Intrinsically smart polymer-matrix structural composites

Topic 4

Reading assignment

- Chung, Composite Materials, Ch. 13.
- No. 81, under "Publications – polymer" in website http://www.wings.buffalo.edu/academic/department/eng/mae/cmrl

Functions

- **Structural**
- **Self-sensing**
- **Electromagnetic (e.g., shielding, low observability)**
- **Lightning protection**
- **Heating (e.g., deicing)**
- **Self-healing**

Types of sensing

- **Strain/stress sensing**
- **Damage sensing**
- **Temperature sensing**
- **Process monitoring**

Importance of sensing

- **Structural health monitoring**
- **Hazard mitigation**
- **Structural vibration control**

Methods of sensing

- **Electrical methods**
- **Optical methods**
- **Acoustic methods**

Electrical methods

- Resistance measurement
- Impedance measurement

Resistance methods

- Volume resistance
- Contact resistance

Piezoresistivity

Change in electrical resistivity with strain

Continuous carbon fiber polymer-matrix composites

For lightweight structures

Composite configuration

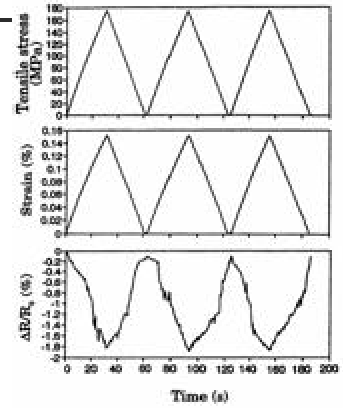
- PAN-based carbon fiber
- Epoxy matrix
- Unidirectional
- 8 laminae in laminate

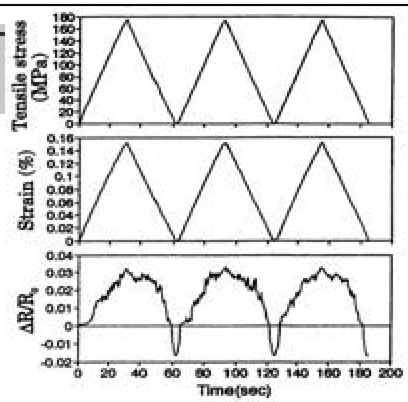
Volume resistance

- Fiber direction
- Through-thickness direction

Tensile stress in the fiber direction

- Resistance in the fiber direction
- Resistance in the through-thickness direction





Strain sensing

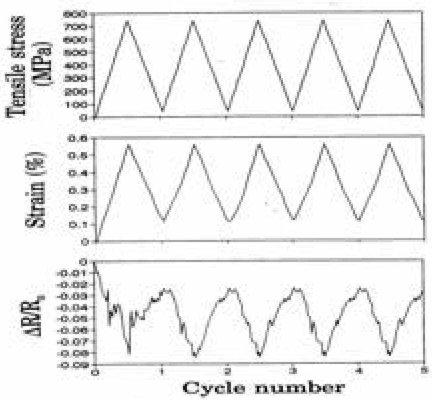
- Tensile strain in the fiber direction – causes the resistance in the fiber direction to decrease reversibly and causes that in the through-thickness direction to increase reversibly
- Compressive strain in the fiber direction – opposite to the above

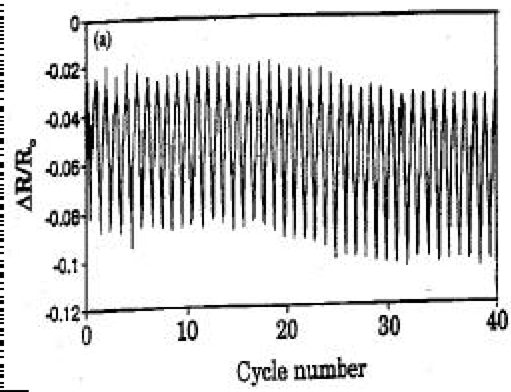
Probable origin of piezoresistivity

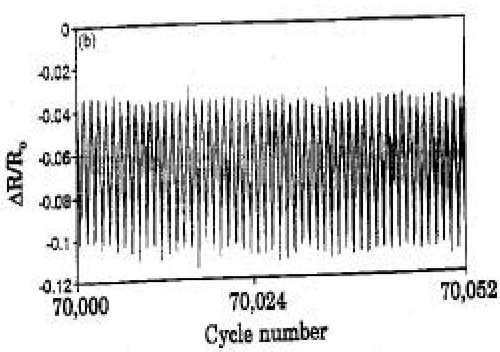
Increase in the degree of fiber alignment upon tension

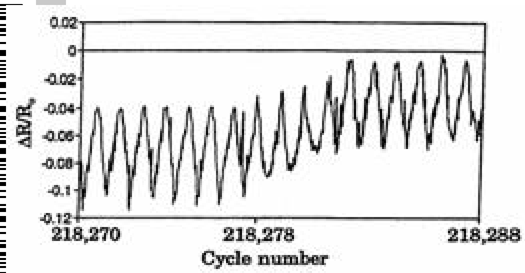
Fatigue monitoring

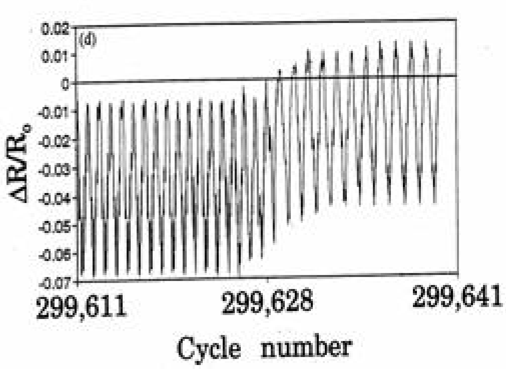
- Cyclic tension in fiber direction
- Resistance in the fiber direction

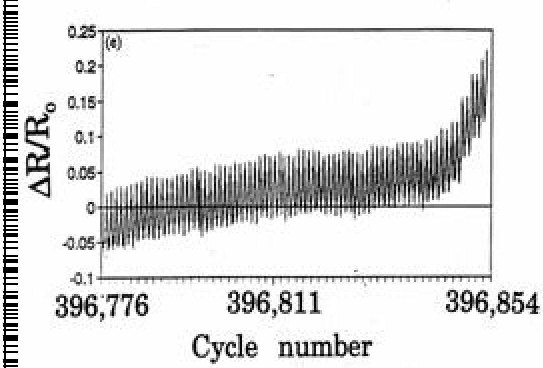

Tensile stress (MPa)
Strain (%)
ΔR/R₀
Cycle number

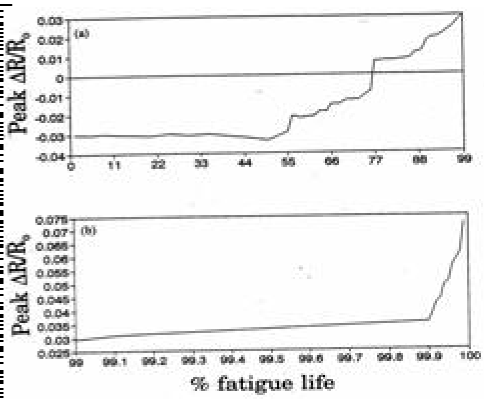

(a)
ΔR/R₀
Cycle number

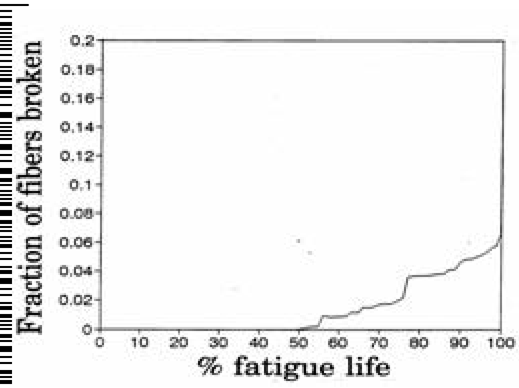

(b)
ΔR/R₀
70,000
70,024
70,052
Cycle number

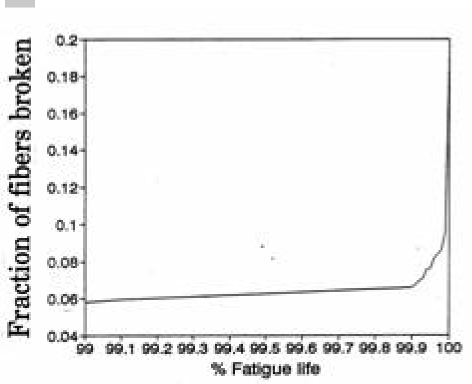

ΔR/R₀
218,270
218,278
218,288
Cycle number

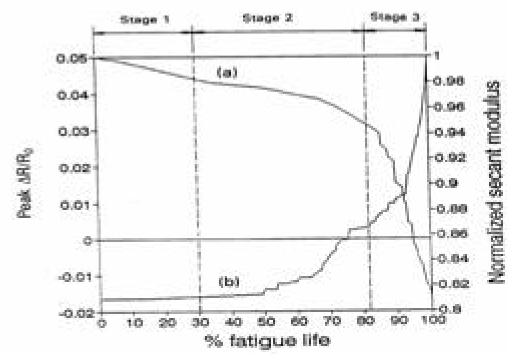

(d)
ΔR/R₀
299,611
299,628
299,641
Cycle number


(e)
ΔR/R₀
396,776
396,811
396,854
Cycle number









Gage factor

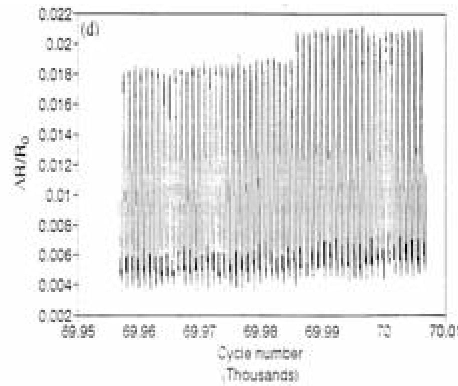
Fractional change in resistance per unit strain

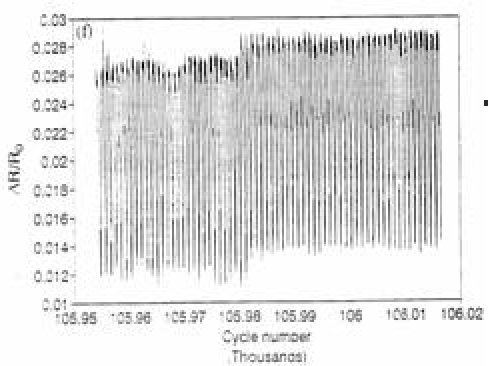
Gage factor

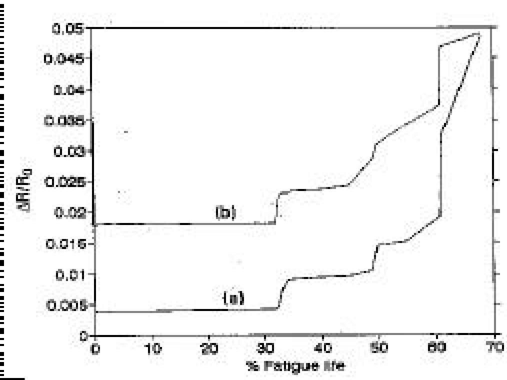
- **Unidirectional composite, longitudinal tension and resistance: -36**
- **Unidirectional composite, longitudinal tension and through-thickness resistance: +34**
- **Crossply composite, longitudinal tension and resistance: -6**

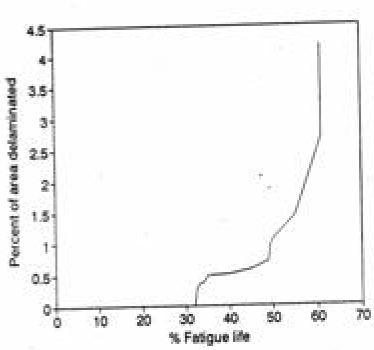
Fatigue monitoring

- Through-thickness resistance
- Cyclic tension in the fiber direction
- Crossply composite
- 12 laminae





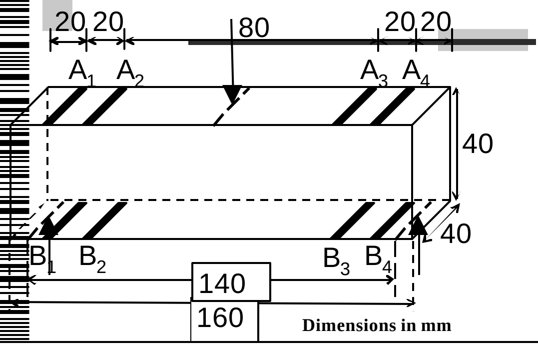




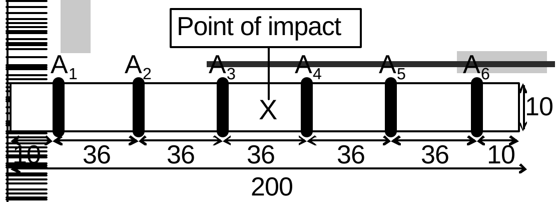
Damage monitoring

- Fiber breakage – causes the resistance in the fiber direction to increase irreversibly
- Delamination – causes the through-thickness resistance to increase irreversibly

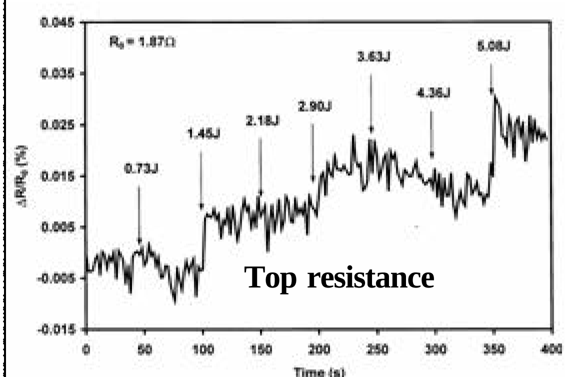
Flexure

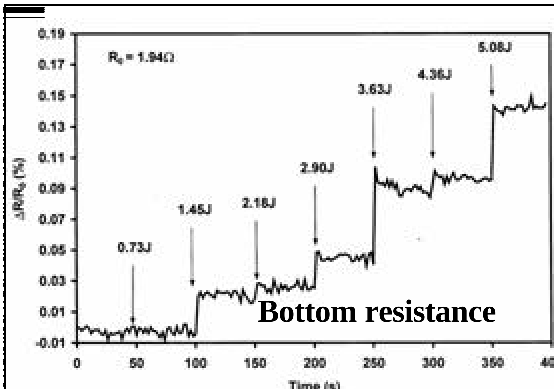


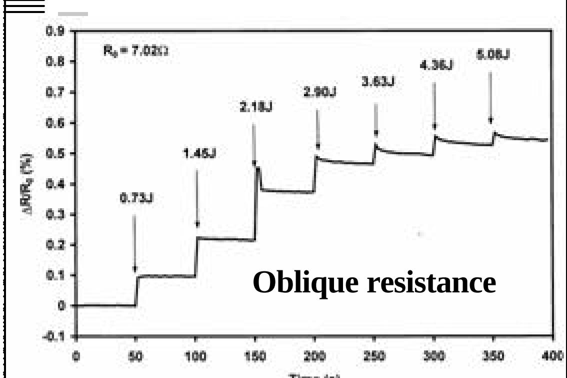
Impact damage monitoring

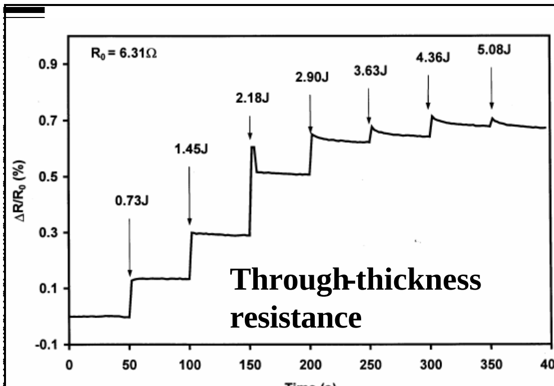


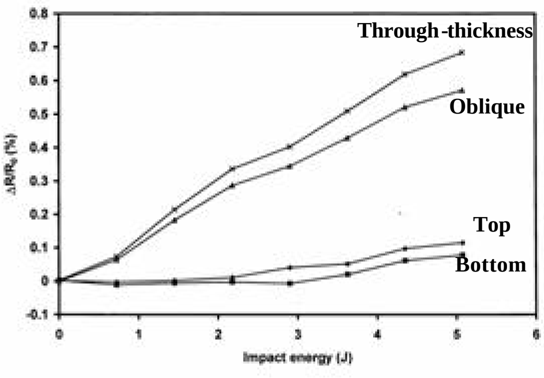
16-lamina quasi-isotropic composite











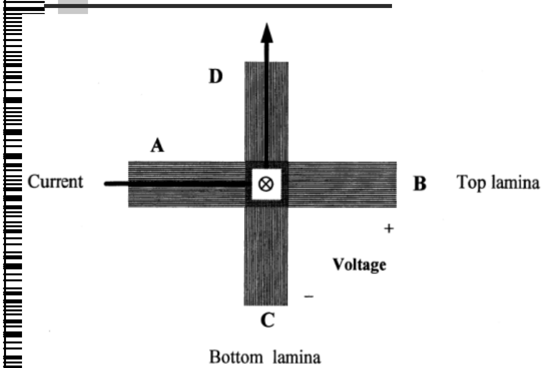
Contact resistance

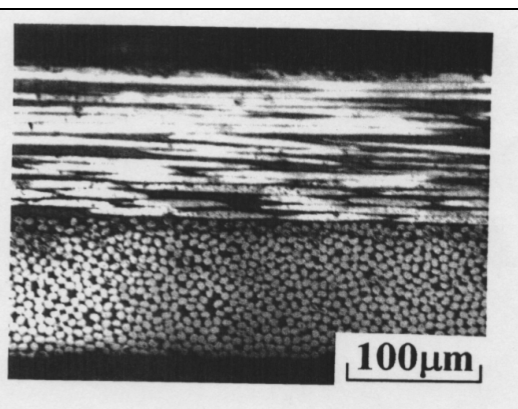
Interlaminar interface

Contact resistivity

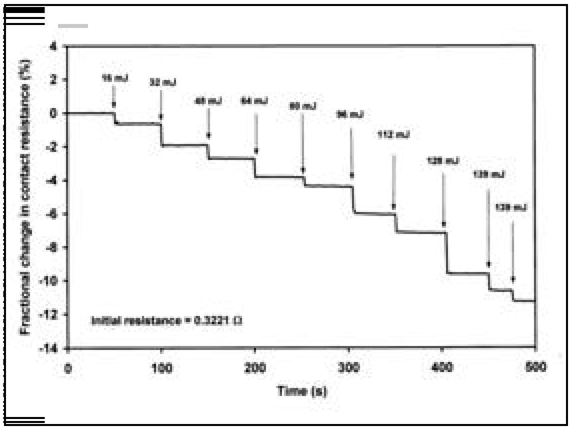
Contact resistance

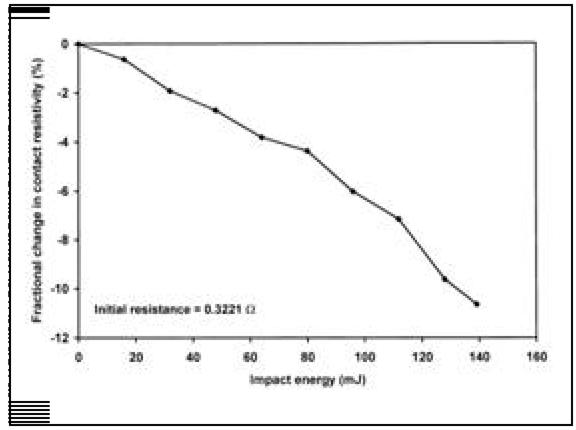
X contact area

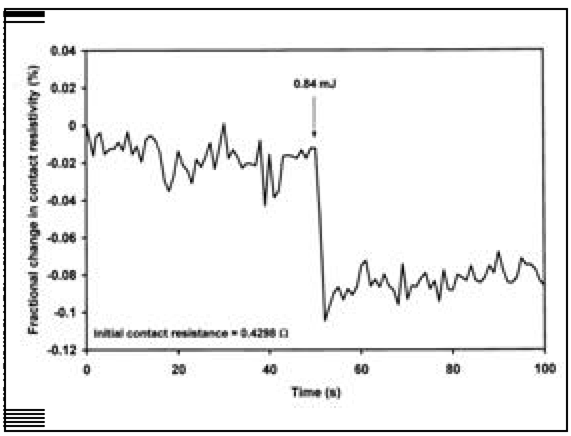


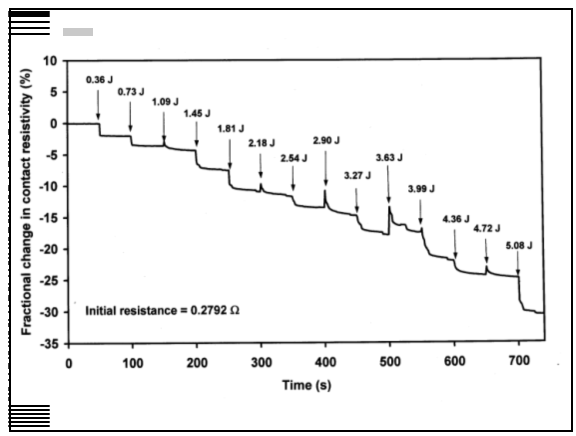


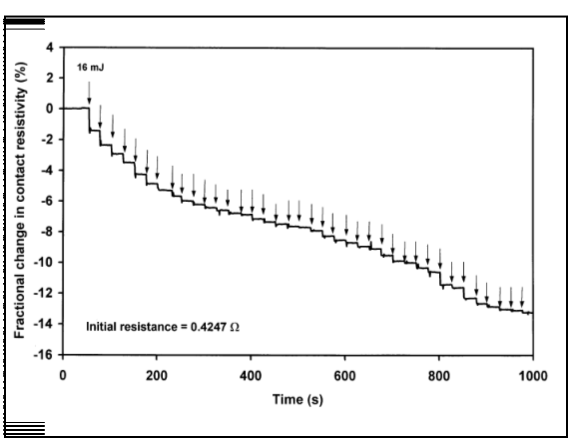
Interlaminar interface as an impact sensor

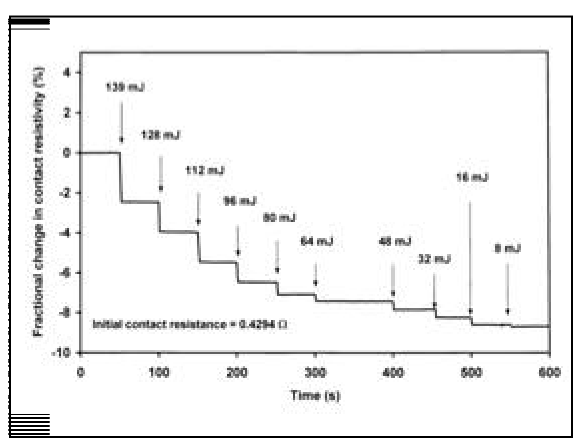

Fractional change in contact resistance (%)
Time (s)
16 mJ
32 mJ
48 mJ
64 mJ
80 mJ
96 mJ
112 mJ
128 mJ
139 mJ
139 mJ
Initial resistance = 0.3221 Ω


Fractional change in contact resistivity (%)
Impact energy (mJ)
Initial resistance = 0.3221 Ω

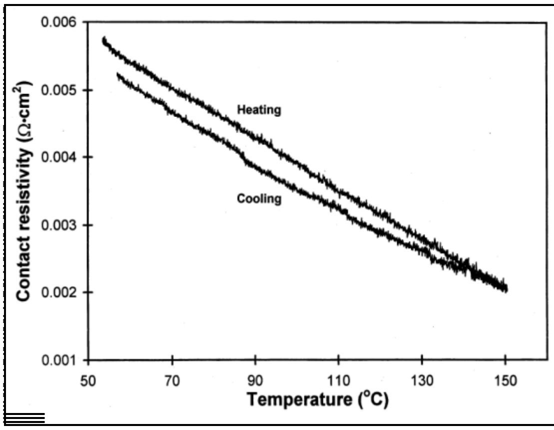

Fractional change in contact resistivity (%)
Time (s)
0.84 mJ
Initial contact resistance = 0.4298 Ω


Fractional change in contact resistivity (%)
Time (s)
0.36 J
0.73 J
1.09 J
1.45 J
1.81 J
2.18 J
2.54 J
2.90 J
3.27 J
3.63 J
3.99 J
4.36 J
4.72 J
5.08 J
Initial resistance = 0.2792 Ω

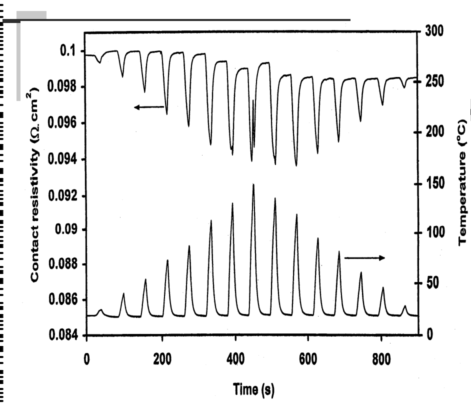

Fractional change in contact resistivity (%)
Time (s)
16 mJ
Initial resistance = 0.4247 Ω

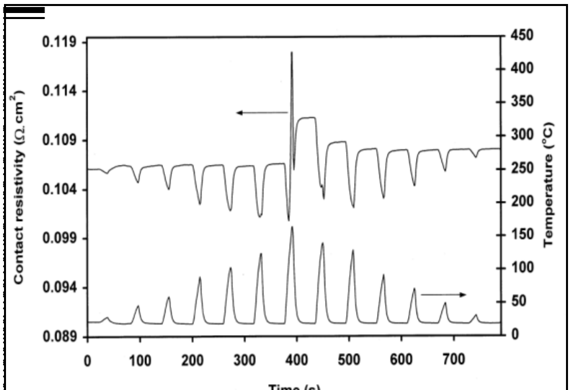

Fractional change in contact resistivity (%)
Time (s)
139 mJ
128 mJ
112 mJ
96 mJ
80 mJ
64 mJ
48 mJ
32 mJ
16 mJ
8 mJ
Initial contact resistance = 0.4294 Ω

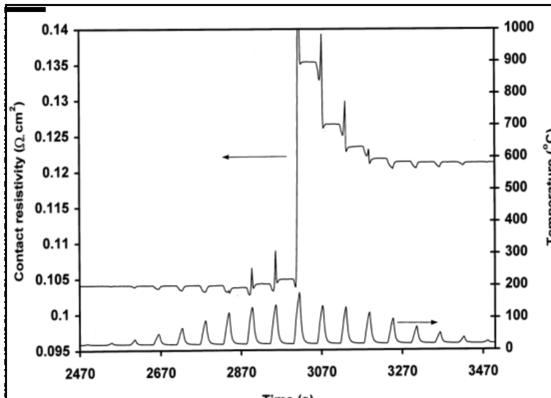
Interlaminar interface as a thermistor

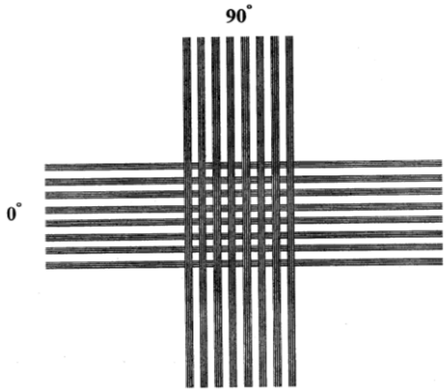


Interlaminar interface as a thermal damage sensor







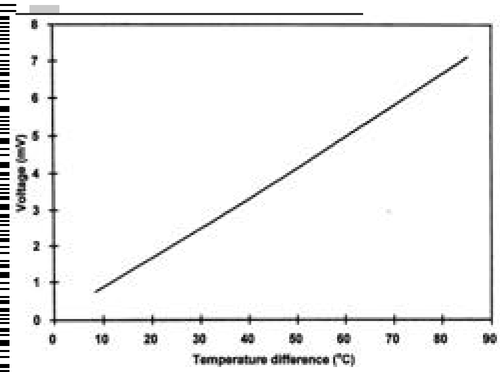


Thermocouples in the form of structural composites

- **Dissimilarity by choice of reinforcing fibers – Seebeck effect in the longitudinal direction**
- **Dissimilarity by choice of interlaminar filler - Seebeck effect in the through-thickness direction**

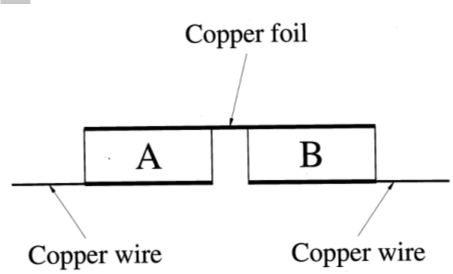
Longitudinal Seebeck effect

- P-type carbon fiber in one lamina
- N-type carbon fiber in the adjacent lamina
- Interlaminar interface as the thermocouple junction
- 82 µV/°C.



Through-thickness Seebeck effect

- Tellurium particles as interlaminar filler in one composite
- Bismuth telluride particles as interlaminar filler in the adjacent composite
- The interlaminar junction of the two composites as the thermocouple junction
- 34 µV/°C.



Self-healing concept

- Embedding microcapsules of monomer in composite
- Having catalyst in composite outside the microcapsules
- Upon fracture of microcapsule, monomer meets catalyst, thereby former a polymer which fills the crack.

Problems with self-healing

- **Toxicity of monomer**
- **High cost of catalyst**

Conclusion 1

- **Multifunctional polymer-matrix structural composites with continuous carbon fibers have been attained by exploiting the electrical behavior of the composites.**
- **The functions attained include the self-sensing of strain, impact, damage and temperature.**

Conclusion 2

- **Strain self-sensing was made possible by piezoresistivity, in which the electrical resistivity in the longitudinal or through-thickness direction changes with strain.**
- **Damage self-sensing was made possible by the effect of fiber fracture and delamination on the longitudinal and through-thickness resistivity respectively.**
- **Damage self-sensing was also attained by measuring the oblique resistance.**

Conclusion 3

- **Temperature self-sensing involved using the interlaminar interface as a thermocouple junction or as a thermistor.**
- **The thermocouples involve thermoelectricity in longitudinal or through-thickness directions.**