Dynamic Studies of Thermoformed Embedded Printed Electronics Using Micro-CT

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Abstract

- In-Mold Electronics (IME) integrates circuits directly into the shape of a product during manufacturing, enabling lightweight and smart designs.
- During thermoforming, conductive inks experience heat, pressure, and stretching, which can lead to cracking or loss of electrical performance.
- The deformation and reliability of these printed features remain poorly understood.
- The long-term goal of this work is to study these effects using dynamic in-situ micro-CT imaging.
- As a first step, preliminary experiments were conducted using tensile testing of polyethylene terephthalate (PET) sheets.
- These results establish the foundation for future in-situ micro-CT studies.

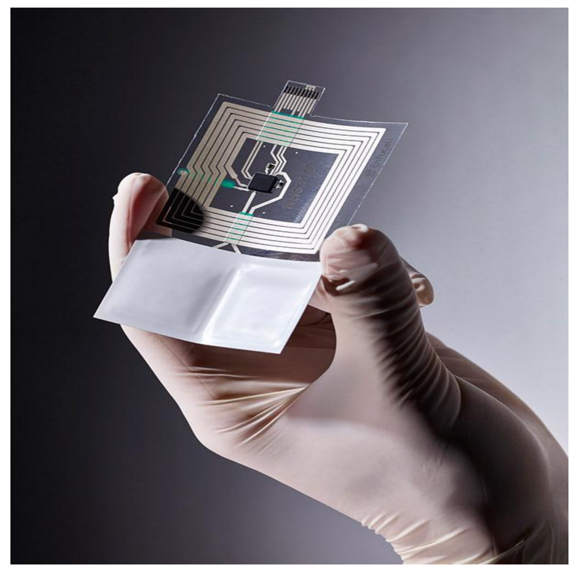

Fig. 1. Flexible Printed Electronics.

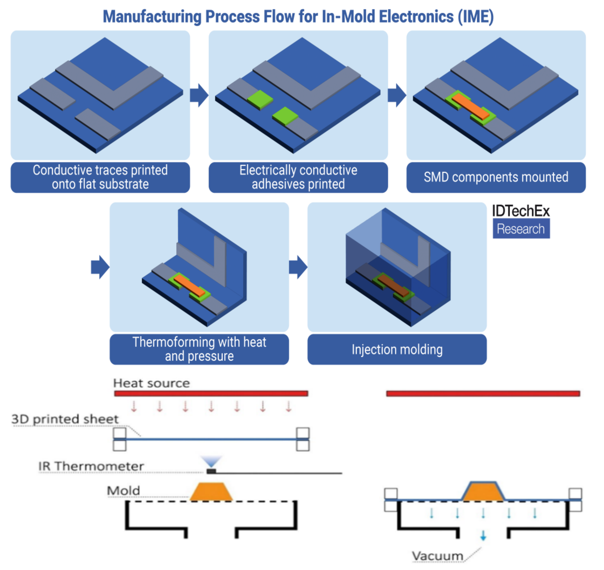

Fig. 2. Manufacturing Process for IME.

Introduction

- In-Mold Electronics (IME) integrates functional electronics into a product's structure, creating products with embedded circuitry [1].
- Applications span automotive (HMI panels), consumer electronics (wearables, smart appliances), healthcare (monitoring patches), and aerospace (weight-saving panels).
- Aircraft such as the Lockheed SR-71 Blackbird demonstrate how materials must withstand extreme temperatures and thermal expansion.
- IME reduces weight (up to 70%) and thickness (up to 90%) while supporting structural electronics [2].
- Understanding deformation and failure of printed conductive features during thermoforming remains challenging.

Fig. 3. Applications of In-Mold Electronics (IME) across industries.

Preliminary Study

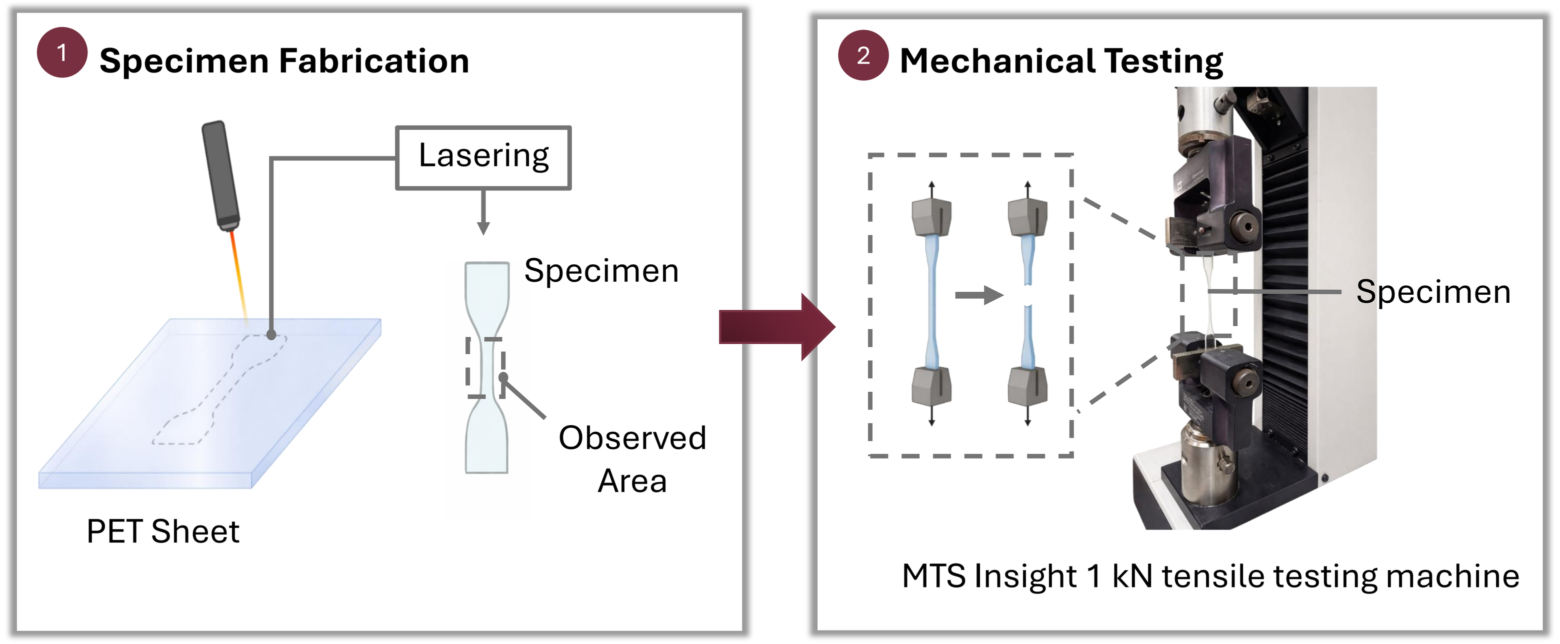

Fig. 4. Specimen fabrication and tensile testing workflow.

- PET thermoformable sheets were laser-cut into dog-bone specimens using a Versa Laser system.
- Samples were tested following ASTM D638 standard.
- Uniaxial tensile testing was performed using an MTS Insight electromechanical machine.
- Force and displacement data were recorded to evaluate mechanical behavior.

Purpose:

- Establish baseline mechanical properties of the PET substrate before thermoforming.
- Understand deformation and fracture behavior of a flexible material.
- Provide a reference for comparison with post-thermoforming and printed samples.

Preliminary Results

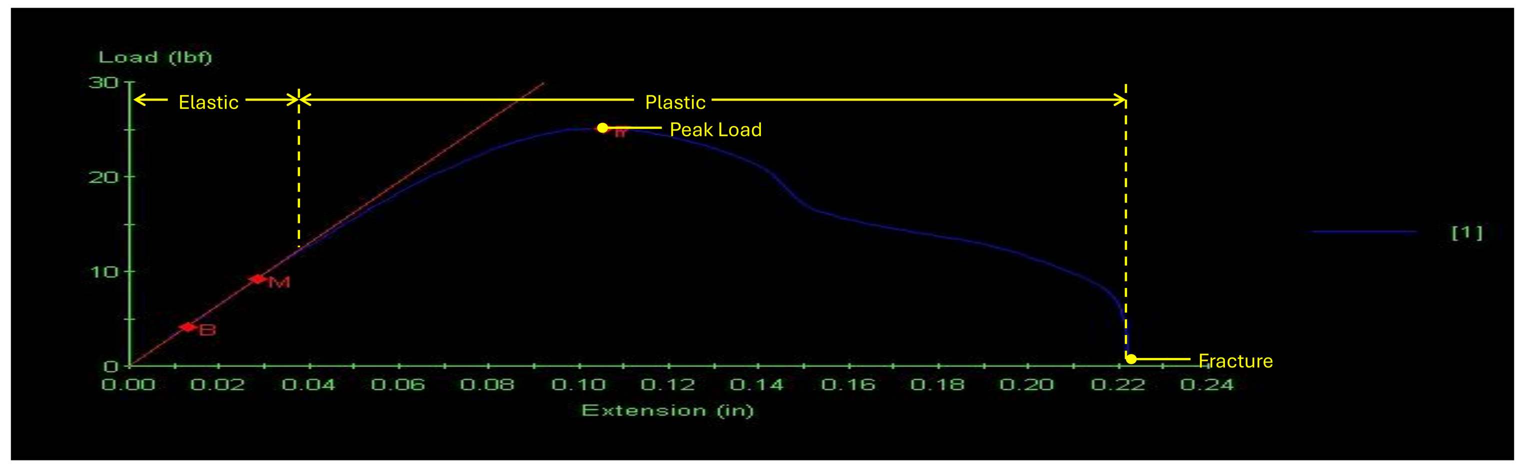

Fig. 5. Load-extension curve of PET showing elastic and plastic deformation.

TABLE I

MECHANICAL PROPERTIES OF PET FROM TENSILE TESTING

Specimen #	Peak Load N	Peak Stress MPa	Strain at Break %	Modulus MPa
1	111.625	13.8	3.077	611.953

- The PET substrate exhibits ductile behavior (i.e., does not fracture suddenly).
- Load increases steadily with extension, indicating elastic and plastic deformation.
- A peak load of approximately 111.6 N (~25 lbf) was reached before failure.
- The results establish a baseline to distinguish material deformation from thermoforming-induced effects.

Future Work

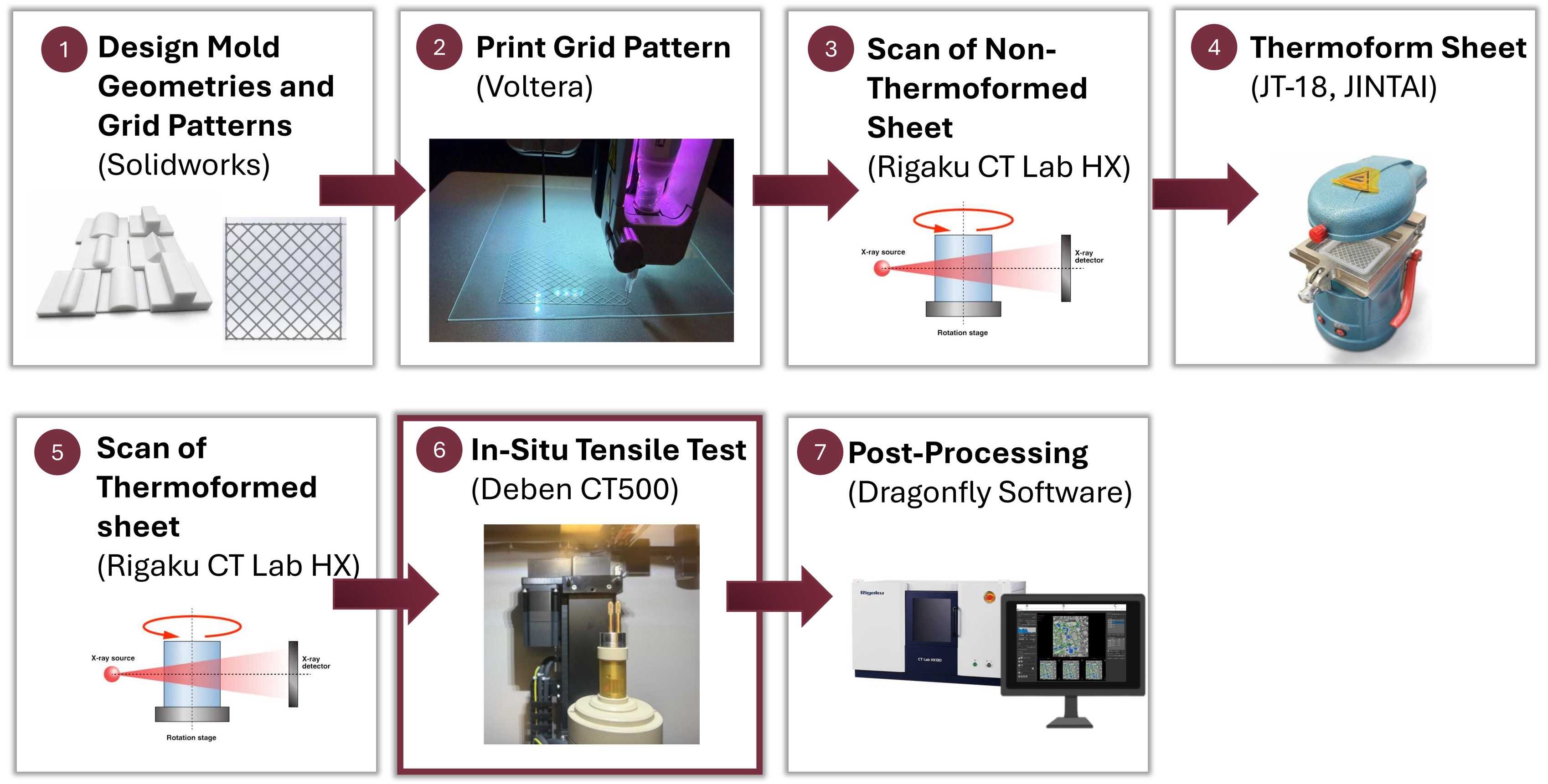

Fig. 6. Future experimental workflow.

What will be analyzed:

- The stress experienced by deposited conductive inks during thermoforming and mechanical loading.
- Micro-CT imaging will be used to identify:
  - Crack initiation and propagation.
  - Voids within the conductive ink structure.
  - Deformation of printed patterns on the substrate.

Conclusion

- The mechanical response confirms that PET is well-suited for thermoforming applications due to its ability to sustain deformation without sudden fracture.
- Tensile testing established baseline mechanical properties prior to thermoforming.
- These results provide a foundation to study how thermoforming-induced stresses affect deposited conductive inks.
- Future work includes:
  - TGA analysis to define safe thermoforming temperatures.
  - In-situ micro-CT imaging to analyze cracks, voids, and deformation.
- Understanding deformation and adhesion will support the design of more reliable flexible electronic systems.

Resources

[1] F. Hong, L. Tendera, C. Myant, and D. Boyle, "Vacuum-Formed 3D Printed Electronics: Fabrication of Thin, Rigid and Free-Form Interactive Surfaces," SN Comput. Sci., vol. 3, no. 4, p. 275, May 2022, doi: 10.1007/s42979-022-01174-1.

[2] T. Simula, P. Niskala, M. Heikkinen, and O. Rusanen, "Component Packages for IMSETM (Injection Molded Structural Electronics)," in 2018 IMAPS Nordic Conference on Microelectronics Packaging (NordPac), Oulu: IEEE, Jun. 2018, pp. 50–54. doi: 10.23919/NORDPAC.2018.8423845.