ON THE SUCCESSFUL FABRICATION OF AUXETIC POLYURETHANE (PU) FOAMS:

KEY INSIGHTS FROM MATERIALS SCIENCE AND POLYMER PROCESSING PERSPECTIVES

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New applications of thermoplastic and foams

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Background
Poisson’s ratio vs. materials

“Poisson's ratio $\nu$ compares the strains in the transverse $\epsilon_t$ and longitudinal $\epsilon_l$ directions under uniaxial stress.”

Nature Materials 2011, 10, 823
What is auxetic PU foam?

First reported by R. S. Lake in 1987

*Science* 1987, 27, 1038
Potential applications:

Protective equipment, damping applications and wave absorption, filters.
How to make auxetic PU foam?

Conventional foam model

Auxetic foam model

Tri-axial compression

Heating and cooling

Honeycomb structure

\[ \nu = - \frac{\text{Lateral strain}}{\text{Axial strain}} > 0 \]

Re-entrant structure

\[ \nu = - \frac{\text{Lateral strain}}{\text{Axial strain}} < 0 \]
The time–temperature profiles for auxetic fabrication reported in the literature

The Successful Fabrication of Auxetic Polyurethane Foams

The structure features in foams I, II, and III

Cellular structure/morphology of conventional PU foams
FTIR-ATR/FTIR

(a) ATR-FTIR spectra of flexible PU foams. (b) FTIR spectra of the extractants of flexible PU foams by DMF.
The DSC results indicated the absence of crystallinity.
WAXS patterns display an amorphous halo, which suggest that very little order exist in the hard segment domains of foams.

This result is consistent with the DSC result.
Cellular Structure

Model Reactions

1. $R-OH + R'NCO \rightarrow R-O-C-N-R'$
   Urethane

2. $H_2O + R'NCO \rightarrow R'NH_2 + CO_2$

   $R'NH_2 + R'NCO \rightarrow R'-N-C-N-R'$
   Urea

Microstructure

- Continuous Soft Phase
- Hard-segment
- Copolymer Particle
Stress-strain curve of polyurethane foam at 0.01 min⁻¹ showing microscopy images of the strain 0, 40, 70 %.
Reinforcing fillers can be deformed from their usual approximately spherical shapes into ellipsoids when they reside at a temperature above the glass transition temperature.
Stress Relaxation

Shape fixity curve of foam II and III at different shape holding temperature (shape strain 40%).
KWW stretch exponential function:

$$1 - R_f = \exp \left[-\left(\frac{t}{\tau(T)}\right)^\beta\right]$$
Relaxation time
Auxetic foam farbication

The relationship between temperature and heating-time
Typical SEM images of auxetic PU foam
Processing window for fabrication of auxetic PU foam
Exploring New fabrication approach

CO₂ assisted fabrication of Auxetic PU foam

1. Conventional PU foam

2. Compression at $T < T_{g,SAN}$

3. $T > T_{g,SAN} - CO₂$

4. Auxetic PU foam

- Continuous Soft Phase
- Copolymer Particle
- Hard-segment

Polymer Plasticization using compressed CO₂
The experimental setup

- Compressed CO₂ Cylinder
- Syringe Pump
- High Pressure Vessel
  - Raw PU Foam
  - Triaxial Compressed Foam

P: Pressure
T: Temperature
Processing window for auxetic manufacture with compressed CO\textsubscript{2}
Effect of processing parameters

![Graph showing Poisson's Ratio over time (min) with data points and error bars.]

- Macroscopic-Level \(\text{CO}_2\) Transport (Convection)
- Microscopic-Level \(\text{CO}_2\) Transport (Diffusion)

![Diagram illustrating flow in a system with pore and PU solid layers.]

Flow In
Mechanical properties

![Graph showing Poisson's ratio vs. engineering strain for Raw PU Foam and Auxetic PU Foam.](image)
Poisson Ratio vs. Piezoresistive Sensing

Fabrication of Auxetic foam sensor

1. Dispersion of CNTs in H₂O
2. Dip coating auxetic foam
3. Coating layer densification/purification

CNT coated auxetic foam
Schematic of the measuring technique

- Video camera
- Copper wire
- Resistance in longitudinal direction
- Resistance in transverse direction
- Silver paste
- Loading machine
- Computer
- Electrometer
The effect of Poisson’s ratio on the resistive pressure response of foams

\[ \frac{\Delta R}{R_0} (\%) \]

Axial direction
Lateral direction

Poisson's ratio

\( \nu = -0.5 \)
\( \nu = 0 \)
\( \nu = 0.4 \)

-0.6 -0.4 -0.2 0.0 0.2 0.4
-10 0 10 20 30 40 50
Variation of relative resistance change with strain

- Conventional foam
  - Variation:
    - ∆R/R₀ (%)
    - Strain (%)
    - 2.63
    - 0.464

- Auxeic foam
  - Variation:
    - ∆R/R₀ (%)
    - Strain (%)
    - 1.45
    - 0.491
Multimodal sensing performance of auxetic foam sensors

Signal output vs. time for different percentages:
- 80%
- 40%
- 20%

Units: kPa

Graphs show the signal output over time for different percentages.
The Application of Smart Foam in Helmet

Our effort to develop a smart helmet with intrinsic sensing capabilities, enabled by replacing the foam pads in the current helmet design with auxetic sensing foams.
Wearable biosignal-measuring

Monitor muscle movement during speech

Monitor the wrist pulse

Heartbeat Sensing
The signal of the foam sensor is faithfully registered with the finger motion to recognize different gestures. The gestures can be converted to different commands to control various electronic devices and robots.
Attaching the AF sensors directly to the fingertip can serve as a means to acquire human intentions of pressing buttons and switches.
Pressure mapping

Measured right foot pressure pattern at different gait phases
Conclusions

• Elucidated microscopic and molecular level mechanisms for auxetic conversion.
• Demonstrated a compressed CO$_2$ assisted auxetic PU foams manufacturing technology.
• Demonstrated a new class of auxetic foams-based piezoresistive sensors and their potential applications.
THANK YOU FOR YOUR ATTENTION!
ANY QUESTION?

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