conventional oven curing.



INK CONDUCTIVITY IMPROVEMENT

Effect of Photonic curing on track resistance, PLA substrate



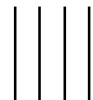
Ink used : Dupont ME603

Substrate : NatureWorks Ingeo 2003D (PLA)

Oven Curing	Config.	Temperature	Duration	source
	P0 PLA	55°C	2h30	Previous work
Photonic Curing	Config.	Frequency	Pulse duration	nb. pulses
	P1	1 Hz	1000 μs	20
	P2	1 Hz	1000 μs	40
	P3	10 Hz	1000 μs	40
	P4	20 Hz	1000 μs	40

Here we compare various settings of photonic curing to find an optimum.
Programs P4 damages the substrate.

Conductivity of the ink is 5 to 6 times better on PLA using photonic curing than with conventional oven curing.



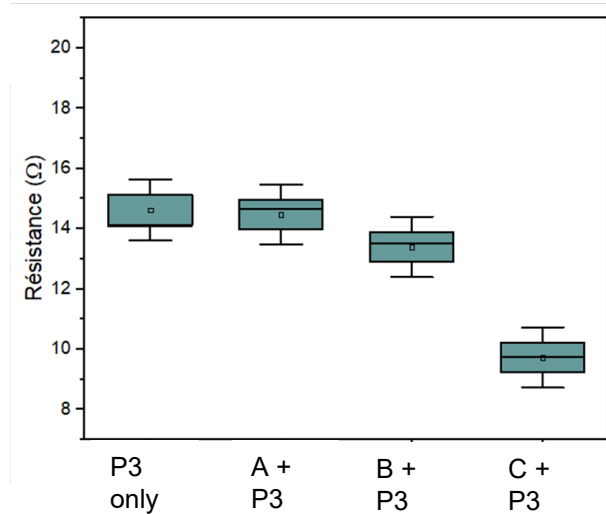


INK CONDUCTIVITY IMPROVEMENT

Effect of thermal pre-curing then photonic curing on track resistance

Ink used : Dupont ME603

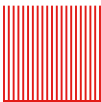
Substrate : Covestro Makrofol DE 1-1



Oven Curing (first step)	Config.	Temperature	Duration		Track resistance after treatment
	A	60°C	20 min		14.4 Ω
	B	90°C	20 min		13.5 Ω
	C	120°C	20 min		9.8 Ω
Photonic Curing (second step)	Config.	Frequency	Pulse duration	nb. pulses	
	P3	10 Hz	1000 μs	40	14.5 Ω

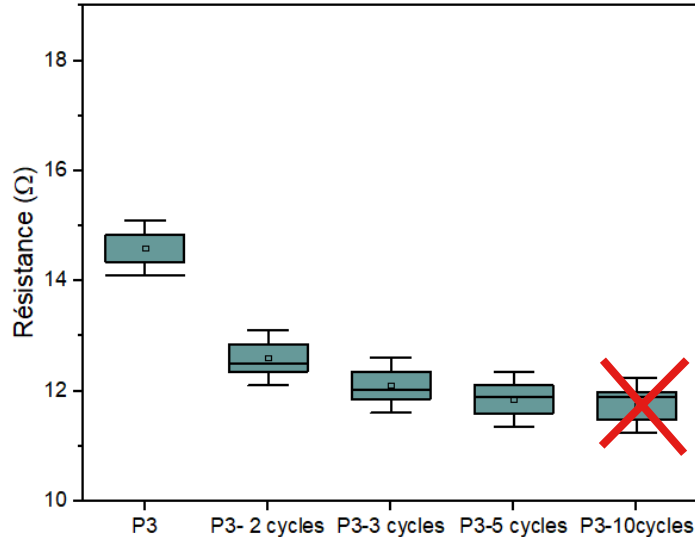
Here the part is placed in an oven **for 20 minutes** at **different temperatures** before the photonic curing, in order to “pre-cure” the conductive ink.

By applying both treatments, conductivity is improved by 50% compared to photonic curing alone, but the process time is not shortened.



INK CONDUCTIVITY IMPROVEMENT

Effect of repeating the process on track resistance



- In this experiment the sample was exposed several times to the same photonic curing configuration.

Config.	Average track resistance	Comment
P3	14.5 Ω	Reference
2x P3	12.5 Ω	
3x P3	12.1 Ω	
5x P3	11.8 Ω	
10x P3	12 Ω	Damage to many tracks

Ink used : Dupont ME603

Substrate : Covestro Makrofol DE 1-1

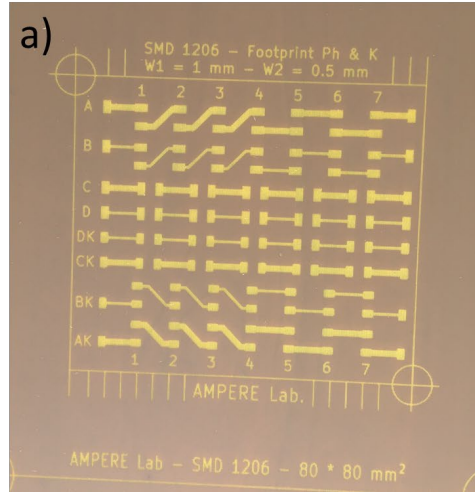
Conductivity of the ink is improved with multiple cycles by about 20% (5 cycles).

More than that will cause damage to the part.

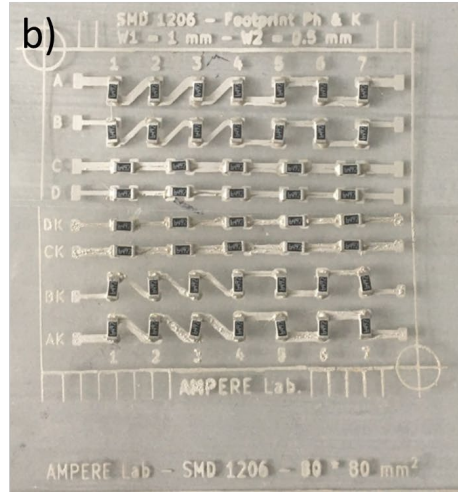
GLUE BOND CONDUCTIVITY IMPROVEMENT

Glue used : Dupont ME902

Substrates : Covestro Makrofol DE 1-1 (PC) or NatureWorks Ingeo 2003D (PLA)



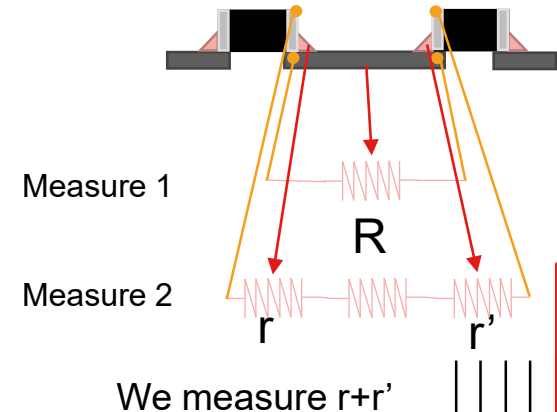
a) Pattern used for this experiment



b) Pattern screen printed on a PC film with 1206 SMDs glued on

Test procedure :

Track curing	Glue curing
Oven curing	Oven curing
Oven curing	Photonic curing
None	Photonic curing
None	Photonic curing, two cycles



GLUE BOND CONDUCTIVITY IMPROVEMENT

Glue used : Dupont ME902

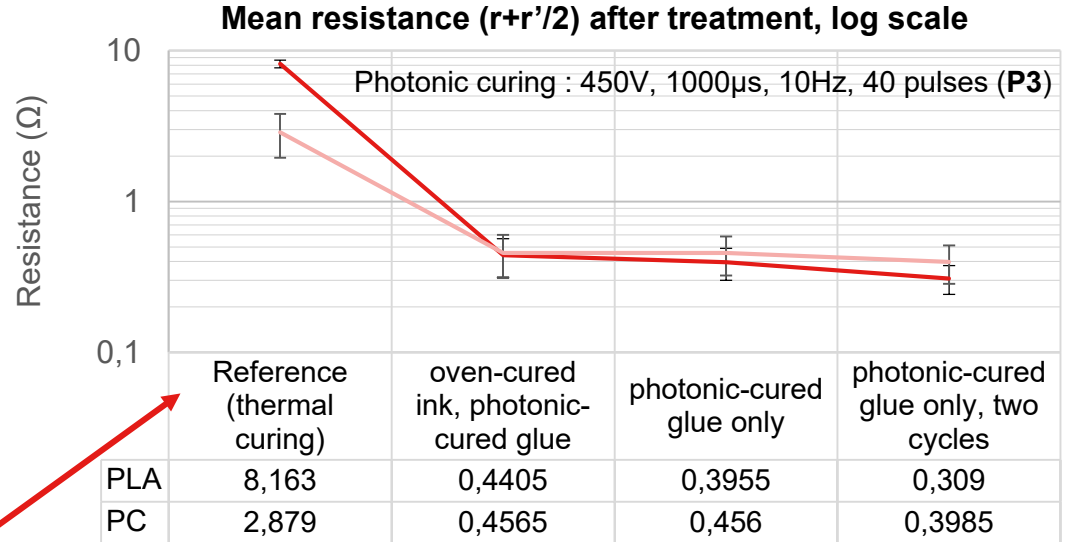
Substrates : Covestro Makrofol DE 1-1 (PC) or NatureWorks Ingeo 2003D (PLA)

Test procedure :

Track curing	Glue curing
Oven curing	Oven curing
Oven curing	Photonic curing
None	Photonic curing
None	Photonic curing, two cycles

Thermal curing parameters:

- 20 min @ 120°C for PC films (supplier recommended settings)
- 2h30 min @ 55°C for PLA films (based on previous work [5])



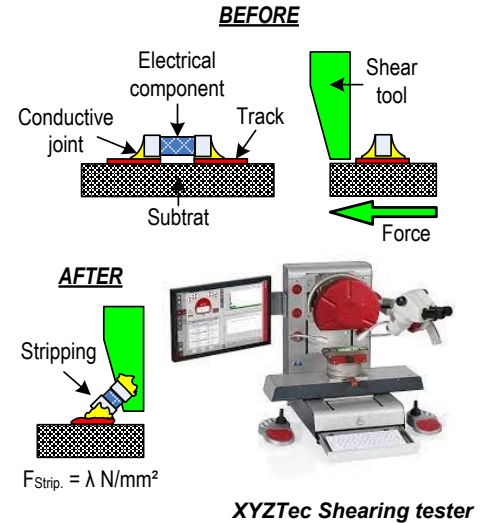
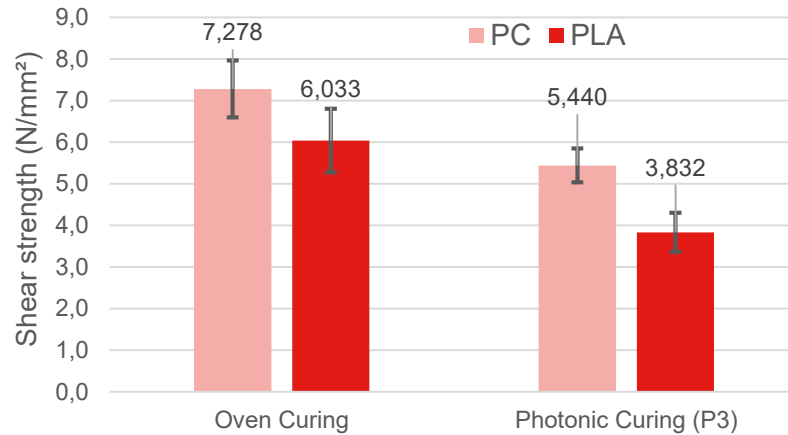
Conductivity of the glue is 6 times better using photonic curing than with conventional oven curing.

GLUE BOND STRENGTH IMPROVEMENT

Glue used : Dupont ME902 – **No structural glue were used in this study**

Substrates : Covestro Makrofol DE 1-1 (PC) or NatureWorks Ingeo 2003D (PLA)

Comparison between conventional oven curing and photonic curing for silver glue bond strength



- Fracture surface is measured with an optical microscope after the shear test

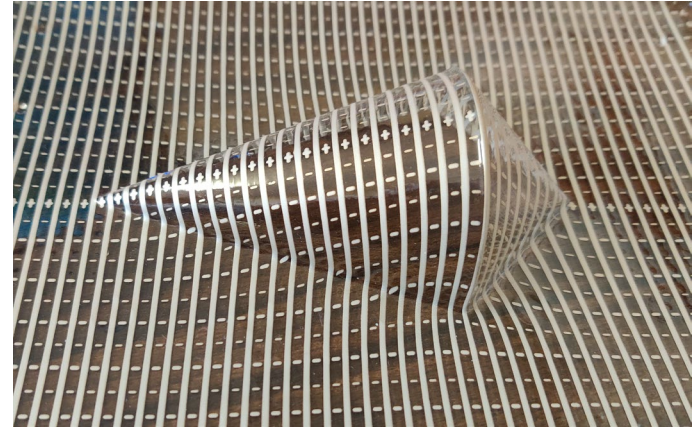
The bond strength is 25% to 30% smaller than conventional curing: structural glue is still needed.

IMPACT ON THERMOFORMABILITY

Ink used : Dupont ME603

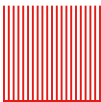
Substrates : Covestro Makrofol DE 1-1 (PC) or NatureWorks Ingeo 2003D (PLA)

- We feared that photonic curing would weaken the ink during thermoforming
- Tests realized : thermoforming of cured films on a conic shape to compare the different curing methods
- Results : the conductive tracks are broken when the radius of the cone gets too high, where the ink is stretched too much, **regardless of the curing method.**



These preliminary results show that photonic curing do not pose a problem in the thermoforming step.

The tracks are not weakened by the improved curing.





CONCLUSION

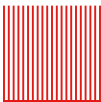
	Oven	Photonic (P3)	Change (%)	
Ink Curing (PC)	28 Ω	10 Ω	-67%	Improved
Ink Curing (PLA)	83 Ω	14 Ω	-82%	
Glue Curing – conductivity (PC)	2.9 Ω	0.4 Ω	-86%	
Glue Curing – conductivity (PLA)	8.1 Ω	0.4 Ω	-95%	Tradeoffs
Glue Curing – bond strength (PC)	7.3 N/mm ²	5.4 N/mm ²	-26%	
Glue Curing – bond strength (PLA)	6.0 N/mm ²	3.8 N/mm ²	-36%	

Photonic Curing substantially **improves track and bond conductivity** compared to regular oven curing.

It comes at the cost of **slightly weaker bond strength**: a **structural adhesive is still needed** to ensure mechanical strength of the whole part.

No difference have been found **during thermoforming** between oven-cured and photonic-cured inks.

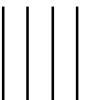
Photonic Curing also allows to make IME parts on low-temperature substrates like **PLA**, with close electrical performance compared to conventional substrates (**PC**).





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- [2] K.A Schroder, S.C. McCool, W.R. Furlan, Technical Proceedings of the 2006 NSTI Nanotechnology Conference and Trade Show, 3, 198-201, 2006.
- [3] van den Ende, Daan & Hendriks, Rob & Cauchois, Romain & Kusters, R.H.L. & Cauwe, Maarten & Groen, Pim & Brand, Jeroen. (2014). Photonic Flash Soldering of Thin Chips and SMD Components on Foils for Flexible Electronics. *IEEE Transactions on Components, Packaging, and Manufacturing Technology*. 4. 1879-1886. 10.1109/TCPMT.2014.2360410.
- [4] Das, Sourav, "Pulsed Photonic Curing of Conformal Printed Electronics" (2015). Thesis. Rochester Institute of Technology
- [5] Quanyi Mu et al 2018 *Smart Mater. Struct.* 27 115007



**Thank you for your attention.
Questions?**

hugo.cauchy-clerc@insa-lyon.fr

michel.cabrera@insa-lyon.fr