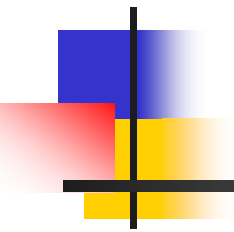


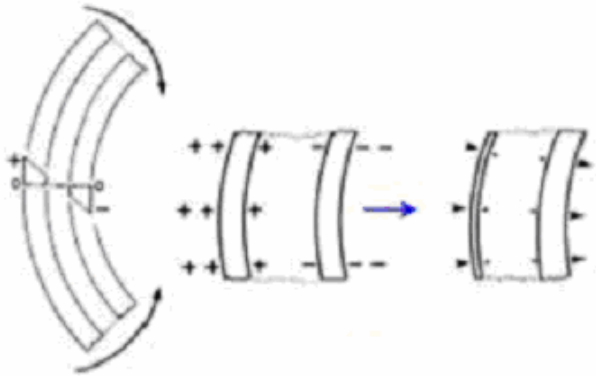
Inherently Adaptive Structural Materials

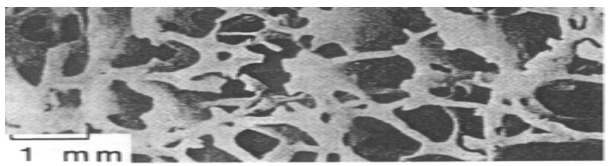
Technova Corporation

Outline of the Presentation

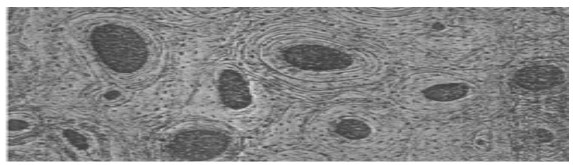
- **Biomimetic Principles**
- Fundamental Concepts
- Functional Constituents
- Modeling and Theoretical Validation
- Experimental Verification
- Conclusions & Future Plans

Adaptive Qualities of Bone

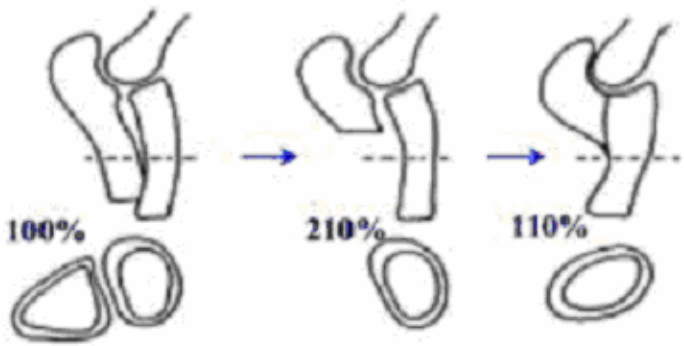




Cancellous Bone



Compact Bone



Inherently Adaptive Structural Materials

- Technova Corporation
- Biomimetic Principles
- Fundamental Concepts
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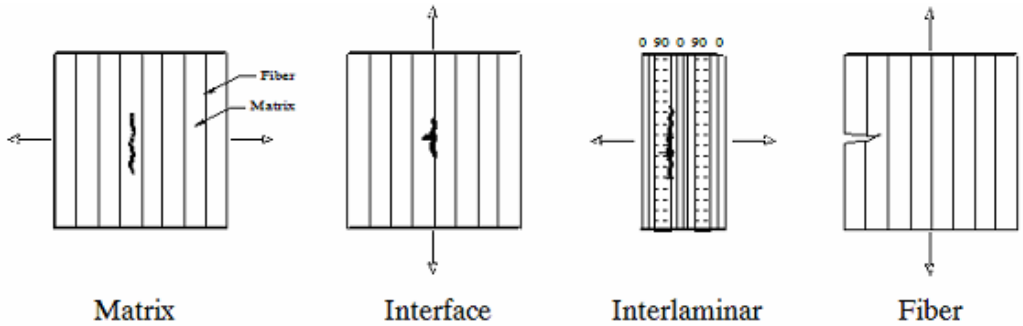
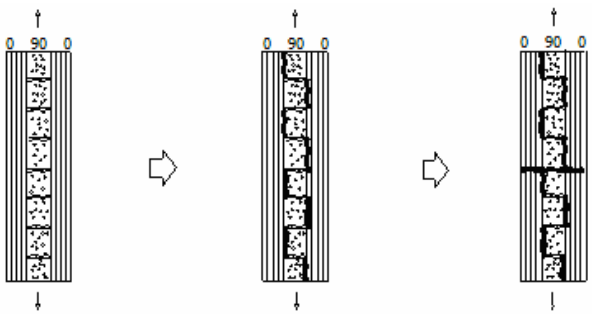
- Experimental Verification
- Conclusions & Future Plans

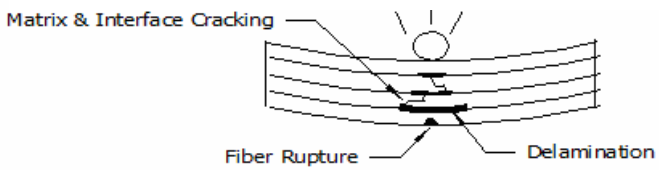
Composite Damage Mechanisms



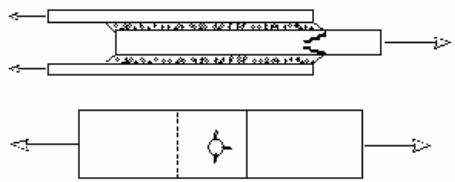
Cracks in Composites



Growth of Fatigue Damage in Composite Laminate

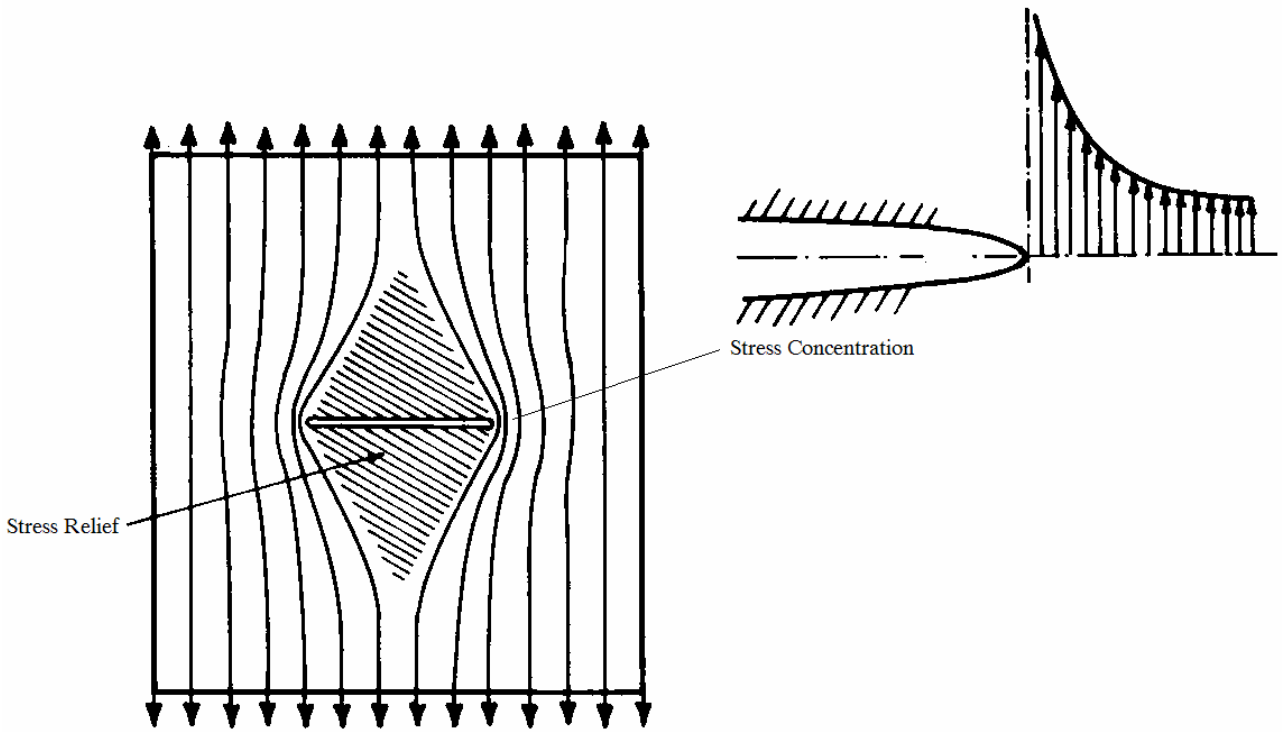


Impact Damage

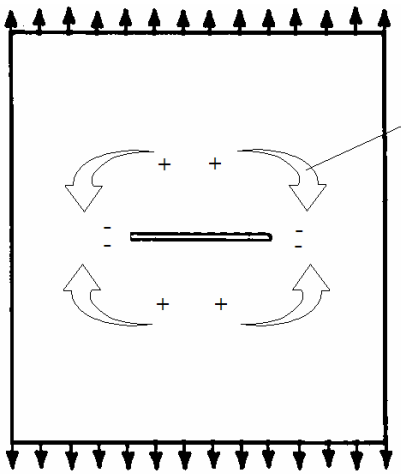


Local Sources of Stress Rise

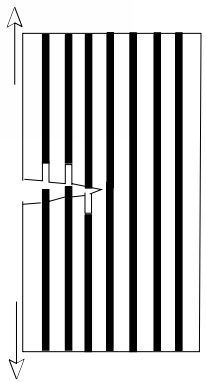
Damaging Concentration of Mechanical Energy

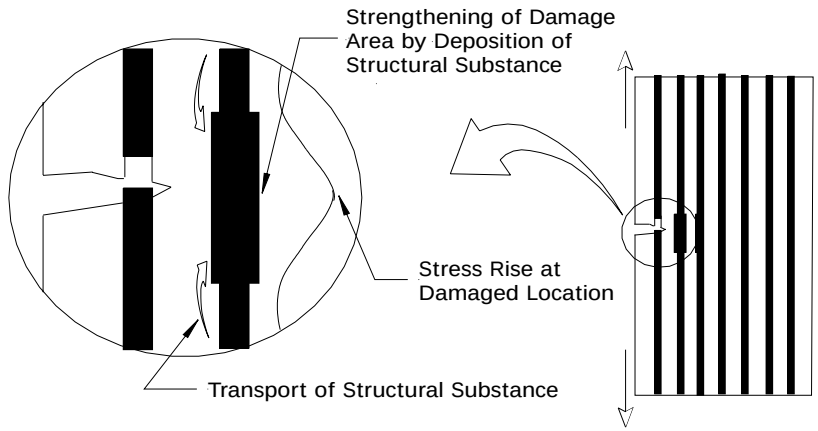


The Adaptive Mechanism



Transport of Structural Substance to Strengthen Critical Areas





Inherently Adaptive Structural Materials

- Biomimetic Principles
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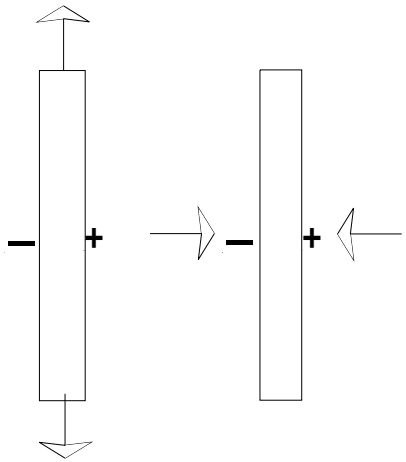
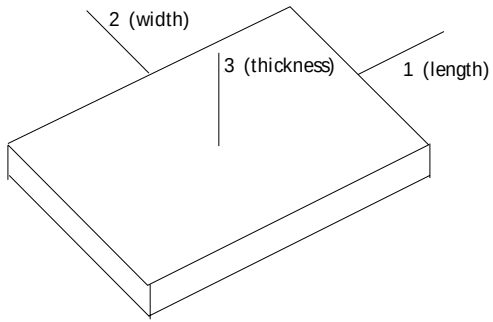
Roles of Functional Materials

- The piezoelectric constituent generates electric potential in response to stress gradient to guide the adaptive process, and also converts the destructive mechanical energy to electrical energy to drive the self-healing process
- Electrolytic transport of mass within solid electrolyte, and its deposition at highly stressed areas strengthen such areas and render adaptive effects.

Piezoelectric Materials



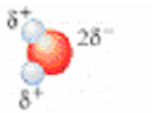


$Q = d_{3n}.X_n.A$

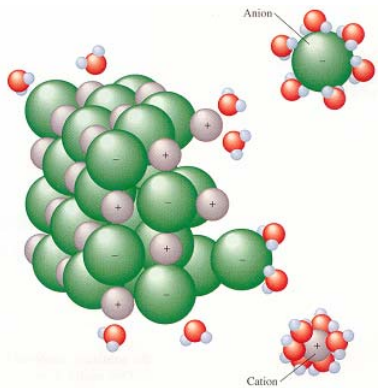
$V = g_{3n}.X_n.t$

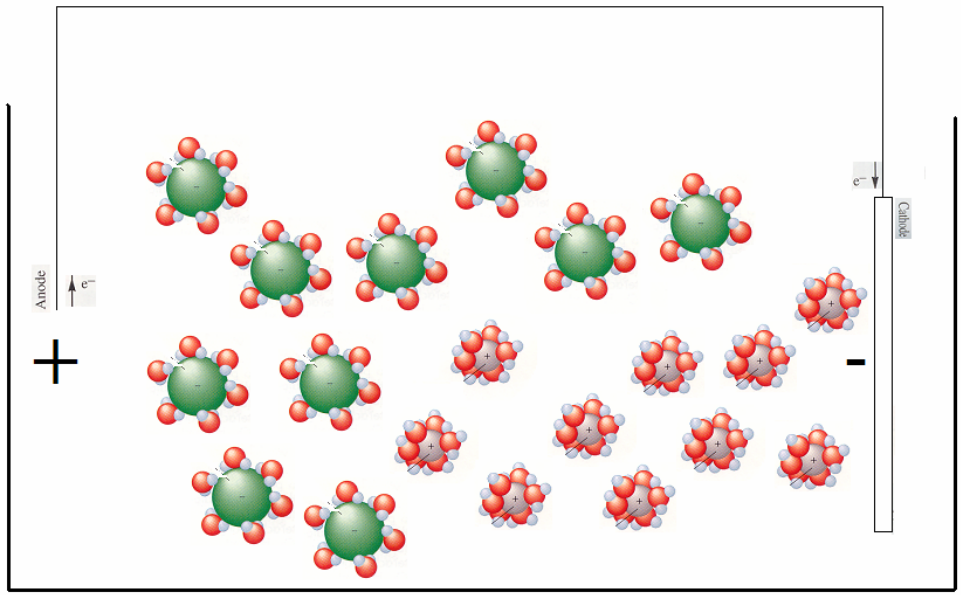
Piezoelectric Material	d_{31} $(C/m^2)/(N/m^2)$	d_{33} $(C/m^2)/(N/m^2)$	g_{31} $(V/m)/(N/m^2)$	g_{33} $(V/m)/(N/m^2)$	k_{31} %	k_{33} %	E GPa
PZT	-122×10^{-12}	285×10^{-12}	-10.6×10^{-3}	24.9×10^{-3}	33	70	65
PVDF	23×10^{-12}	-34×10^{-12}	210×10^{-3}	-500×10^{-3}	12	12	2.5
PMNT	-370×10^{-12}	1600×10^{-12}	-6.8×10^{-3}	15.8×10^{-3}	42	88	110

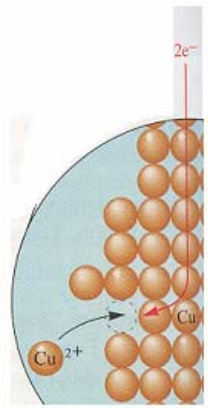
Liquid Electrolyte and Electrolysis



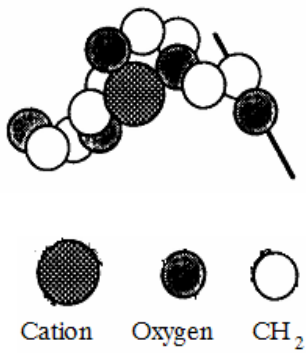
Polar Water Molecule

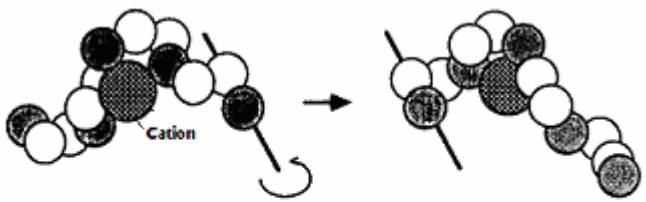




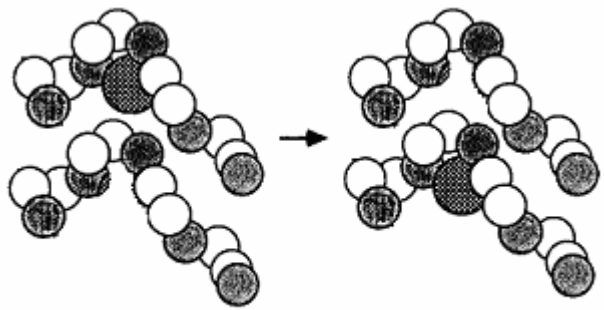


Solid Electrolytes



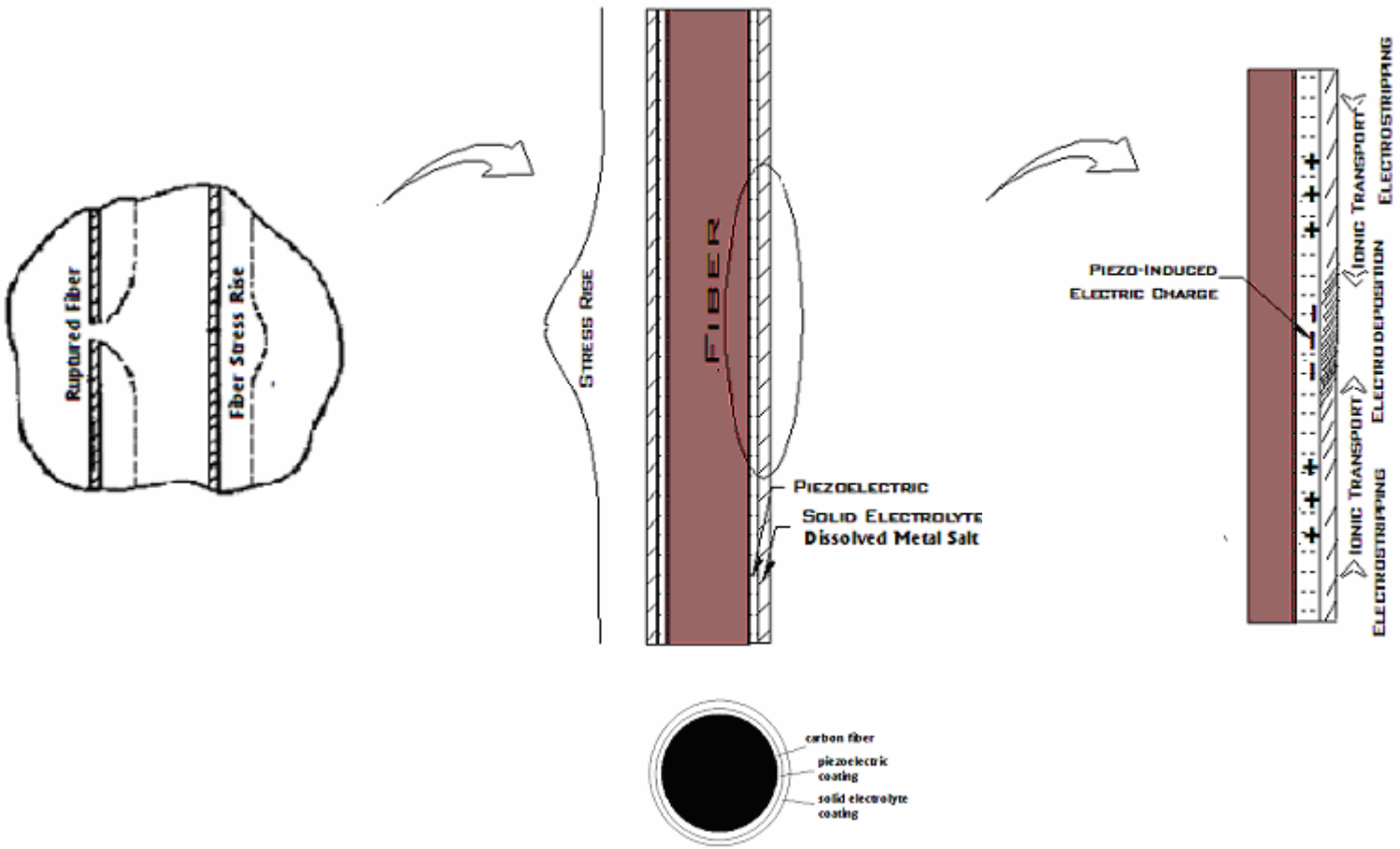


Segmented Motion of Polymer Chain



Cation Transfer Between Chains

Schematic Presentation of the Process



Inherently Adaptive Structural Materials

- Biomimetic Principles
- Fundamental Concepts
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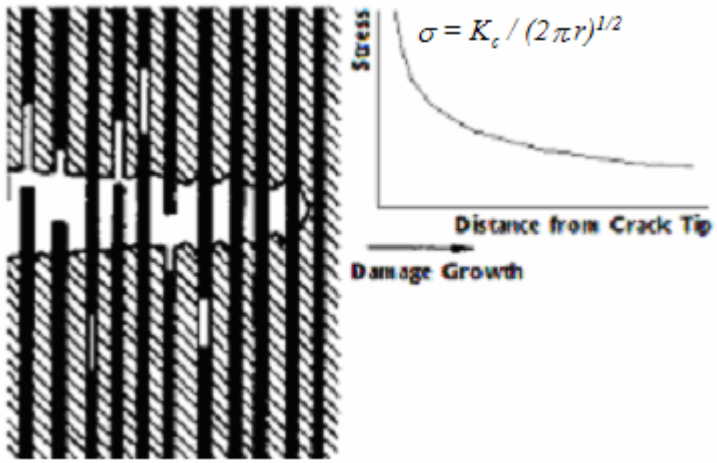
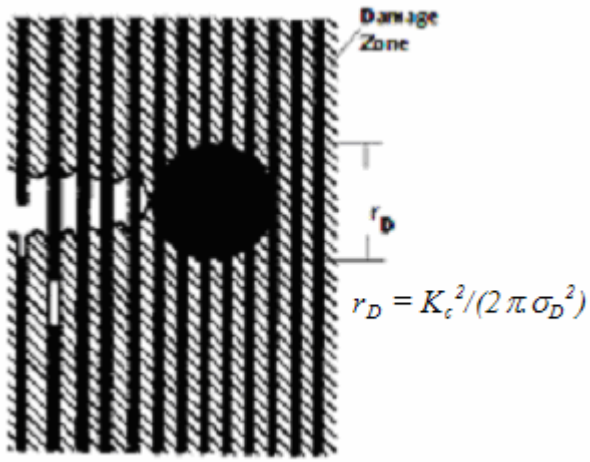
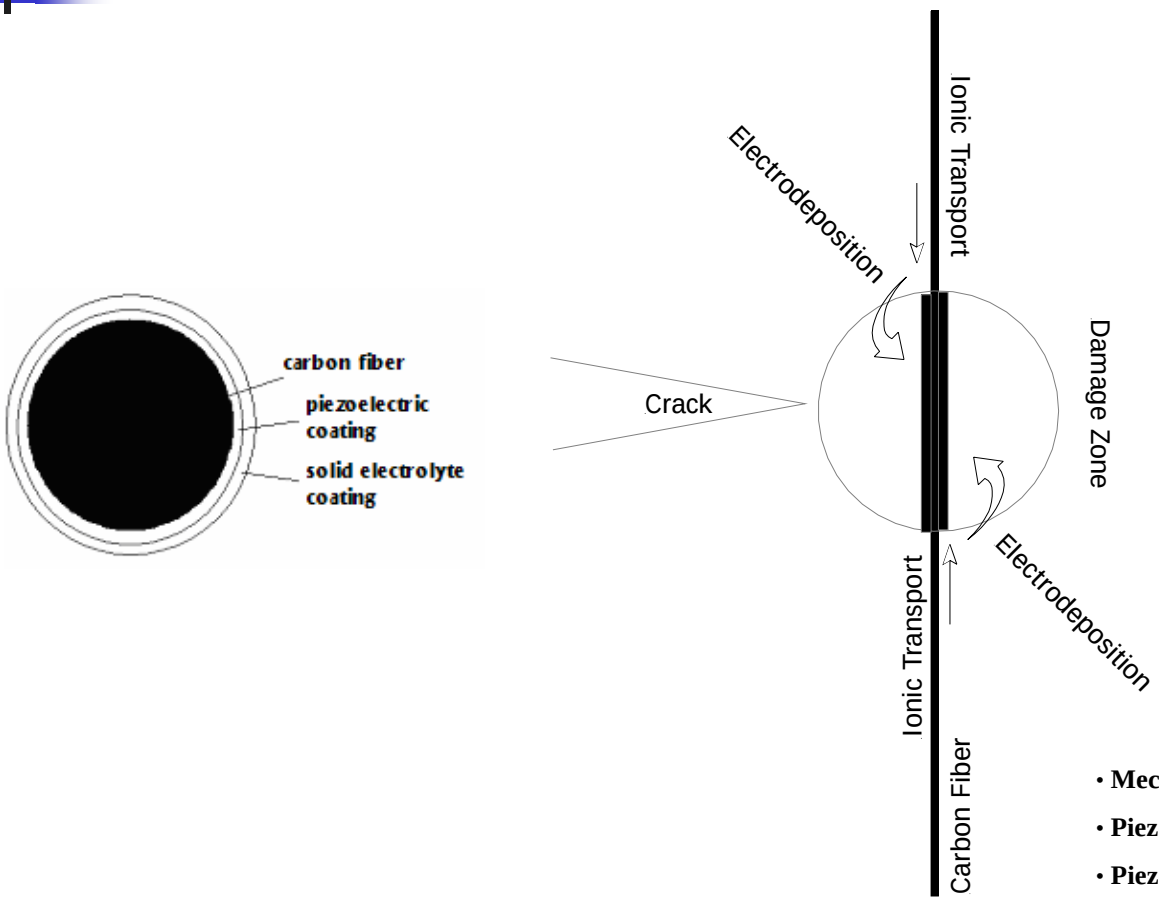
Analytical Assessment of Damage Zone





Analytical Validation of Adaptive Effects



- **Mechanical Analysis to Assess Stress Gradient**
- **Piezo-Induced Potential:** $V = g_{31} \cdot (S_{max} - S_{min}) \cdot Tp$
- **Piezo-Induced Charge:** $Q = d_{31} \cdot (S_{max} - S_{min}) \cdot A$
- **Rate of Mass Transport & Local Strengthening**

Inherently Adaptive Structural Materials

- Biomimetic Principles
- Fundamental Concepts
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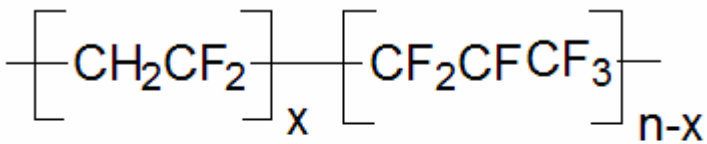
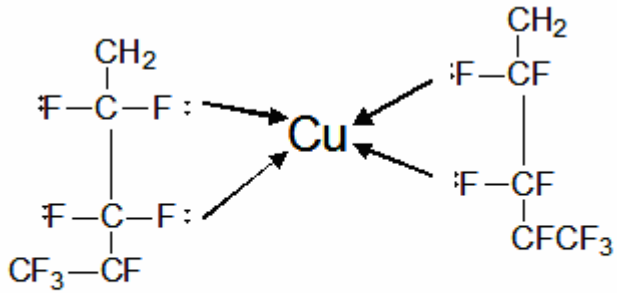
Experimental Verification of Adaptive Mechanisms

- Electrolysis Phenomena and Their Mechanical Implications Within Solid Electrolyte
- Piezo-Driven Electrolysis Within Solid Electrolyte, and Its Mechanical Implications
- Processing of Hybrid Piezoelectric/Solid Electrolyte Coating Systems
- Piezo-Driven Electrolysis in Integrated Piezoelectric/ Solid Electrolyte Coating Under Stress Gradient

Solid Electrolyte

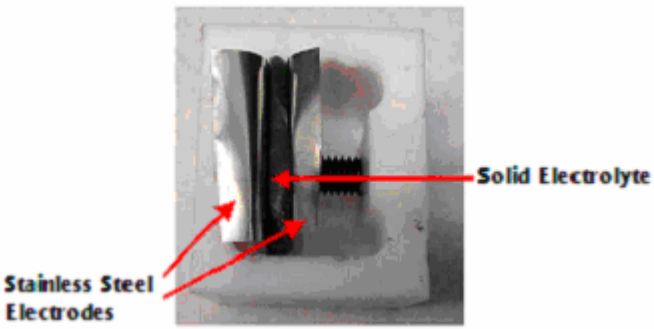


PVDF-HFP

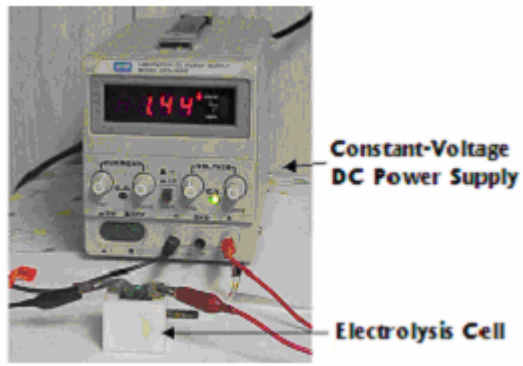


Binding of Metal Cation

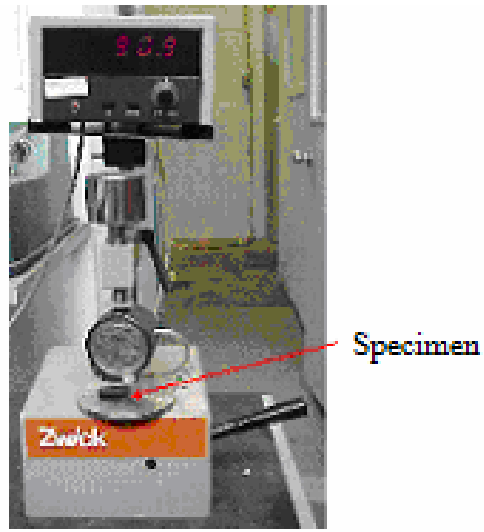
Electrolysis and Material Test Procedures



Electrolysis Cell



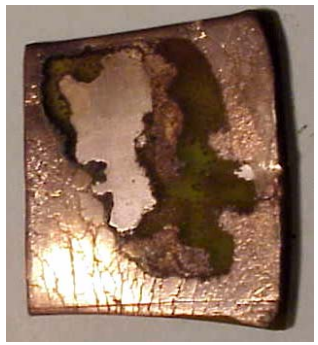
Electrolysis Set-Up



Hardness Test

Experimental Results

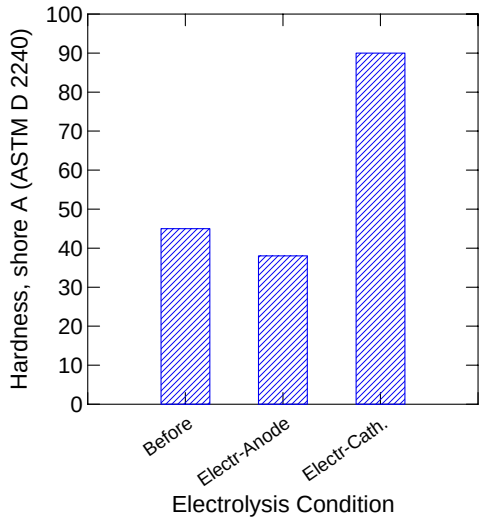
Prior to Electrolysis



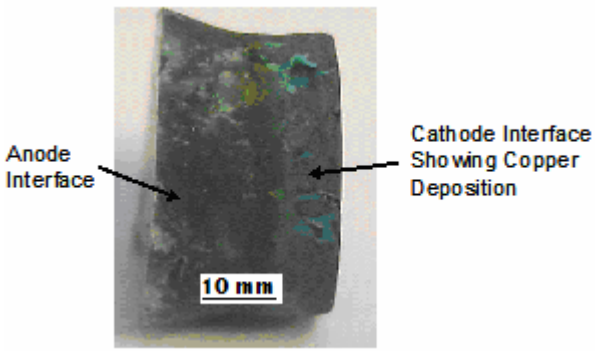
Cathode Interface

Anode Interface

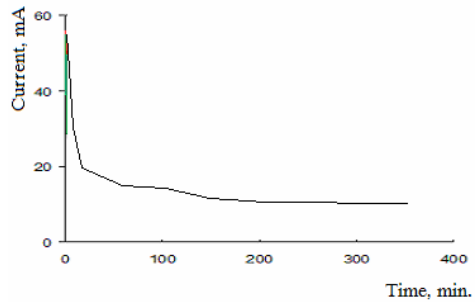
After Electrolysis



Hardness Test Results



Electrolysis in Thicker Solid Electrolyte



Current Time-History

Experimental Verification of Self-Healing Principles

- Electrolysis Phenomena and Their Mechanical Implications Within Solid Electrolyte
- Piezo-Driven Electrolysis Within Solid Electrolyte, and Its Mechanical Implications
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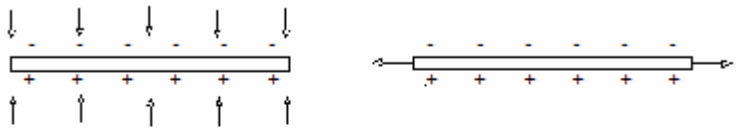
- Piezo-Driven Electrolysis in Integrated Piezoelectric/ Solid Electrolyte Coating Under Stress Gradient

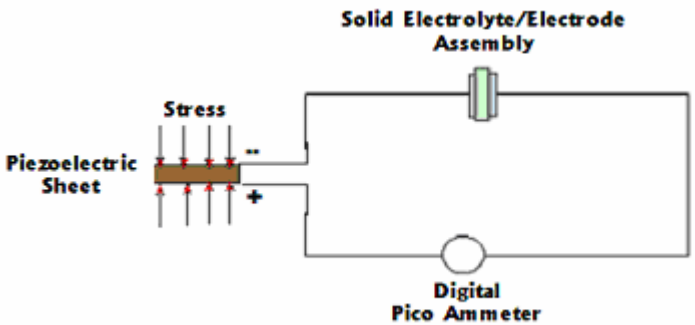
Piezo-Driven Electrolysis Set-Up



$$Q = d_{3n}.X_n.A$$

$$V = g_{3n}.X_n.t$$

Piezo-Induced Charge & Potential



Piezo-Driven Electrolysis Set-Up

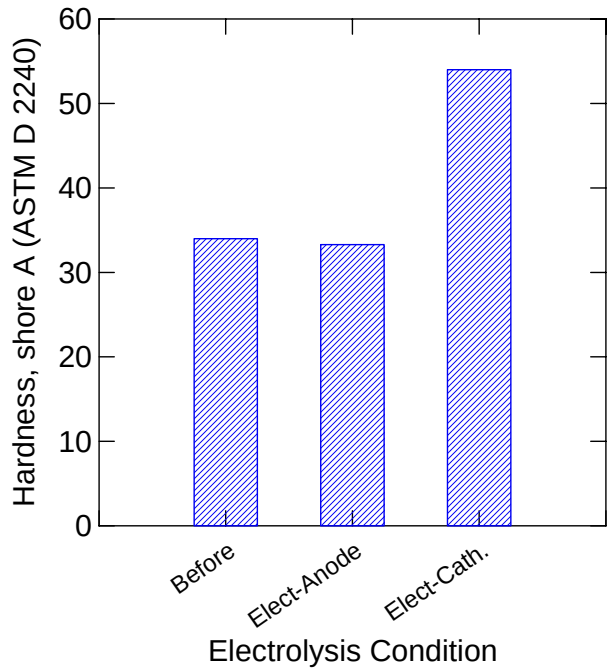
Experimental Results

Prior to Electrolysis

After Piezo-Driven Electrolysis

Cathode Interface

Anode Interface



Mechanical Implications

Experimental Verification of Self-Healing Principles

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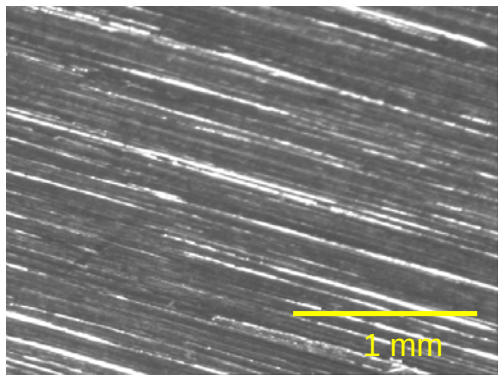
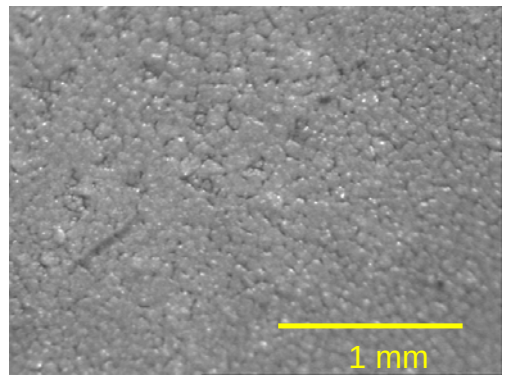
Sol-Gel Processing of Piezoceramic Coating

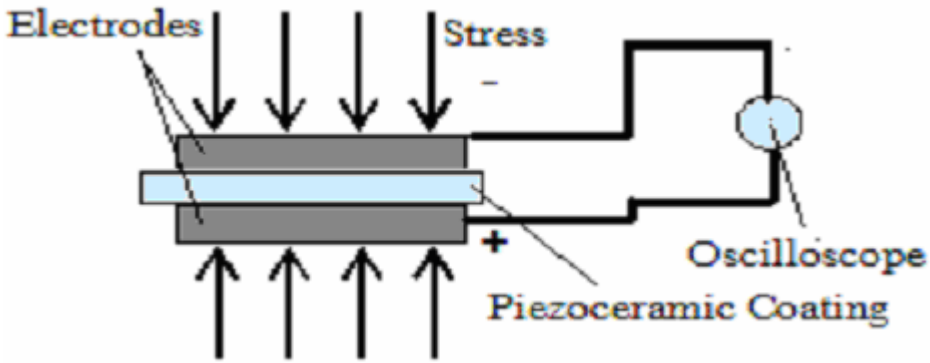


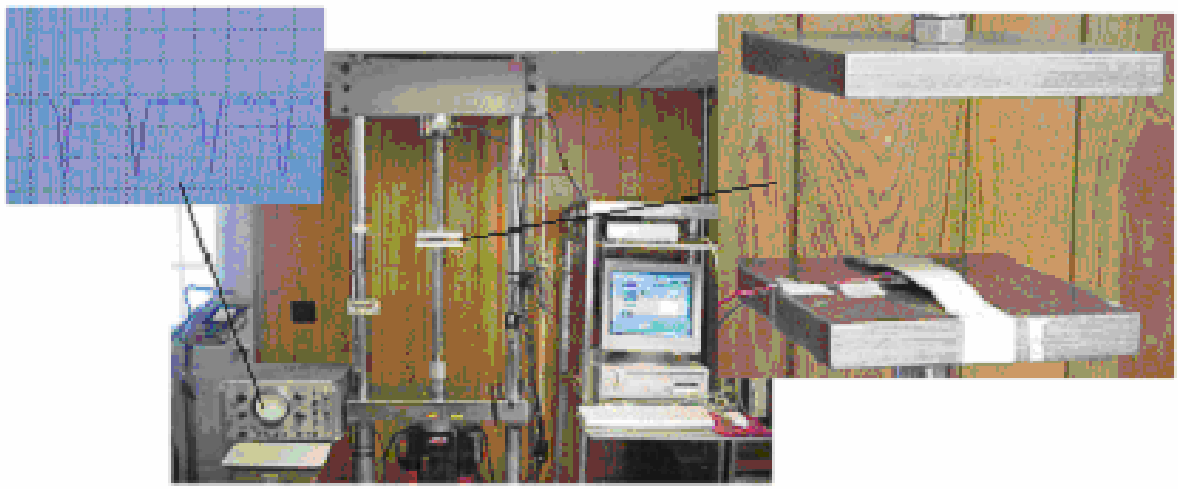
Copper Sheet



Piezo-Coated Copper Sheet

Characterization of Piezoelectric Coating





Processing of Integrated Piezoelectric/Solid Electrolyte Coating

Copper Sheet

Piezo-Coated Copper Sheet

Copper Sheet with Integrated Piezoelectric/Solid Electrolyte Coating

Experimental Verification of Self-Healing Principles

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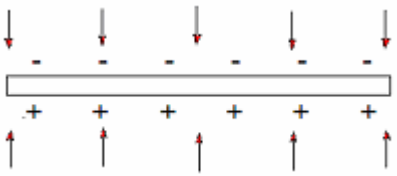
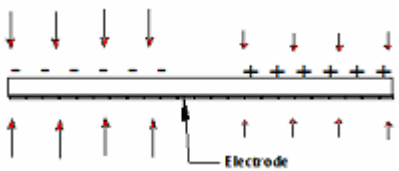
- Piezo-Driven Electrolysis In Integrated Piezoelectric/ Solid Electrolyte Coating Under Stress Gradient

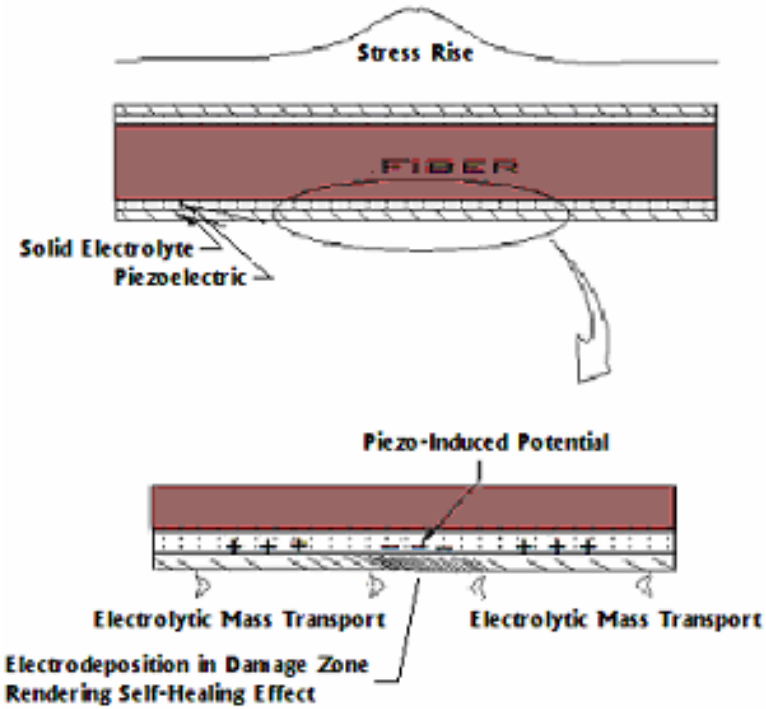
Basic Principles & Test Set-Up



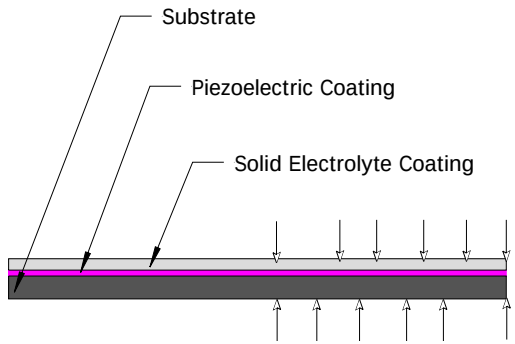
Conventional Piezoelectric Effect



Piezoelectric Effect Under Stress Gradient



Piezoelectric Effect in Self-Healing Composites



Test Set-Up

Experimental Results

Prior to Test

Unstressed

Stressed

After Test

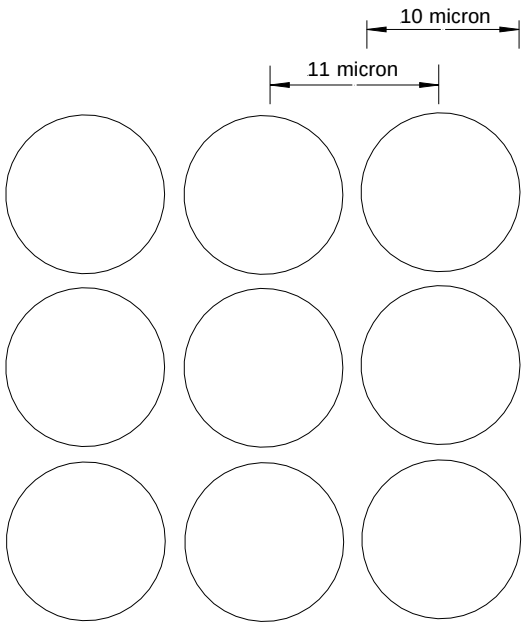
Inherently Adaptive Structural Materials

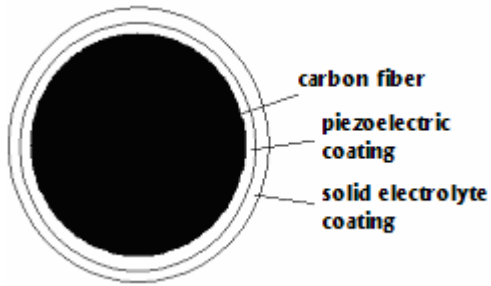
- Biomimetic Principles
- Fundamental Concepts
- Functional Constituents
- Modeling and Theoretical Validation
- Experimental Verification
- Conclusions & Future Plans

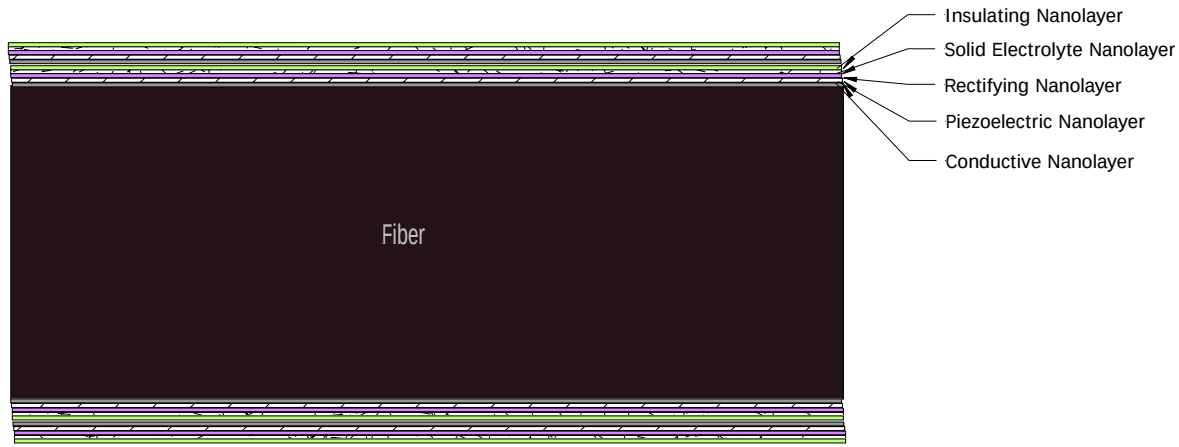
Conclusions

- Analytical Validation of Adaptive Mechanisms
- Piezo-Driven Electrolytic Mass Transport in Solid Electrolyte, and Its Mechanical Implications
- Initial Steps Towards System Integration Within a Hybrid Coating, and Verification of the Integrated System

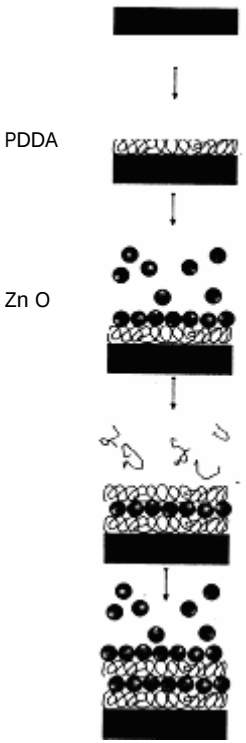
Future Plans





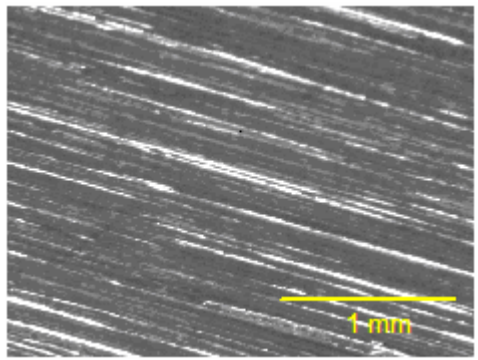


Layer-By-Layer Self-Assembly of Piezoelectric Coating

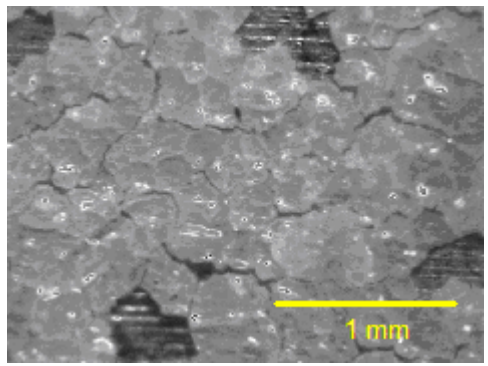


Layer-By-Layer

Self-Assembly

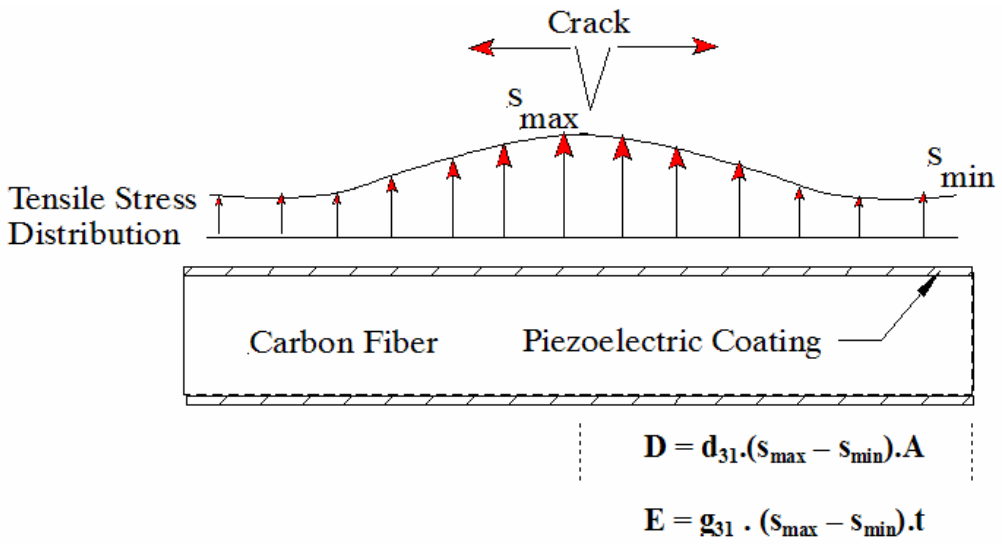


Copper Sheet



Piezo-Coated Copper Sheet

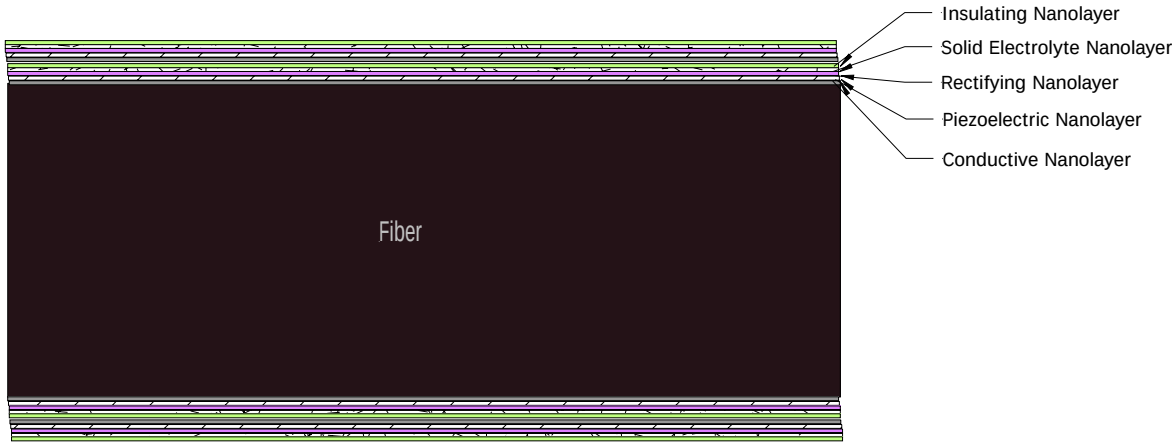
Benefits of Piezoelectric Nano-Composites

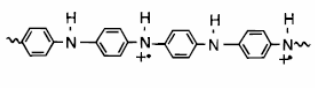


Bulk Piezo-Ceramic: $A = \pi.(d+t).l$

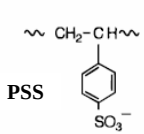
Nanotube Reinforced Piezo-Composite: $A = \pi.(d+t).l.(4t.V_f/d_f)$

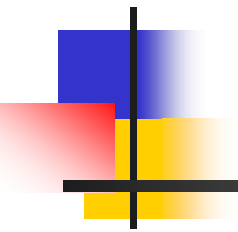
Self-Assembly & Validation of the Hybrid, Nanostructured Fiber Coating





Doped Polyaniline





Thank You!