Could Nano-Structured Materials Enable the Improved Pressure Vessels for Deep Atmospheric Probes?

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2\textsuperscript{nd} International Planetary Probe Workshop, Aug 23-27, 2004,
High Temperature/Pressure in Key X-Environments

Pressure - Temperature Atmospheric Profiles Provided\(^2\) by Rich Young, NASA Ames Research Center

Artists Concept of Pioneer-Venus Small "Day" Probe on Venus' Surface. \(T = 740 \text{ K}, P = 96 \text{ bars}\) Sealed Vessel with Xenon at 102 Kpa (15 psia).

Operated\(^3\) for 68 minutes on Venus' surface - December, 1978
The Case for Use of Nano-Structured Materials
Pressure Vessel Design

- Pressure vessel structure is a mass driver for probe
- Reduction in structure mass can be used for science

<table>
<thead>
<tr>
<th>Probe</th>
<th>Pressure Vessel Mass (kg)</th>
<th>Total* Probe Mass (kg)</th>
<th>Pressure Vessel Structure Mass Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pioneer Venus Large Probe</td>
<td>62</td>
<td>193</td>
<td>32</td>
</tr>
<tr>
<td>Pioneer Venus Small Probe</td>
<td>18</td>
<td>61</td>
<td>30</td>
</tr>
</tbody>
</table>

* Excludes deceleration module mass
Carbon based Nanomaterials

1985

diamond
Bulk 2

C_{60}
"buckminsterfullerene"

1991

graphite Bulk 1

(10,10) tube

http://cnst.rice.edu/images/allotropes.jpg
Nanotube production & purification

Micrographs illustrating purification of multiwalled nanotube sample

MWNTs
D = 2.5 – 30 nm

Ebbesen et al.,
Nature 367, 519 (1994)
Nanomechanics of Carbon Nanotubes

- **Elastic properties**: \( E \approx 1.2 \text{ TPa} \)
  \( (E = k/a) \)
- **Plastic/Fracture properties**: compression & tension
  yield strain \( \geq 15 - 20\% \) (?)
  - Strain rate?
  - Defects?
  - Mechanisms?
  - Applications?
- **Superstrong Material**: \( \sigma_Y = 750 - 1000 \text{ GPa}! \)
  - Diamond (50 GPa), WC (6 GPa), Steel (0.5-2 GPa)
SEM images of epoxy-CNT composite ribbon contained CNT fibers & knotted CNT fibers

SEM images of polymer (polyvinylacohol) (B. Vigolo et.al., Science, V290 P1331, 2000)

Effect of Loading sequence on Composite with 8% by volume

Simulations of CNT-Polyethylene Composites

Work hardening of composite with stretching

TEM images of alignment of CNTs in a polymer matrix by stretching

- Young’s modulus of CNT composites 30% higher than polymer matrix
- Stretching treatments enhance Y by 50%  \((L/D \sim 2, N_p=10)\)

Models for Particulate Reinforced Composites

Mittal et.al., NASA Technical Report, 1996

Micromechanics Models for for Particulate Reinforced Composites

\[
\rho_{pc} = V_f \rho_f + (1 - V_f) \rho_m
\]

- **Density of composite**

\[
E_{pc} = \frac{V_f^{0.67} E_m}{1 - V_f^{0.33} (1 - \frac{E_m}{E_f})}
\]

- **Elastic Modulus of Composite**

\[
K_{pc} = \frac{V_f^{0.67} K_m}{1 - V_f^{0.33} (1 - \frac{K_m}{K_f})}
\]

- **Thermal Conductivity of Composite**

Where \( V_f \) is volume fraction

**Assumption:** Ideal Interface – perfect bonding at the interface
Fullerene/Ti Composite for High Strength-Insulating Layer

Composite Spherical Shell -Ti+C60

(Ef=860 GPa, Em=116 GPa, Kf=0.25 W/m-k, Km=17 W/m-k, df=1.745 g/cc, and dm=4.5 g/cc)
Composite Spherical Shell - ABS+C60 (Ef=860 GPa, Em=1.8 GPa, Kf=0.25 W/m-k, Km=0.25 W/m-k, df=1.745 g/cc, and dm=1.05 g/cc)

Fullerene/Epoxy Composite for High Strength-Insulating Layer
Halpin-Tsai Equations

\[
\frac{E}{E_m} = \frac{1 + \xi V_f}{1 - \eta V_f}
\]

where

\[
\eta = \frac{(E_f / E_m) + \xi}{(E_f / E_m) - 1}
\]

\[
\xi = \frac{2l}{d} \quad \text{for longitudinal modes and} \quad = 2 \quad \text{for transverse modes}
\]

with \(\xi = 2l/d\) for longitudinal modes and \(= 2\) for transverse modes.

For limiting cases, the measure of fiber reinforcement could be 0 (series model) or infinity (parallel model).

where \(\xi\) is a measure of fiber reinforcement depends on fiber geometry, packing geometry, and loading conditions at the interface.
Tensile Strength for Discontinuous Fiber Composites

Critical length for discontinuous composite

\[ l_c = \frac{\sigma_f d}{\tau_c} \]

where \( \tau_c \) is the shear strength of the bond at the interface

and \( \sigma_f \) is the tensile strength

\[
TS_{comp} = TS_f V_f \left( 1 - \frac{l_c}{2l} \right) + TS_m (1 - V_f) \quad \text{for} \quad l > l_c
\]

\[
TS_{comp} = \left( \frac{l \tau_c}{d} \right) V_f + TS_m (1 - V_f) \quad \text{for} \quad l < l_c
\]
Composite Spherical Shell -Ti+SWNTs

Based on Halpin-Tsai Equations

\(E_{\text{long}}=1000 \text{ GPa}, \ F_{\text{trans}}=860, \ E_m=116 \text{ GPa}, \ K_f=2000 \text{ W/m-k}, \ K_{ft}=0.25 \text{ W/m-k}, \ K_m=17 \text{ W/m-k}, \ df=1.745 \text{ g/cc}, \text{ and } dm=4.5 \text{ g/cc}\)
Composite Spherical Shell - Ti+SWNTs
Based on Halpin-Tsai Equations
(E_{\text{flong}}=1000 \text{ GPa}, F_{\text{trans}}=860, E_{\text{m}}=116 \text{ GPa}, K_{\text{fl}}=2000 \text{ W/m-k}, K_{\text{ft}}=0.25 \text{ W/m-k}, K_{\text{m}}=17 \text{ W/m-k},
\text{df}=1.745 \text{ g/cc}, \text{and dm}=4.5 \text{ g/cc})
Ti + SWNT Composites: Tensile Strength

Longitudinal Tensile Strength (TS) of Nanotube-Titanium Composite for L > L_c (TS_f = 15GPa and TS_m = 220 MPa)
Ti + SWNT Composites: Tensile Strength

Tensile Strength (TS) of Nanotube-Polymer Composite. Results for Polymer with TS of 80 MPa and Bond Shear Strength of 50 MPa (L<Lc)
Nano-structured Shell for Pressure Vessels

Nano-enabled Spherical Shell
Compressional Loading and Temperature

- 0.35 Fullerene / 0.65 Ti Composite
  Modulus (+100%)
  Density (-25%)
  Th Cond. (-50%)

- 0.35 CNT / 0.65 Ti Composite
  Modulus (+250%)
  Density (-25%)
  Th Cond (L) (x 15-20)
  Th Cond (T) (x 0.75)
  Tensile S (X 20  L > Lc)
  Tensile S (X 40  L < Lc)

- These are upper-limits for stiffness and thermal conductivity estimates:
  Assumption: micro-mechanical models with mostly perfect interfaces