Electromechanical Optimization of Stretchable Liquid Metal-Based Conductors through Percolative Networks Design

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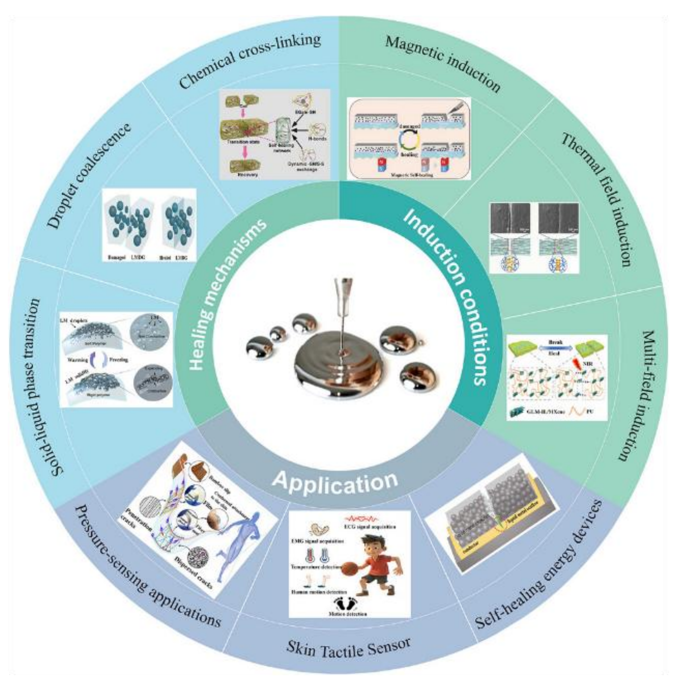
Introduction



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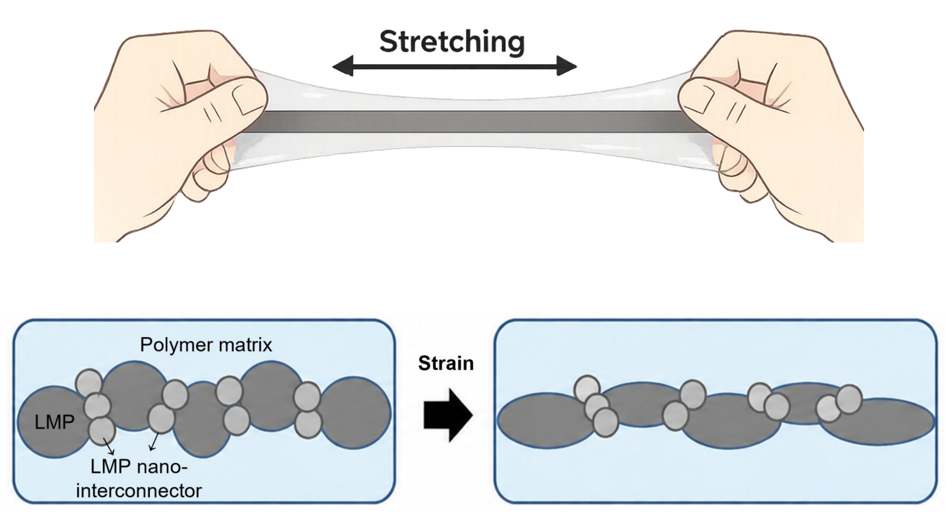
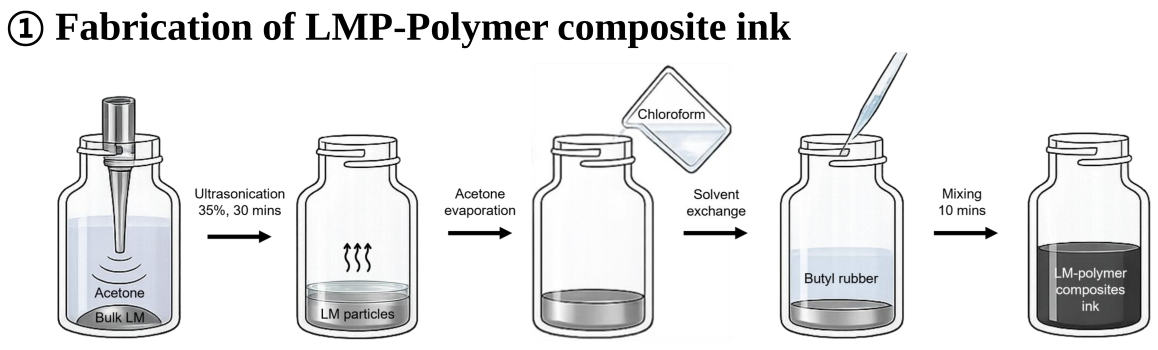
- Stretchable electronic devices require both high electrical conductivity and mechanical stretchability for applications such as wearable electronics, soft robotics, and electronic skin. However, conventional conductive composites often exhibit unstable electrical performance under mechanical deformation.
- Liquid metals (LMs), such as eutectic gallium-indium (EGaIn), are promising stretchable conductors owing to their metallic conductivity and intrinsic deformability.



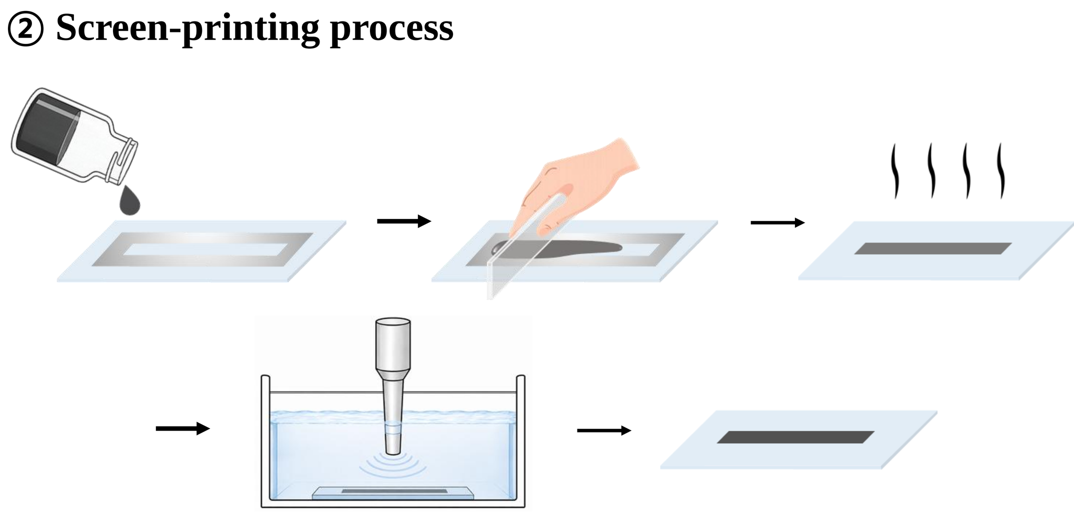
- LM particles are naturally covered by a thin oxide layer, which electrically isolates neighboring particles and limits conductive pathway formation. In addition, rupture of the oxide shell can cause leakage of the liquid metal core, reducing device reliability.
- To overcome these limitations, LM particles were dispersed in an elastomer matrix and activated by sonication. The acoustic energy partially disrupts the oxide layer and forms nanoscale LM interconnectors between adjacent particles, creating conductive percolation networks while suppressing LM leakage.
- This study investigates the effects of LM volume fraction on electrical and mechanical properties and identifies the optimal composition that balances conductivity and stretchability.

Experimental

① Fabrication of LMP-Polymer composite ink

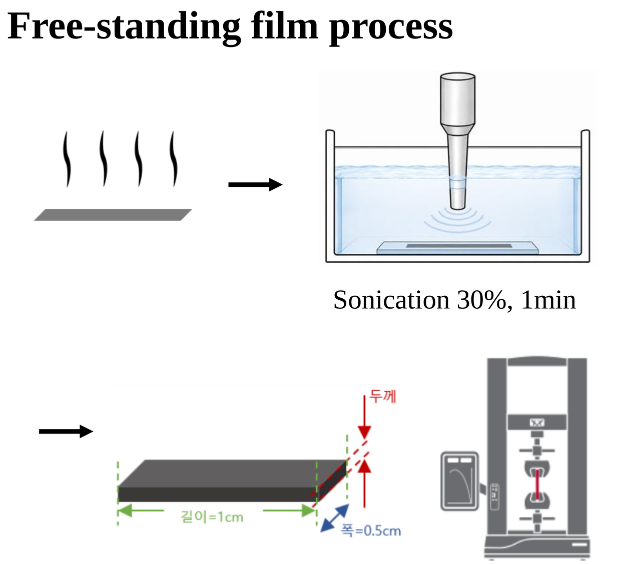


② Screen-printing process



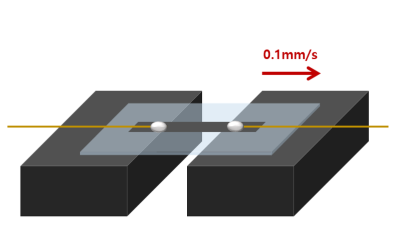
Sonication 30%, 1min

③ Free-standing film process

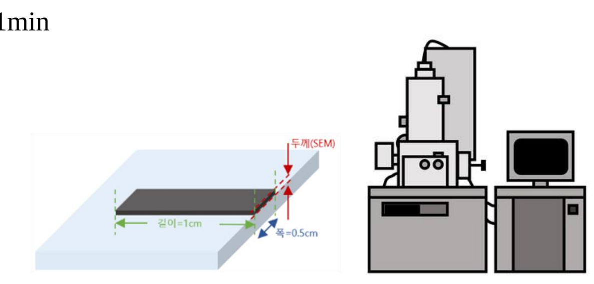


Sonication 30%, 1min

Mechanical Characterization Using UTM



Measuring relative resistance change during stretching



Dimensional Analysis Using Cross-sectional SEM Images

$$\sigma = \frac{L}{RA}$$

R: Resistance [Ω]
L: conductor's length [m]
A: conductor's area m^2]
σ: Conductivity [S/m]

Calculating conductivity

Results

Analysis of SEM Image of LMP-Polymer

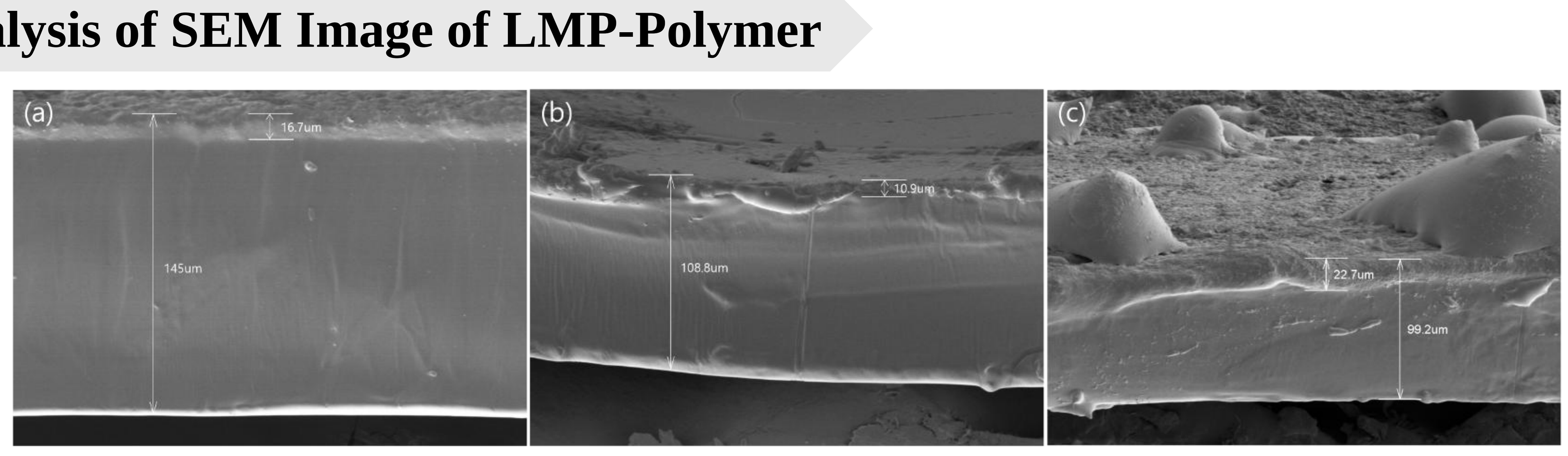
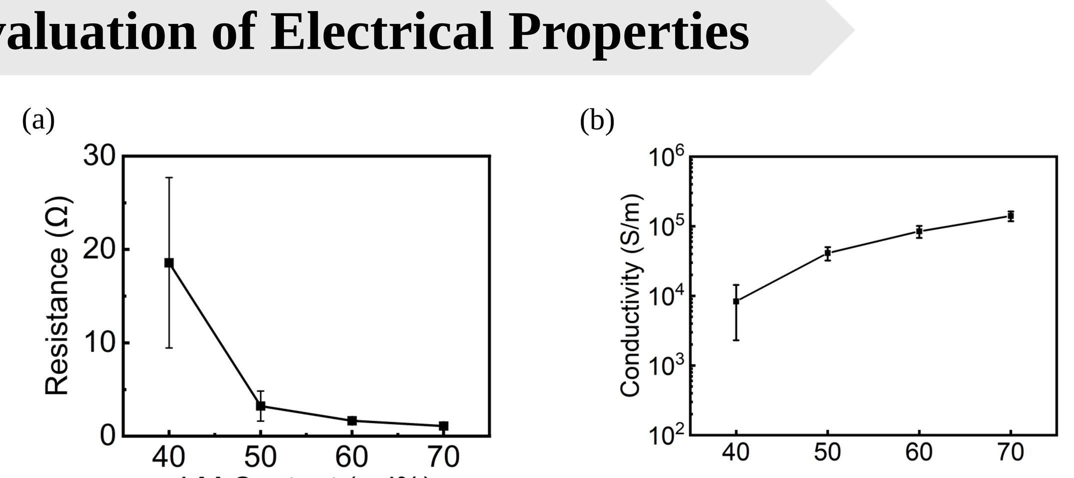


Fig. 1. Cross-sectional SEM images of the 60 vol% LM/polymer conductor (average thickness: 17 µm).

- The measured thickness was used to calculate the electrical conductivity of the printed LM/polymer conductors.

Evaluation of Electrical Properties



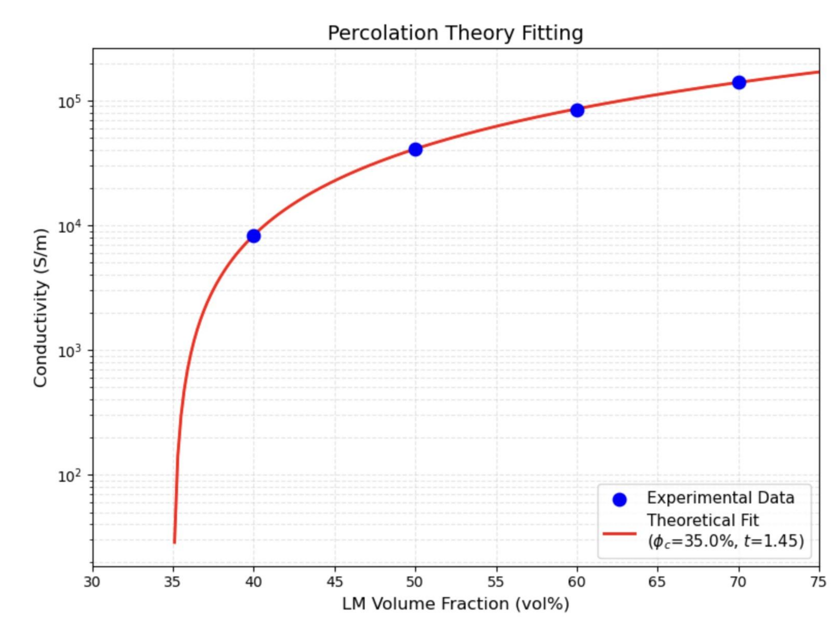
LM vol%	Resistance [Ω]	Conductivity [S/m]
40	16.89	8.32×10^3
50	2.58	4.12×10^4
60	1.42	8.45×10^4
70	0.82	1.41×10^5

Graph. 1. Initial resistance and electrical conductivity as a function of LM volume fraction.

- The initial resistance decreased from 18.3 Ω to 0.82 Ω with increasing LM volume fraction, indicating enhanced electrical connectivity between LM particles.
- The electrical conductivity increased from 8.32×10^3 to 1.41×10^5 S/m, suggesting progressive formation of conductive pathways within the composite.

Results

Percolation Network Formation and Threshold Analysis

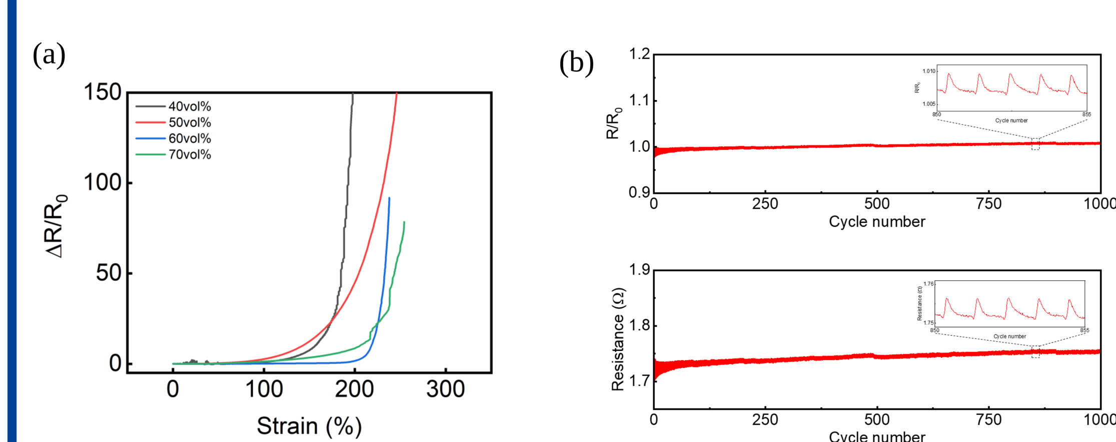


Graph 2. Electrical conductivity as a function of LM volume fraction fitted using the percolation power-law model.

$$\sigma = \sigma_0(\phi - \phi_c)^t \quad (\phi > \phi_c)$$

- Conductivity increased with LM volume fraction due to percolation network formation.
- Percolation Threshold (ϕ_c) was determined to be 35.0 vol%, indicating that a continuous conductive network forms above this LM content.
- The conductivity data were well fitted by the percolation power-law model with a critical exponent of t = 1.45 and an excellent fitting accuracy (R^2 = 0.9999).
- The fitted exponent indicates the formation of a quasi-2D conductive pathway within the printed conductor.

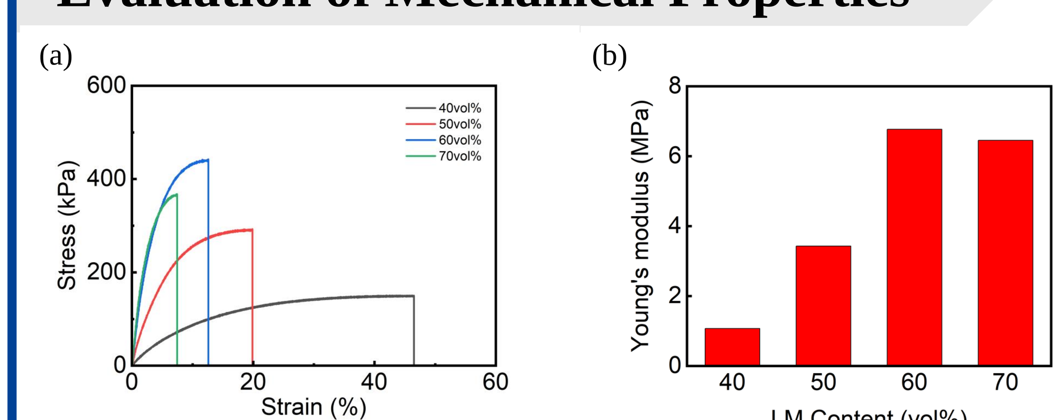
Evaluation of Electrical Stability under Deformation



Graph 3. (a) Relative resistance change under strain. (b) cyclic stability test.

- The 60 and 70 vol% conductors exhibited superior electrical stability with low $\Delta R/R_0$ variation, and the 60 vol% conductor maintained stable cyclic durability.
- Higher LM contents enabled the formation of multiple conductive pathways, allowing stable electrical conduction during stretching.

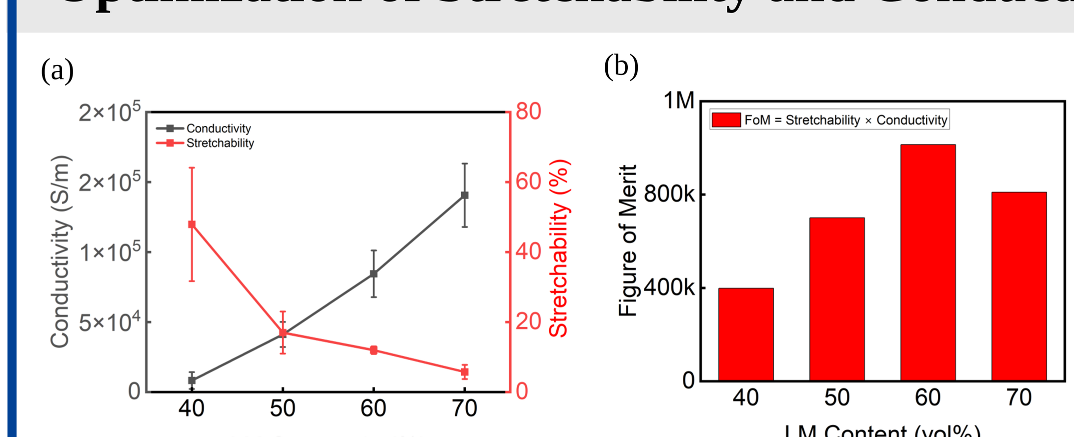
Evaluation of Mechanical Properties



Graph 4. (a) Stress-strain curve. (b) Young's Modulus

- Maximum stress and Young's modulus increased with increasing LM content due to the reinforced conductive network.
- The 60 vol% conductor achieved the best balance between mechanical strength and deformability, indicating the optimal composition.

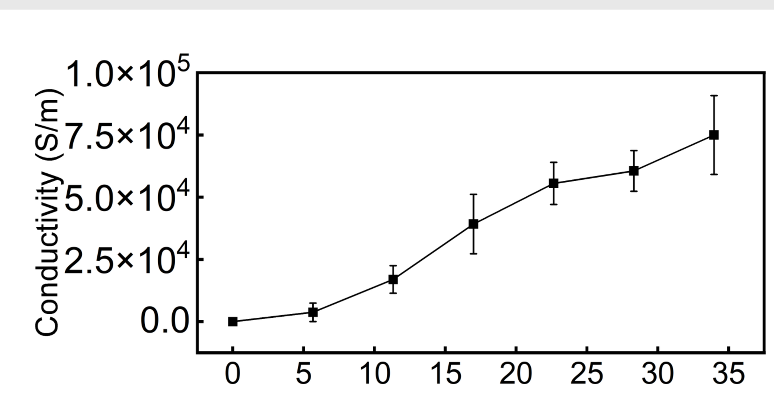
Optimization of Stretchability and Conductivity



Graph 5. (a) Stretchability-Conductivity trade-off. (b) Figure of Merit (FoM)

- Electrical conductivity increased while stretchability decreased with increasing LM content, demonstrating a trade-off relationship.
- The highest Figure of Merit (FoM) was achieved at 60 vol%, identifying it as the optimal composition.

Effect of Sonication Activation



Graph 6. Conductivity of accumulated sonication energy density

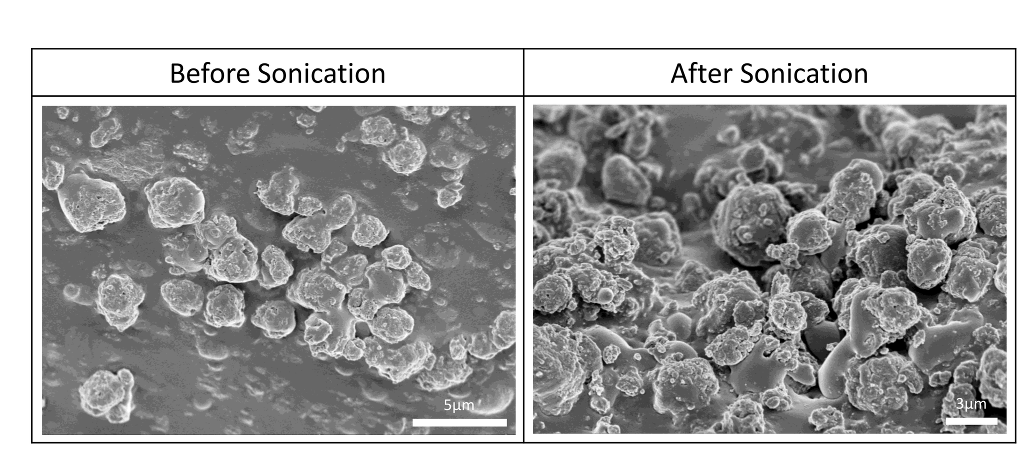


Fig 2. SEM images before/after sonication

- Electrical conductivity increased with accumulated sonication energy density.
- SEM images confirmed the formation of nanoscale LM interconnectors after sonication activation.
- These interconnectors promoted conductive pathway formation and enhanced conductivity.

Conclusion

- Conductive percolation networks were successfully formed through sonication-induced activation of LM particles.
- Electrical conductivity increased with LM content, while stretchability decreased, resulting in a conductivity–stretchability trade-off.
- The 60 vol% conductor achieved the highest Figure of Merit and the best balance between electrical and mechanical performance. Therefore, 60 vol% was identified as the optimal composition for stretchable LM/polymer conductors.
- This study provides design guidelines for optimizing conductive network formation in liquid metal-based stretchable conductors.