Reliability of Screen-Printed In-Mold Electronics on Polycarbonate Substrates Under Thermal Cycling

Shriram Kulkarni[1], Pradeep Lall [1], Scott Miller [2]

(1). Auburn University, Auburn University Electronics Packaging Research Institute, Auburn, AL 36849

(2). NextFlex National Manufacturing Institute, San Jose, CA

Tele: (334) 844-3424, Email: lall@auburn.edu

IPACK 2025: 174749

Problem Statement

- **Increased use of wire harnesses** in the automotive sector adds weight, leading to higher CO_2 emissions.
- **IME (In-Mold Electronics) offers a solution** by integrating printed electronics, reducing wire harness reliance, and enhancing design flexibility.
- **Thermoforming is crucial** in IME but can impact the performance of conductive traces.
- **Limited research exists** on how thermoforming affects screen-printed samples.
- This study investigates the **effects of thermoforming on the electrical performance and reliability** of screen-printed samples on polycarbonate substrates.

Objectives

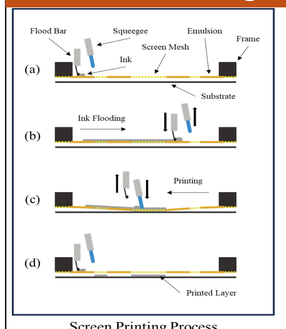
- Evaluate the **impact of thermoforming** on the electrical performance of screen-printed circuits on polycarbonate substrates.
- Determine the **optimal thermoforming parameters** to maintain the integrity of conductive traces.
- Investigate the **changes in electrical performance**, before and after thermoforming.
- Assess the **long-term reliability** of screen-printed electronics under sustained high-temperature and thermal cycling conditions.

Ink & Interconnect Materials

Ink Properties (Silver Nanoparticle Conductive Ink)	
Viscosity	10000-18000cp
Sheet Resistance	<40mΩ/sq./mil
Sintering Temperature	120℃ for 20 mins.

Electrically Conductive Adhesive (ECA) Properties	
Material	Silver Conductive Epoxy
Viscosity	40000 cP to 90000 cP
Sintering Temperature	120℃ for 20 mins.
Sheet Resistance	100-150 mΩ/sq./mil

Screen Printing – Process & Equipment



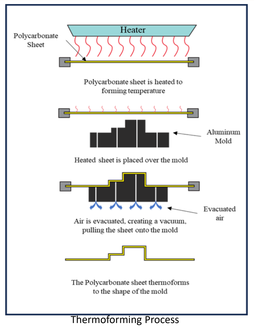
Screen Printing Process

ATMA AT-70PD Screen Printer

ATMA AT-70PD	
Working Table Size	700 mm X 800 mm
Substrate Thickness	0-120 mm
Table Adjustments (X, Y)	± 10mm, ± 10mm

Printing Parameters	
Squeeze Speed	230 mm/s
Flood Bar Speed	260 mm/s
Screen Mesh and Material	300 Stainless Steel Mesh

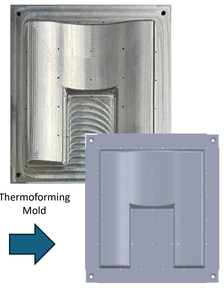
Thermoforming – Process & Equipment



Thermoforming Process

- The samples were thermoformed using the Formech 508FS machine at **200°C** (80% of max temperature) for **30 seconds**.

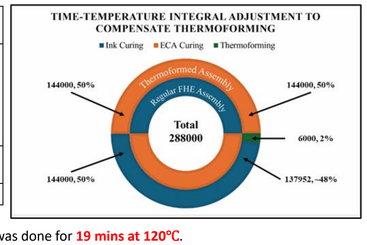
Formech 508FS vacuum thermoforming machine



Thermoforming Mold

Time-Temperature Profile

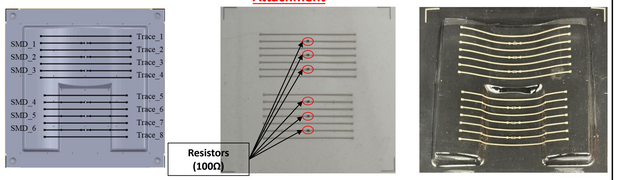
Regular FHE Assembly	Thermoformed Assembly
Ink Curing (120℃ for 20 mins) + **ECA Curing** (120℃ for 20 mins)	**Ink Curing** (120℃ for 19 mins) + **ECA Curing** (120℃ for 20 mins) + **Thermoforming** (200℃ for 30 sec)
120x1200 + 120x1200	120x1150 + 120x1200 + 200x30
288000	288000



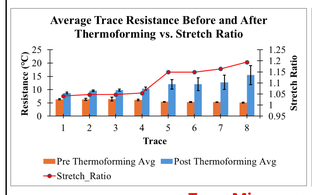
- Using the calculation the ink curing was done for **19 mins at 120℃**.

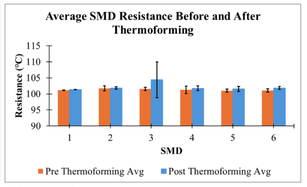
Traces and Component Attachment

Test Vehicle Design | **After Component Attachment** | **After Thermoforming**

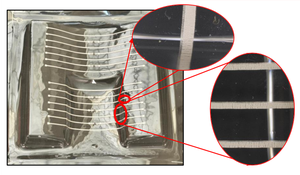


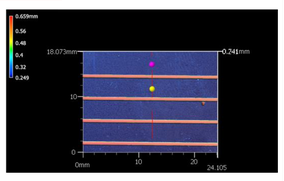
$$\text{Stretch Ratio} = \frac{\text{Post-thermoforming Trace Length}}{\text{Pre-thermoforming Trace Length}}$$

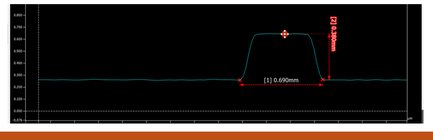




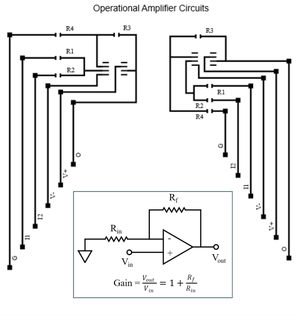
Trace Microscopy & Profiling







Demonstrator Circuit: Non-Inv Amplifier



Test Vehicle 2	
Resistor (R)	0 Ω ±5%
Resistor (Rf)	10 kΩ ±5%
Resistor (Rin)	1.5 kΩ ±5%
Operational Amplifier	Op07

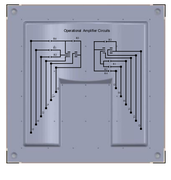
$$Gain = \frac{V_{out}}{V_{in}}$$

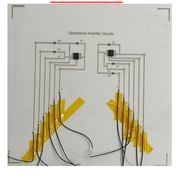
$$Gain = \frac{R_2 + R_1}{R_2}$$

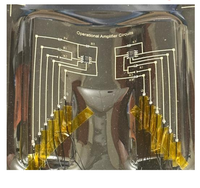
$$Gain = 7.6$$

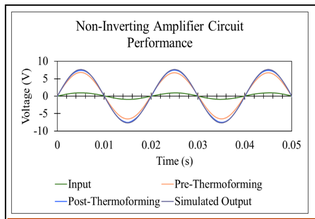
Pre- vs Post - Thermoforming

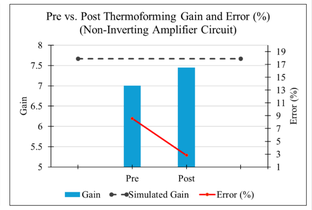
Test Vehicle Design | **After Component Attachment** | **After Thermoforming**









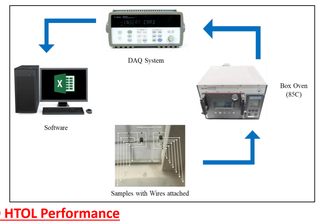


Thermal Reliability: HTOL & Thermal Cycling

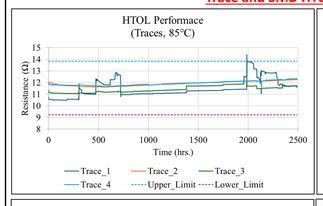
HTOL Study

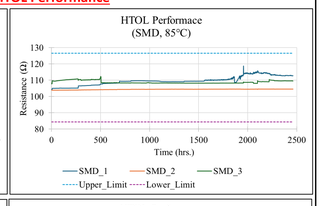
Standard
(AEC-Q100 Grade III) 85°C for 1000 hrs.

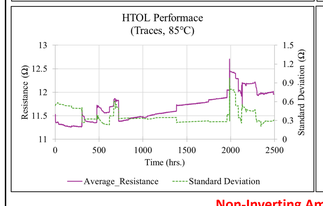
HTOL Data Acquisition

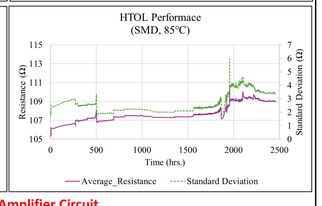


Trace and SMD HTOL Performance

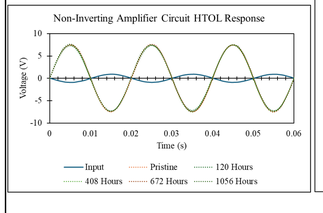


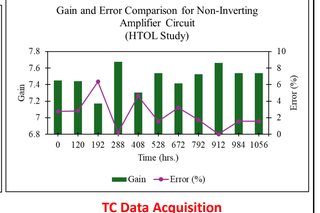






Non-Inverting Amplifier Circuit

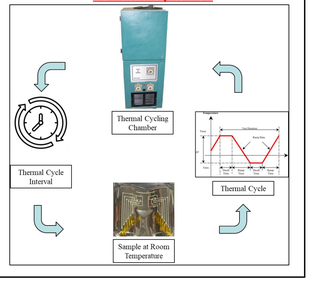




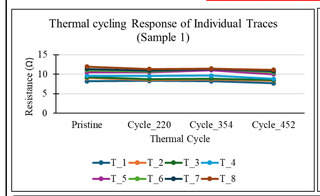
Thermal Cycling (TC) Study

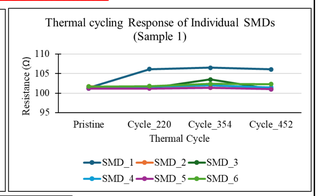
Standard
AEC-Q007 BLR-TCC-3
(-40°C to 85°C)

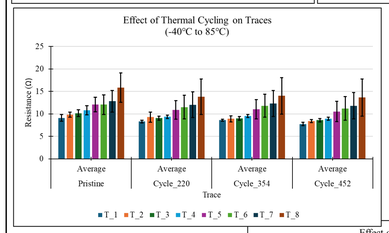
TC Data Acquisition

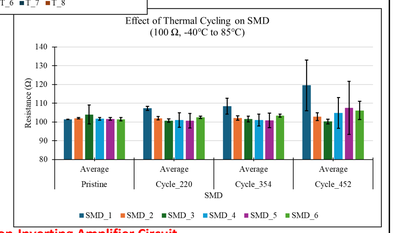


Trace and SMD HTOL Performance

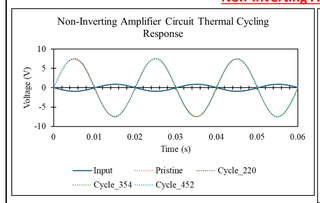


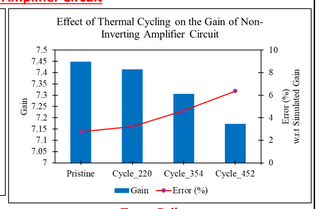




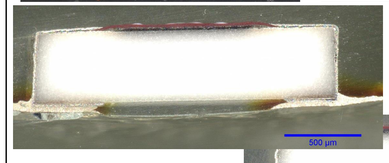


Non-Inverting Amplifier Circuit



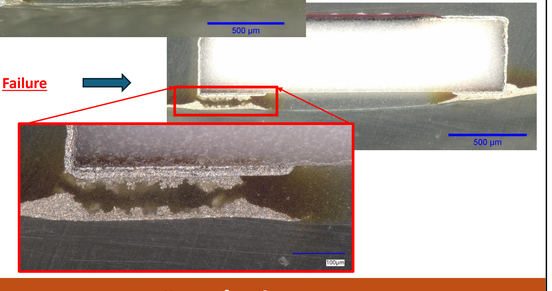


Pristine Trace | **Trace Failure**



Pristine Sample

Failure



Conclusions

- **Pre vs. Post Thermoforming**: Traces remained stable after curing but showed minor resistance increase in high-stretch regions; SMDs and circuits retained consistent performance.
- **HTOL (85 °C, 1,056–2,500 h):** Traces and amplifier circuits remained reliable with <7% error, exceeding AEC-Q100 Grade III requirements.
- **Thermal Cycling (–40 °C ↔ 85 °C, 452 cycles):** Samples maintained stable electrical behavior with early signs of performance degradation.
- **Overall:** Screen-printed thermoformed IME samples demonstrated robust electrical reliability across thermoforming, HTOL, and TC conditions.

Acknowledgment

The project was sponsored by the NextFlex Manufacturing Institute under PC8.3 Project titled – In-Mold Flexible Electronics Reliability for Harsh Automotive Applications. This material is based, in part, on research sponsored by Air Force Research Laboratory under agreement number FA8650-20-2-5506, as conducted through the flexible hybrid electronics manufacturing innovation institute, NextFlex. The US Government is authorized to reproduce and distribute reprints for Governmental purposes notwithstanding any copyright notation thereon. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of Air Force Research Laboratory or the US Government.