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

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High Temperature/Pressure in Key X-Environments

Pressure - Temperature Atmospheric Profiles provided by Rich Young, NASA Ames Research Center

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

Operated 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

1991

- C_{60} “buckminsterfullerene”
- (10,10) tube

graphite
- Bulk 1

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)
• *Elastic properties*: $E = \sim 1.2 \text{TPa}$
  
  $(E = k/a)$

• *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)
CNT-composites: Example (Polymer)

SEM images of epoxy-CNT composite


SEM images of polymer (polyvinylacohol) ribbon contained CNT fibers & knotted CNT fibers

(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

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

Models for Particulate Reinforced Composites

Micromechanics Models for Particulate Reinforced Composites

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

Density of composite

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

Elastic Modulus of Composite

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

Thermal Conductivity of Composite

Where \( V_f \) is volume fraction

**Assumption:** Ideal Interface – perfect bonding at the interface
Composite Spherical Shell - Ti+C60

\((E_f=860 \text{ GPa}, E_m=116 \text{ GPa}, K_f=0.25 \text{ W/m-k}, K_m=17 \text{ W/m-k}, d_f=1.745 \text{ g/cc, and } d_m=4.5 \text{ g/cc})\)
Fullerene/Epoxy Composite for High Strength-Insulating Layer

Composite Spherical Shell - ABS+C60 (Ef=860 GPa, Em=1.8 GPa, Kf=0.25 W/m-\(\text{K}\), Km=0.25 W/m-\(\text{K}\), df=1.745 g/cc, and dm=1.05 g/cc)
Models for Continuous Fiber Reinforced Composites

IC Finegan et. al., Composite Science and Tech (2003)

Halpin-Tsai Equations

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

where

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

where \( \xi \) is a measure of fiber reinforcement depends on fiber geometry, packing geometry, and loading conditions at the interface

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

For limiting cases, the measure of fiber reinforcement could be 0 (series model) or infinity (parallel model).
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_{long}=1000 \text{ GPa}, F_{ftrans}=860, E_m=116 \text{ GPa}, K_f=2000 \text{ W/m-k}, K_t=0.25 \text{ W/m-k}, K_m=17 \text{ W/m-k},
d_f=1.745 \text{ g/cc}, \text{ and } d_m=4.5 \text{ g/cc})
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_{f1}=2000 \text{ W/m-k}, K_{ft}=0.25 \text{ W/m-k}, K_{m}=17 \text{ W/m-k},
d_f=1.745 \text{ g/cc, and } d_m=4.5 \text{ g/cc})

[Graph showing the relationship between SWNTs Volume Fraction and various properties such as E-long, E-trans, Trans. Thermal Cond., E-2Drandom, and Density for different aspect ratios (l/d=10, 20, 50, 100, 500).]
Longitudinal Tensile Strength (TS) of Nanotube-Titanium Composite for L>Lc (TSf=15GPa and TSm=220 MPa)
Tensile Strength (TS) of Nanotube-Polymer Composite. Results for Polymer with TS of 80 MPa and Bond Shear Strength of 50 MPa (L<Lc)

Ti + SWNT Composites: Tensile Strength
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