The Case for a New Metallurgy for Meteorites

Phyllis Z. Budka
Technical Communications Unlimited
e-mail: abudka@nycap.rr.com
For nearly 200 years, the meteoritic Widmanstätten Structure has been used to:

Understand the fundamentals of irons and steels
1800s to 1930s
- Invar effect 1900s to Present
- Martensite 1920s to 1930s

• Develop metallurgical tools and techniques
  - Metallograph - 1850s
  - X-ray 1920s to 1930s
  - Microprobe - 1950s

• Develop the Fe-Ni phase diagram - 1904 to Present

• Calculate “Metallographic Cooling Rates” - Serve as the “thermometer” (geo-speedometer) for the study of small planetary bodies and asteroids - 1960s - Present

**Assumptions** made long ago about nickel-iron meteorite formation conditions must be re-evaluated in the light of modern metallurgical understanding.
Assumptions - 1904

- The meteoritic Widmanstätten structure is an equilibrium structure formed on slow cooling.
- The meteoritic Widmanstätten structure is formed by a solid state phase transformation below 800°C.
- Meteoritic irons are similar to terrestrial irons except that meteoritic irons are in equilibrium, whereas terrestrial irons are metastable.
1948 Metals Handbook Fe-Ni Phase Diagram includes region above 1300 °C

**Body Centered Cubic**

**Delta Ferrite**

- A primary crystallization structure formed above ~1500 °C.
- Can be retained at room temperature.
- Cannot be distinguished metallographically from body-centered cubic alpha iron.

Kamacite can also be interpreted as Delta Ferrite, formed by solidification from a melt.
Today - Fe-Ni Phase Diagrams: Metallurgy vs Earth & Planetary Sciences

**Metallurgy**

![Fe-Ni Phase Diagram](image)

- **Body Centered Cubic**
- **Delta Ferrite**
- **Face-centered cubic**
- **Austenite**
- **Alpha Ferrite**

**Meteoritics**

![1987 McSween Diagram](image)


Phyllis Z. Budka  September 1, 2005
Metallurgical Equilibrium
Binary Phase Diagram Determination Today

Today, equilibrium metallurgical binary phase diagrams are determined in carefully controlled laboratory experiments.

Nickel-iron meteorites are “metallurgical garbage cans,” containing elements such as carbon, sulfur, phosphorus, etc. that impact phase formation.

Nickel-iron meteorites are completely inappropriate for metallurgical phase diagram determination.
Assumptions about meteoritic Widmanstätten Structure made in 1904 remain unchanged today in the Earth & Planetary Sciences.

After Owen & Liu 1949 ++++

1987 McSween

Assumptions
- The meteoritic Widmanstätten structure is an equilibrium structure formed on slow cooling.
- The meteoritic Widmanstätten structure is formed by a solid state phase transformation below 800°C.
- Meteoritic irons are similar to terrestrial irons except that meteoritic irons are in equilibrium, whereas terrestrial irons are metastable.

Kamacite is not necessarily an equilibrium structure.
Definition of Widmanstätten Structure:
Change in meaning from Morphology to Mechanism over Time

1948 ASM Metals Handbook

Between 6 and 25% Ni, the alloys are martensitic after fast cooling; after slow cooling or reheating, they decompose into alpha + gamma. The structure varies from the martensitic to the Widmanstätten type observed in meteorites.

1985 ASM Metals Handbook

Widmanstätten structure. A structure characterized by a geometrical pattern resulting from the formation of a new phase along certain crystallographic planes of the parent solid solution. The orientation of the lattice in the new phase is related crystallographically to the orientation of the lattice in the parent phase. This structure was originally observed in meteorites, but is readily produced in many other alloys, such as titanium by appropriate heat treatment.
Widmanstätten Structure: 1813 - Today
A change in meaning over time: From Morphology to Mechanism

Agpalilik Nickel-Iron

Specimen courtesy of Dr. V. Buchwald

Vacuum deposited nickel superalloy

Morphology does not imply mechanism.
**Equilibrium Assumption** Microstructures are considered to be unchanged from their structure inside the meteorite parent body, except for a 10 mm heat-affected zone.

**Implication:** In the transition from inside the meteorite parent body to Earth arrival, these materials never reached their melting point.

The melting point of pure iron is 1538 °C.
Metallographic Cooling Rate Theory and the "Widmanstätten Mechanism"
After Wood 1967
Assumed equilibrium composition of FCC taenite **inside** the meteorite parent body.

After Wood **1967**
Metallographic Cooling Rates are derived from the slope of this line through a mathematical model based on the assumption that this point is the equilibrium composition of taenite/"austenite" inside the meteorite parent body.

After Mc Sween 1987
Metallographic Cooling Rates

• 1985 Narayan and Goldstein: Major revision of iron meteorite cooling rates: 150 to 600°C per million years.
• 1987 McSween: “Cooling rate data for iron meteorites favor the last 3 models, unless parent bodies with central cores were very small.”

Phyllis Z. Budka  September 1, 2005
Metallographic Cooling Rate Theory

The Metallographic Cooling Rate theory is founded on the 1904 assumption that kamacite (alpha ferrite) is formed from taenite (austenite) in a solid state phase transformation.

This is circular reasoning!
Potential Factors Influencing the Macro/Microstructural Development of the Meteoritic Widmanstätten Structure

• Solidification
  • Microgravity / Low Gravity / Free Fall
  • Undercooling
• Thermal and Compositional Gradients
  • Local Equilibrium
• Solid State Phase Transformations
• Other??

It is time for a New Metallurgy for Meteorites!
# Budka Publications on Meteorite Metallurgy

<table>
<thead>
<tr>
<th>Year</th>
<th>Author</th>
<th>Title</th>
<th>Journal</th>
<th>Vol., Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>P.Z. Budka and J.R.M. Viertl</td>
<td>Industrial X-Ray Technique Applied to Mundrabilla</td>
<td>64th Meteoritical Society Meeting</td>
<td></td>
</tr>
</tbody>
</table>