Emerging Concepts for Synthesis of Thermally Engineered Materials and Structures

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ONR Workshop
Cambridge, UK
May 30 – June 1, 2001
Work supported by ONR (Dr. S. Fishman)
## Emerging Concepts for Synthesis of Thermally Engineered Materials and Structures

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### Sponsoring/Monitoring Agencies
- Office of Naval Research International Field Office
- Washington, DC

### Abstract
- Heat Exchanger Concepts
- Stochastic Cellular Metal Microheat Exchangers
- Periodic Cellular Metal Heat Exchangers
- Thermal Protection Coatings
- Pore Morphology Control
- Manufacturing Concepts for Low K Multi-component Oxides

### Security Classification
- Unclassified
Emerging Concepts for Synthesis of Thermally Engineered Materials and Structures

OUTLINE

Heat Exchanger Concepts
- Stocastic Cellular Metal Microheat Exchangers
- Periodic Cellular Metal Heat Exchangers

Thermal Protection Coatings
- Pore Morphology Control
- Manufacturing Concepts for Low K Multi-component Oxides
HEAT EXCHANGER CONCEPTS
Stochastic Cellular Metal MicroHeat Exchangers
Stochastic Cellular Metals

Closed Cell Foam

- fire retardating and low relative thermal conductivity

Open Cell Foam

- ability to flow fluids through structure leads to high heat transfer
Stochastic Cellular Metal Heat Sink

Mode of Heat Transfer

Conduction through metal ligaments that are cooled by passage of a fluid through pores

Duocel® Foam

ERG Aerospace, Inc.

www.ergaerospace.com

- Materials: Al, Cu, Ni alloys
- Cell sizes: 5, 10, 20, 40 ppi
- Relative density $0.04 < p^* < 0.15$

When this material is made by investment casting the ligaments are solid.

A.G. Evans, J.W. Hutchinson, M.F. Ashby, Prog. in Mater. Sci. 43 pp. 171-221 (1999)
Thermal Management and Heat Transfer

Reference:
“Metal Foams – A Design Guide”, M. Ashby, A. Evans, N. Fleck, L. Gibson, J. Hutchinson, H. Wadley.
Template: Open Cell, Reticulated Polyurethane Foam

Polymer Foams:
• Cell sizes: 5 - 120 ppi
• Cusp-shaped ligaments (ideal for capillary driven flow)
Multifunctional Heat Exchanger

\[ q = h \int_{x_1}^{x_2} \left[ T_S(x) - T_f(x) \right] dx \cdot C \]

Where, \( h \) - heat transfer coefficient
\( C \) - projected heat pipe circumference in the fluid flow direction
Conventional Heat Pipe

**Construction:**
- an evaporator or heat addition region
- an adiabatic or isothermal region
- a condenser or heat rejection region

**Operation:**
- heat is added to the evaporator region,
- the fluid vaporizes, resulting in an increased pressure which causes the vapor to flow to the cooler condenser region
  - the vapor condenses releasing its latent heat of vaporization.
- capillary forces in the wicking structure forces the liquid back to the evaporator region.

A Foam Based Multifunctional Micro Heat-Pipe Concept

Solid Face-sheets and Stochastic Cellular Metal Sandwich Panel
Electron Beam - Directed Vapor Deposition

- **Electron beam gun**
  - beam accelerating voltage = 70 kV
  - maximum power = 10 kW
  - high speed scanning ~ 100 kHz
  - spot size < 0.5 mm

- **Multi-pump vacuum system**
  - high to low vacuum (10^{-5} – 0.5 mbar)
  - non-reactive carrier gas (0 – 20 slm)
  - reactive carrier gas (O_2, N_2, etc.)

- **Hollow cathode plasma**
  - high density plasma of gas and vapor stream

- **Integrated substrate biasing**
  - constant or alternating, positive then negative, bias (0 – ±300 V)
Vapor condenses by binary scattering from streamlines that carry flow around the vapor. The local coating thickness depends on the number density of the atoms (i.e. local pressure) and the flow velocity.

\[ n \] = number density of background atoms (#/m\(^3\))
\[ d \] = molecular diameter (m)
\[ c_r \] = relative velocity (m/s)
\[ c \] = thermal speed (m/s)

Mean collision frequency, \( \nu \)
\[ \nu = \pi nd^2c_r \]

Mean free path, \( \lambda \)
\[ \lambda = \frac{c}{\nu} \]

Collision rate, \( N \)
\[ N = \frac{1}{2} n \nu \]

For He, \( \lambda \sim 200\mu m @ 0.5\) Torr
Coating Open Cell Reticulated Ligaments (Directed Vapor Deposition)

**Metal/Alloy Deposition**
Al, Cu, Ni, Stainless Steel, many other alloys

**Non Line-of-Sight Coatings**
Promoted by low vacuum environment

**High Deposition Rates**
Up to 100 µm/min
Electron Beam – Directed Vapor Deposition

Plasma-assisted DVD combines four process technology components

- high voltage electron beam evaporation
- low-vacuum, flowing-gas vapor transport
- high-density gas and vapor plasma activation
- pulsed or constant substrate biasing
EB-DVD on Open Cell Reticulated Templates

Step 1: Metal Deposition

Step 2: Thermal Decomposition of Polyurethane Foam

- thermally decompose the foam in vacuum (~10^{-5} Torr) by heating at 1°C/min to 250°C, and holding for two hours
- results in complete removal of the polymer core with minimal carbon residue

Deposition Process Variables:

- electron beam power
- carrier gas flow
- chamber pressure
- pressure ratio, $P_u/P_c$
**DSMC Simulations:** Carrier gas (helium) speed axial direction

Carrier gas speed increases with chamber pressure.
Vapor focusing increases with chamber pressure
Gas Jet Flow Effects

$P_c = 0.042$ torr, $P_u/P_c = 5.71$

$P_c = 0.075$ torr, $P_u/P_c = 5.00$

$P_c = 0.105$ torr, $P_u/P_c = 4.79$

$P_c = 0.135$ torr, $P_u/P_c = 4.67$

$P_c = 0.165$ torr, $P_u/P_c = 4.50$

$P_c = 0.195$ torr, $P_u/P_c = 4.23$

Polyurethane foam template, cell size = 20 pores per inch (ppi)
Copper Deposition: $P_c = 0.1$ Torr, $P_u/P_c = 4.6$, 7.5 slm (He)

- **2.80 kW**
  - $T_f = 138 \, ^\circ C$

- **3.50 kW**
  - $T_f = 194 \, ^\circ C$

- **4.20 kW**
  - $T_f = 233 \, ^\circ C$

- **4.90 kW**
  - $T_f = 279 \, ^\circ C$

planar glass substrate, deposition time = 10 min
Copper Deposition: beam power = 4.2 kW

\[ P_c = 0.042 \text{ torr, } \frac{P_u}{P_c} = 5.71 \]
\[ P_c = 0.075 \text{ torr, } \frac{P_u}{P_c} = 5.00 \]
\[ P_c = 0.105 \text{ torr, } \frac{P_u}{P_c} = 4.79 \]
\[ P_c = 0.135 \text{ torr, } \frac{P_u}{P_c} = 4.67 \]
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\[ P_c = 0.195 \text{ torr, } \frac{P_u}{P_c} = 4.23 \]

planar glass substrate, deposition time = 10 min
Plasma Activated EB-DVD Deposition of Copper

beam power = 4.2 kW, 7.5 slm Argon carrier gas

Deposition Conditions:
no plasma

Deposition Conditions:
plasma activated (DC$^+$ 9V preheat to ~500°C, DC$^-$ 75V during deposition)
Synthesis of Open Cell, Reticulated Copper Foams

Deposition Conditions:
electron beam power – 4.2 kW
He gas flow – 7.5 slm
chamber pressure – 0.14 torr
nozzle pressure – 0.67 torr
pressure ratio – 4.8

Template:
open cell, reticulated polyurethane foam
nominal pore size – 20 pores per inch
two-sided deposition (no rotation)
One Sided Deposition of Copper (front surface)

Polyurethane Foam: 20 pores per inch, 15 mm thick
Uniform Coating - Copper Foam Ligaments

Polyurethane Foam: 20 pores per inch, 15 mm thick
Optimized Multifunctional Truss Structures?
Periodic Cellular Metal Heat Exchangers
Metal Textile Can Be Made In Many Forms

REFERENCE:


Lamination Construction

a) 2D woven metal structure

b) Woven metal micro-truss laminate

\[
\frac{\rho}{\rho_s} \approx \pi \frac{d}{4(w+d)} \quad \frac{E}{E_s} \approx 0.5 \frac{\rho}{\rho_s} \quad \frac{\sigma_c}{\sigma_{ys}} \approx 0.5 \frac{\rho}{\rho_s}
\]
## Low Density Laminates

**Plain Square Woven Metal Cloth**

<table>
<thead>
<tr>
<th>Designation</th>
<th>$d$ (mm)</th>
<th>$w$ (mm)</th>
<th>Relative density</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (mesh/in)</td>
<td>2.03</td>
<td>23.4</td>
<td>0.06</td>
</tr>
<tr>
<td>10 (mesh/in)</td>
<td>0.635</td>
<td>1.91</td>
<td>0.20</td>
</tr>
<tr>
<td>100 (mesh/in)</td>
<td>0.114</td>
<td>0.140</td>
<td>0.35</td>
</tr>
<tr>
<td>Insect screening</td>
<td>0.229</td>
<td>1.18</td>
<td>0.13</td>
</tr>
<tr>
<td>High Transparency</td>
<td>0.0305</td>
<td>0.478</td>
<td>0.05</td>
</tr>
</tbody>
</table>
**Bonding Method**

- Micro-truss laminate core construction

- Sandwich panel construction
Multifunctional Micro-Truss Laminate (nichrome)

Easy Fluid Flow

Excellent Load Support

a) Front view

b) Side view

Gap

Load

1 mm

10 mm
Materials Diversification

a) 110 copper (braze: Ni-25Cr-10P)

b) 304 stainless steel (braze: Ni-25Cr-10P)
Actively Cooled Vehicle Skin Structures

Possible solution: Open Cell Metal Core Sandwich Panel Wingskins
Sandwich Panel Structure Skin

Structurally efficient sandwich construction: two stiff, strong skins with a lightweight core, with a relative density in 3% range (to optimize mechanical response).

Advantages:
- High fluid permeability, complex shapes, many materials choices, utilize relatively inexpensive materials, (aluminum, titanium, nickel alloys). Low cost manufacturing.
THERMAL PROTECTION COATINGS
Pore Morphology Control for Low K Materials
Conventional Thermal Barrier Coatings

• Pore volume fraction and morphology strongly effects both the thermal conductivity and thermomechanical performance of the TBC layer.

• The deposition process establishes the initial pore fraction and morphology.

• Sintering during service evolves the pore volume fraction, and morphology (and the thermal and thermo-mechanical properties).

• We are exploring concepts to manipulate porosity during deposition. Concepts extendable to other materials (lower thermal conductivity and sinter rates).
Porosity Can Be Manipulated Via Flux Shadowing Mechanisms

- Increasing adatom surface mobility reduces flux shadowing by allowing an adatom to move to a shadowed region on the substrate.
- Broadening the incidence angular distribution enhances the significance of shadowing and increases pore fraction.

Flux angular distribution width = 120°, distribution peak = 0°
Pore Distribution in Vapor Deposited Coatings
(Thermally Limit Surface Transport, Exploit Shadowing)

Substrate rotation is used in EB-PVD to broaden the effective incidence angle distribution and create thermo-mechanically beneficial intercolumnar pores.
Gas phase scattering of vapor (by collisions with background gas) enables the incidence angle distribution to be broadened.
EB-DVD Process Environment

- E-beam
- Nozzle
- Vapor Flux
- Crucible
- Heater
- Substrate
EB-DVD Versus EB-PVD

A. EB-DVD (no rotation)
- Parallel column growth
- Wide intercolumnar pore
- Domed column surface

B. EB-PVD (substrate rotation)
- Tapered growth column
- Faceted column surface
- Intercolumnar pore
Coating Characterization

Type I Pore Parameters

- Pore width $\rho$
- Pore inclination $\omega$
- Pore spacing $\varepsilon$

Layers:
- YSZ
- TGO
- Bondcoat
Coating Properties Constant Upstream Pressure ($P_u=2\text{Torr}$)

- Total pore volume fraction greatly increase with chamber pressure.
- High evaporation rates and low pressure ratios also promoted a high pore volume.
Morphology at Constant Upstream Pressure

Type I Pore Spacing

Type I Pore Width

- Type I pore spacing and width increase with chamber pressure
Thermal Conductivity (Constant Upstream Pressure)

Rate = 5.0 μm/min.  Flow = 8.0 slm He  Temp. = 1000°C

\[ \kappa = 1.9 \text{ W/mK} \]
\[ \rho = 5.3 \text{ g/cm}^3 \]

\[ \kappa = 1.3 \text{ W/mK} \]
\[ \rho = 3.9 \text{ g/cm}^3 \]
Asperity Height

**kMC Simulations**

**Asperity Height**

Large asperities promote Type I pore formation.
Pore Morphologies

"Motion and Dwell" Substrate Manipulation (+/- 45°)

$T/T_m = 0.22$, Rate = 3.0 $\mu$m/min., 32000 nickel atoms

- **stationary substrate**
  - (density = 0.74)

- **inclined substrate (45°)**
  - (density = 0.67)

- **40mL dwell**
  - (density = 0.69)

- **20mL dwell**
  - (density = 0.70)

- **10mL dwell**
  - (density = 0.71)

- **5mL dwell**
  - (density = 0.73)
Pore morphology optimized for low thermal conductivity and high thermomechanical resistance
TBC Microstructure

- Stationary Substrate
- Angled Substrate (45°)
- Zig-Zag \( \lambda = 31.7\mu m \)
- Zig-Zag \( \lambda = 13.4\mu m \)
- Zig-Zag \( \lambda = 6.6\mu m \)
- Zig-Zag \( \lambda = 3.1\mu m \)

Types:
- Type II Pore
- Type I Pore
Thermal Conductivity Measurements

*Type I pore nucleation control
Summary

• Emerging manufacturing concepts (rapid prototyping), directed vapor deposition and 3D weaving are creating new opportunities for meso structure control.

• These manufacturing approaches facilitate novel thermal engineering concepts:
  - Microheat pipe structures for 3D heat exchangers
  - Low backpressure multifunctional heat exchangers
  - Ultralow conductivity thermal protection systems that utilize pore morphology control