MATERIALS SCIENCE RESEARCH IN MICROGRAVITY

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ABSTRACT

There are several important attributes of an extended duration microgravity environment that offer a new dimension in the control of the microstructure, processing and properties of materials. First, when gravitational effects are minimized, buoyancy driven convection flows are also minimized. The flows due to density differences, brought about either by composition or temperature gradients will then be reduced or eliminated to permit a more precise control of the temperature and the composition of a melt which is critical in achieving high quality crystal growth of electronic materials or alloy structures. Secondly, body force effects such as sedimentation, hydrostatic pressure and deformation are similarly reduced. These effects may interfere with attempts to produce uniformly dispersed or aligned second phases during melt solidification. Thirdly, operating in a microgravity environment will facilitate the containerless processing of melts to eliminate the limitations of containment for reactive melts. The noncontacting forces such as those developed from electromagnetic, electrostatic or acoustic fields can be used to position samples. With this mode of operation, contamination can be minimized to enable the study of reactive melts and to eliminate extraneous crystal nucleation so that novel crystalline structures and new glass compositions may be produced. In order to take advantage of the microgravity environment for materials research it has become clear that reliable processing models based on a sound ground based experimental experience and an established thermophysical property data base are essential.
Materials Science Research in Microgravity

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MATERIALS SCIENCE DISCIPLINE

Goals

• Develop the basic understanding of relationships between microstructure and properties of materials during microgravity processing.

• Apply process modeling and advanced processing concepts to achieve designed microstructures.

Objectives

• Utilize the microgravity environment to advance the understanding of materials processing, including phase transformations during solidification and deposition, transport phenomena and structure-property relationships.
<table>
<thead>
<tr>
<th>Microgravity Environment</th>
<th>Materials Response</th>
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<tbody>
<tr>
<td>• Buoyancy Driven Convection Flows Minimized</td>
<td>Precise Temperature and Composition Control for High Quality Crystals</td>
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<tr>
<td>• Body Force Effects Minimized</td>
<td>Uniform Spacing and Alignment in Multiphase Materials</td>
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<td>• Containerless Melt Processing</td>
<td>Eliminate Contamination and Nucleation Due to Containment</td>
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<td>• Interfacial Phenomena</td>
<td>Wetting and Surface Energy Driven Flows</td>
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Benchmark Materials

Priorities

Technological Applications

> Containerless Processing
> Directional Solidification/Crystal Growth
> Casting

Science Knowledge Base

1. Solidification Kinetics and Undercooling
2. Microstructural Morphology/Prediction
3. Process Analysis and Modeling
4. Interfacial Phenomena

Critical Support Base

• Ground based experience
• Thermophysical property data
Research Areas

• Solidification Kinetics and Undercooling
  - Nucleation
  - Undercooling
  - Metastable Phase Development
  - Competitive Growth
  - Microstructural Transitions
  - Glass Formation

• Microstructural Morphology/Prediction
  - Plane Front Solidification
    > Single Crystals
    > Aligned Composites
    > Phase Spacing

• Interface Instability
  > Cells
  > Dendrites
  > Segregation

• Microstructural Scale
  > Coarsening/Coalescence
  > Scaling Laws

• Process Analysis and Modeling
  > Macrosegregation
  > Heat and Mass Transport Analysis
  > Structure Prediction
• Interfacial Phenomena

> Surface Energy Driven Flows
  (Temperature or Composition Gradients)
> Particle Incorporation
> Wetting Behavior
> Bubble Formation - Porosity Control
> Joining Applications
B. SUPERCOOLING (UNDERCOOLING)

\[ \Delta H = \int_{T_2}^{T} C_p \, dT \]

\[ \text{LATENT HEAT OF SOLIDIFICATION} \]

\[ \text{TEMP} \]

\[ T_L \]

\[ T_5 \]

\[ T_1 \]

\[ T_2 \]

\[ \alpha \]

\[ \alpha + \beta \]

\[ C_0 \]

\[ \text{COMPOSITION} \]

\[ \text{TIME} \]

Marshall Space Flight Center
4.6 second Drop Tube Facility
As-Cast

Drop Tube Processed
(ΔT = 530K)

MELTING POINT OF PURE A

LIQUID

MELTING POINT OF PURE B

LIQUIDUS LINE

LIQUID + SOLID

SOLIDUS LINE

SOLID

T1

T2

C0

C1

C2

PURE A

PURE B

SOLUTE CONCENTRATION

TEMPERATURE
Distance along sample

Temperature vs. distance along sample

Bulk melt

Freezing point of bulk melt

Primary arm spacing

Secondary arm spacing

Rejected solute

Freezing point of solute rich melt

Mushy zone

Solute rich solid
G-1. COLUMNAR - EQUIAXED TRANSITION

POSSIBLE MECHANISMS

COLUMNAR DENDRITES

EQUIAXED DENDRITES

CHILL ZONE

MOLD

LIQUID

CONSTITUTIONAL SUPERCOOLING PROMOTES NUCLEATION IN CENTER OF INGOT

MOLD

LIQUID

NECKED CRYSTAL DETACHES FROM MOLD WALL AND CARRIED TO CENTER OF INGOT

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GRAIN MULTIPLICATION

ONE \( g \)

Convection causes melting or breaking off of dendrite tips.

LOW \( g \)

Dendrites grow with minimal convective disturbance

491
Examples of in situ composites. An electron emitter formed from 0.3 micron tungsten single crystal fibers embedded in a zirconia matrix is shown at the top. A section of a nickel-based superalloy used for turbine blades is shown at the bottom. The matrix material has been etched away to reveal the single crystal tantalum carbide reinforcing fibers that allow the blade to operate for longer times at higher temperatures. Such structures can generally be made on earth only at the eutectic composition. Microgravity offers the possibility of extending the range of compositions to optimize the resulting structure.

(Photographs courtesy of General Electric)
Process Analysis and Modeling

- Assess role of individual variables
- Control and Vary Independently Process Parameters
- Reduce Complex Processes to Fundamental Units
- Explore Regimes Unavailable to Experiment
- Design Experiments to Emphasize Phenomena of Interest
- Interpret Results
- Improve Yield from Microgravity Experiments
Solidification Processes

Mushy Zone

Heat Transfer Coefficients
Interface, environment

Heat evolution
Mushy zone model

Material properties

G - 3. SEGREGATION

MACROSEGREGATION

$\bar{V} = -K \frac{\nabla p + \rho_L g}{\mu_{GL}}$

MICROSEGREGATION

AVE COMP. OF SOLID IN VOLUME ELEMENT

$C_E$

$C_0$

VOLUME FRACTION SOLID

DISTANCE

+ ENRICHMENT OF ALLOYING ELEMENTS
- DEPLETION OF ALLOYING ELEMENTS
A-1. DENDRITE COARSENING

0.5 mm

CD-85-16832
C-4. THERMAL MIGRATION

TEMPERATURE GRADIENT \( \frac{dT}{dx} \)

INTERFACIAL TENSION GRADIENT \( \frac{dy}{dT} \)

FLUID FLOW

FLUID A

DISPERSED PHASE B

DROPLET VELOCITY, \( V \)

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G-4. SURFACE TENSION DRIVEN FLOW

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Thermophysical Properties

- Emissivity, Electrical Conductivity, Optical Properties

- Calorimetry
  - Specific heats
  - Heats of mixing, formation, transformations, ...

- Transport Coefficients
  - thermal conductivity
  - viscosity
  - diffusion constants

- Density Data

- Thermodynamic Modulii
  - thermal expansion coefficients
  - compressibility, etc.

- Vapor Pressures and Activity Coefficients

- Surface Tension/Interfacial Energies

Research Opportunities

- Electrodeposition
- Powder Processing
- Joining
- Novel Materials
- Extraterrestrial Materials