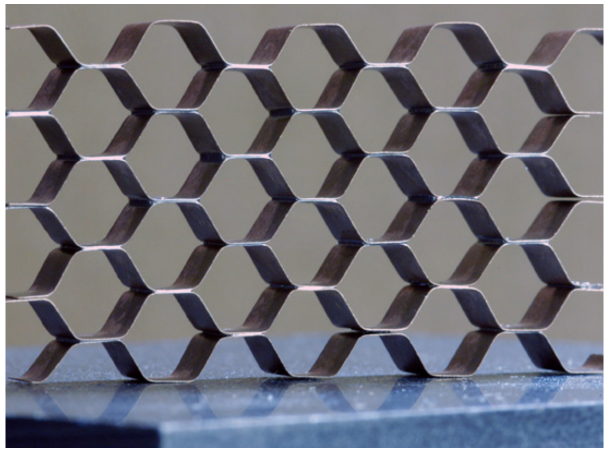
Cellular Shape Memory Alloy Structures: Experiments & Modeling



J. Shaw (UM), N. Triantafyllidis (UM), D. Grummon (MSU)

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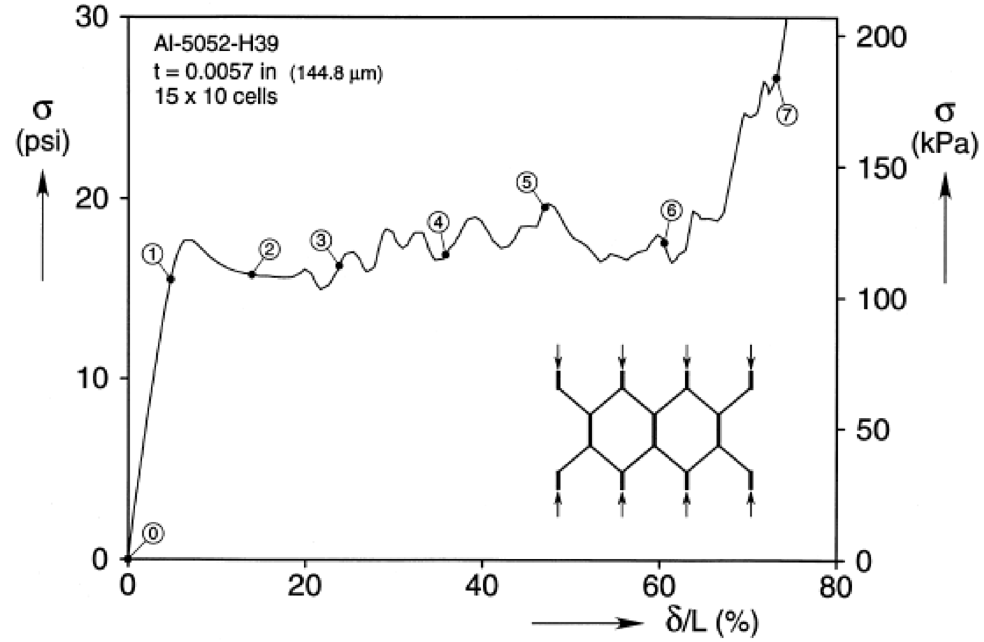
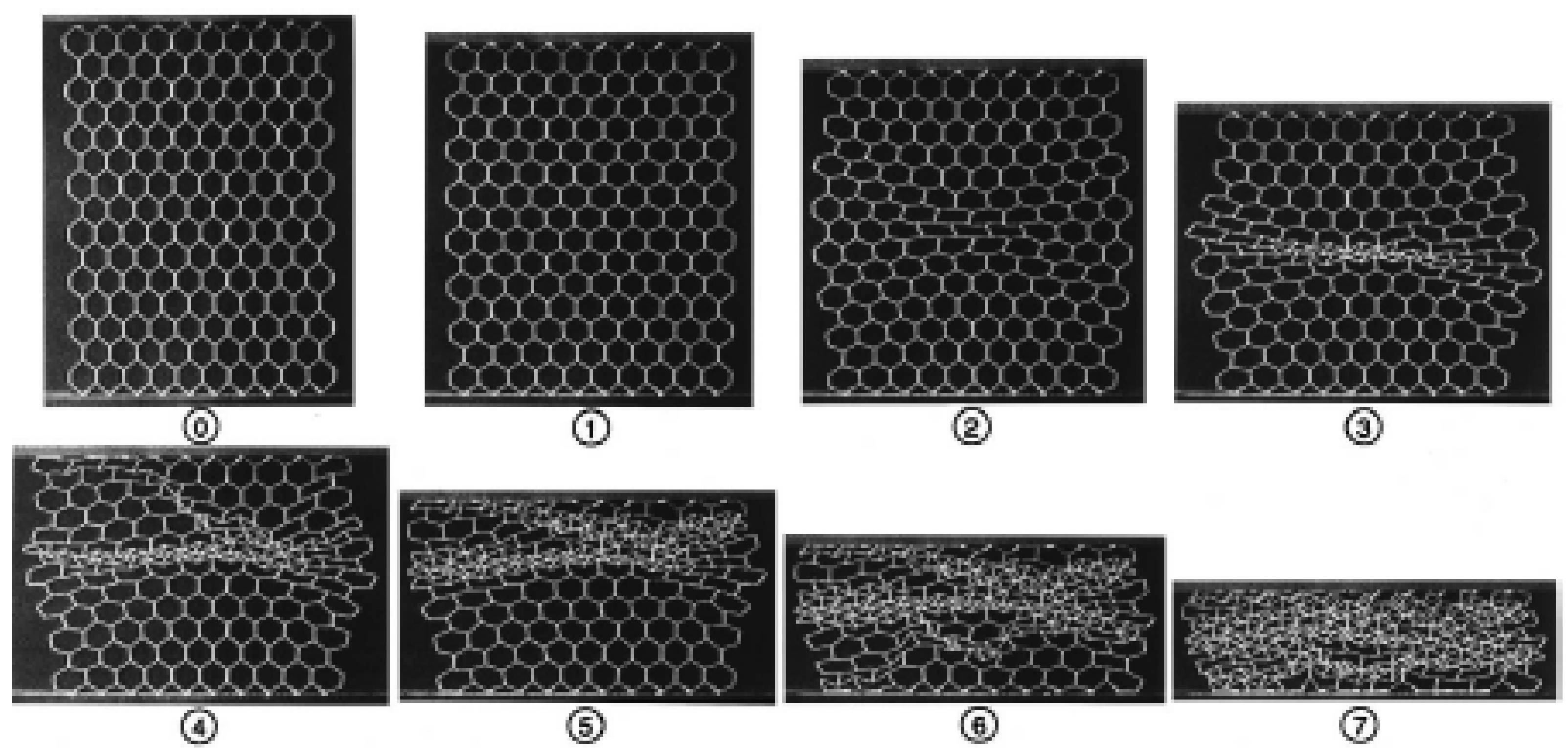
Outline

- Background
- Honeycomb specimen fabrication
- Honeycomb characterization
- SMA bending

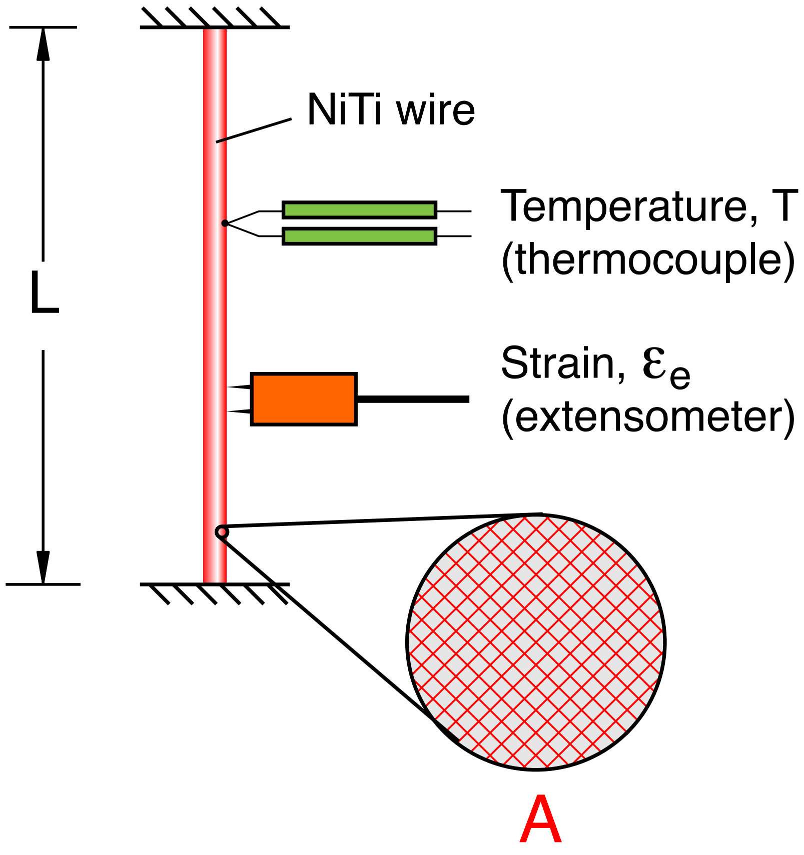
Background

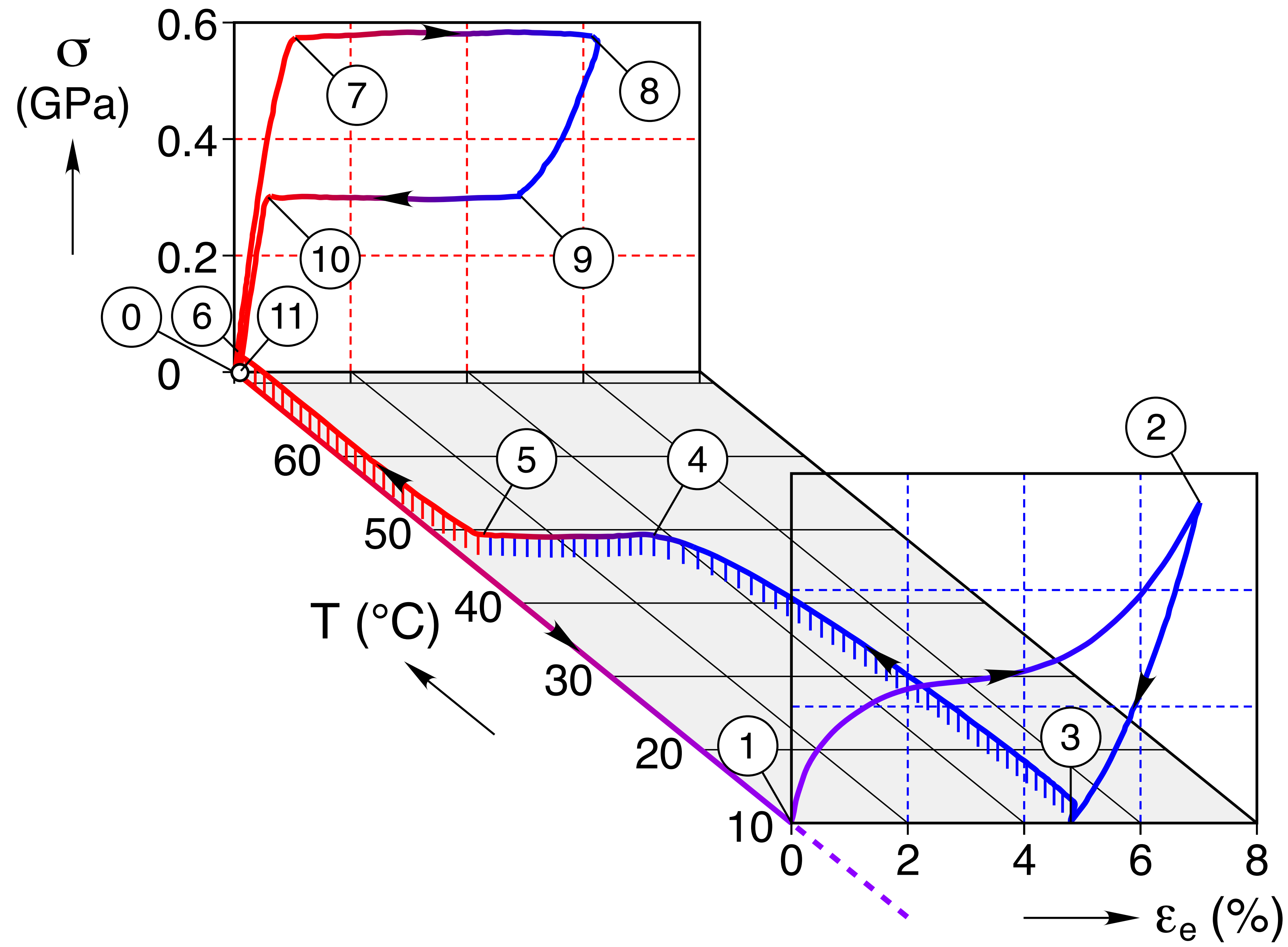




[Papka/Kyriakides, 1998]

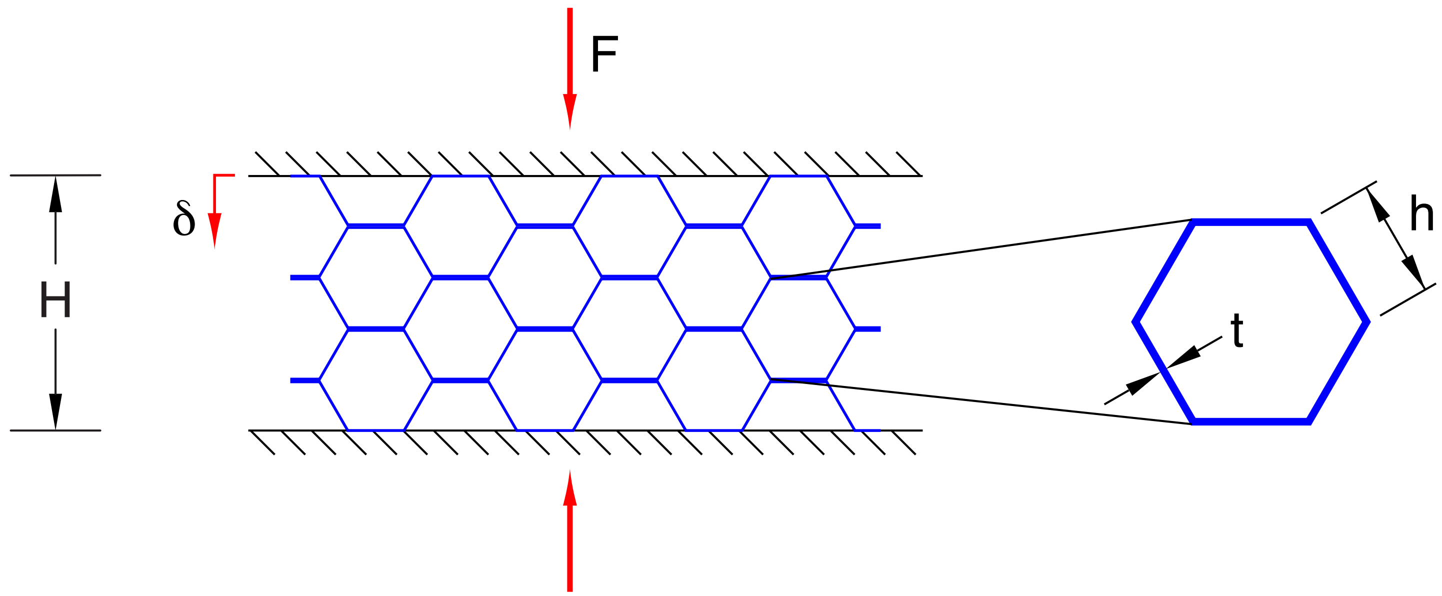
Nitinol (SM) wire: shape memory & superelasticity





Shape memory & superelasticity

Thin-walled honeycomb: scaling laws



relative density $$\frac{\rho^*}{\rho_s} \propto \frac{t}{h}$$

global/local bending strain $$\frac{|\varepsilon^*_{dense}|}{\varepsilon_{s,max}} \propto \frac{t}{h}$$

global/local plateau stress $$\frac{|\sigma^*_0|}{\sigma_{s,0}} \propto \left(\frac{t}{h}\right)^2$$

global/local modulus $$\frac{E^*}{E_s} \propto \left(\frac{t}{h}\right)^3$$

[Gibson/Ashby, 1997]

Comparison of Aluminum & NiTi honeycomb for same recoverable global strain

Property	Al	NiTi	NiTi/Al
ε^*_{dense}	-50%	-50%	1
$\varepsilon_{s,max}$	0.5%	5%	10
t/h	10^{-2}	10^{-1}	10
$\lvert\sigma^*_0\rvert/\sigma_{s,0}$	10^{-4}	10^{-2}	100
E^*/E_s	10^{-6}	10^{-3}	1000

Combine benefits of light-weight cellular structures
with Shape Memory Alloy (SMA) adaptive behavior

Metallic honeycombs

- Low density
- High specific stiffness
- Large specific energy absorption

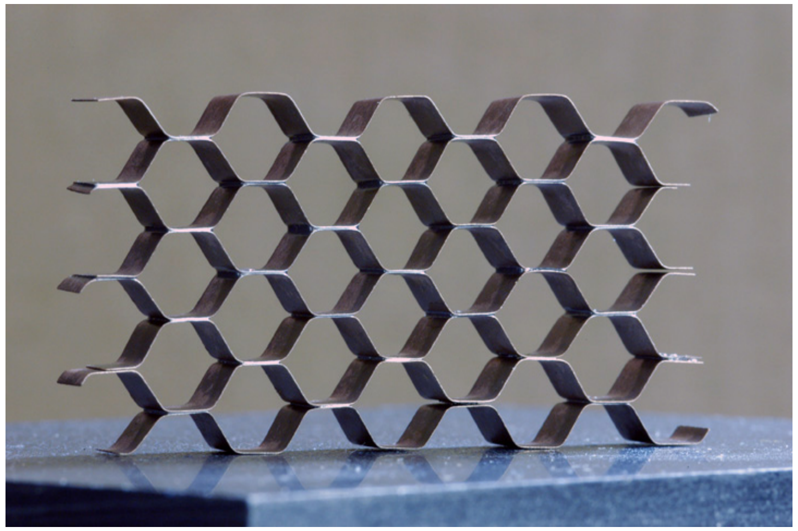
Combination

- Amplified strain recovery

  5% ➡ 50%

- Reduced thermal lag

  τ ➡ τ /10



NiTi hexagonal honeycomb
(5.7% dense, 0.37 g/cc)

NiTi SMA

- Shape memory effect & superelasticity
- High strength, ductility,
- Corrosion resistance, biocompatibility

Potential applications of NiTi Cellular Structures

Overload protection

- Amplified superelasticity, reusable energy absorber
- Lightweight, resilient, damage tolerant

Vibration isolation

- Adaptive damping

Thermal actuators & adaptive structures

- Improved response time, amplified stroke

Thermal & acoustic management

- Adaptive thermal conductivity & acoustic impedance

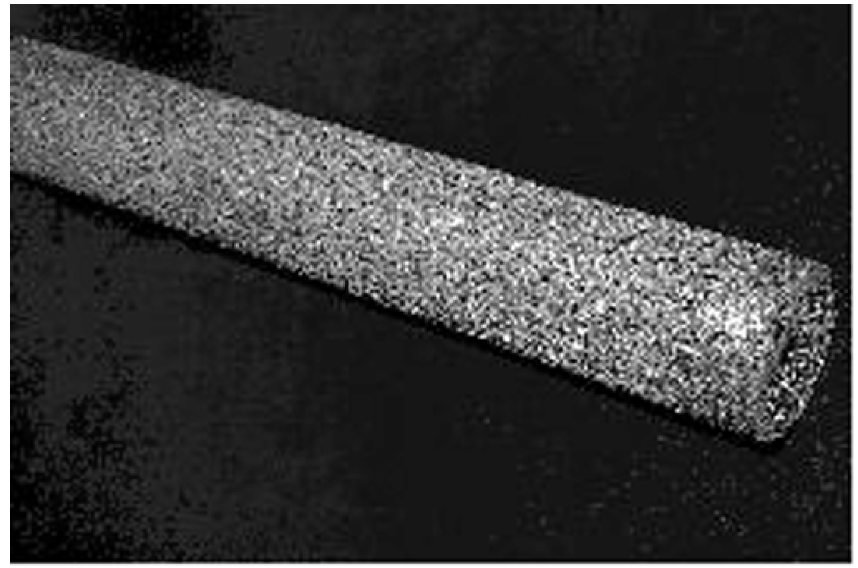
Biomedical implants & devices

- Lightweight, sparse, tailorable properties, deployable

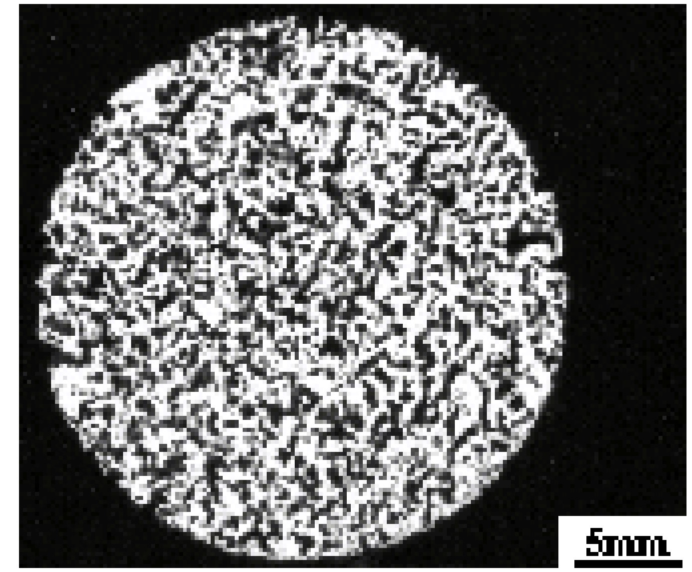
Fabrication & Metallurgy

Prior Attempts: Powder Metallurgy

Porous SMAs

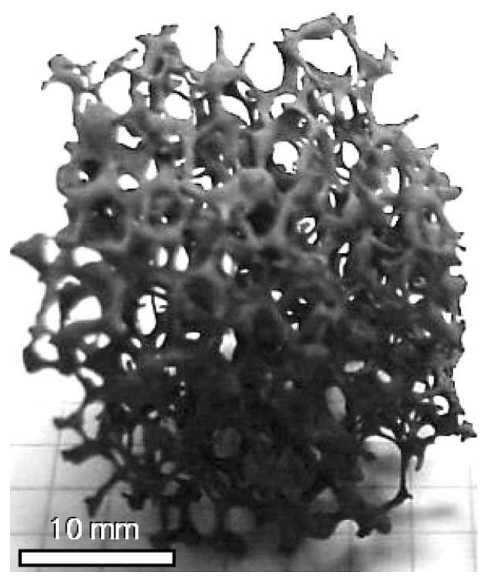


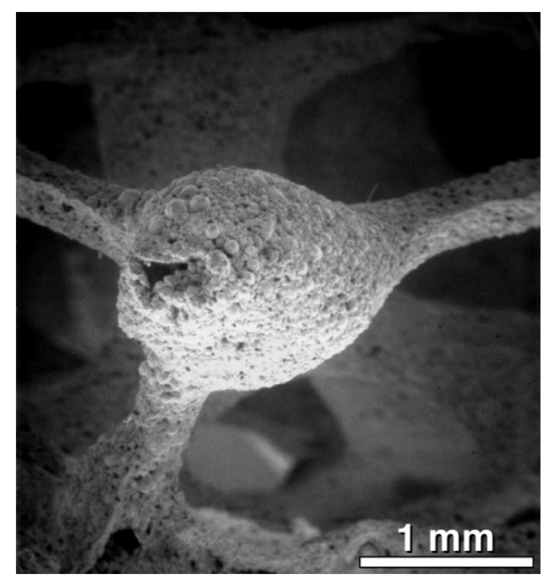
50% dense NiTi bar
hot isostatic pressing of elemental powders
[Naval Research Lab, V. DeGiorgi]



40% dense NiTi bar
combustion synthesis
[Li Rong, China]

SMA foam





5% dense NiTi open-cell foam
Powder process with sacrificial precursor
[Grummon/Shaw, 2002]

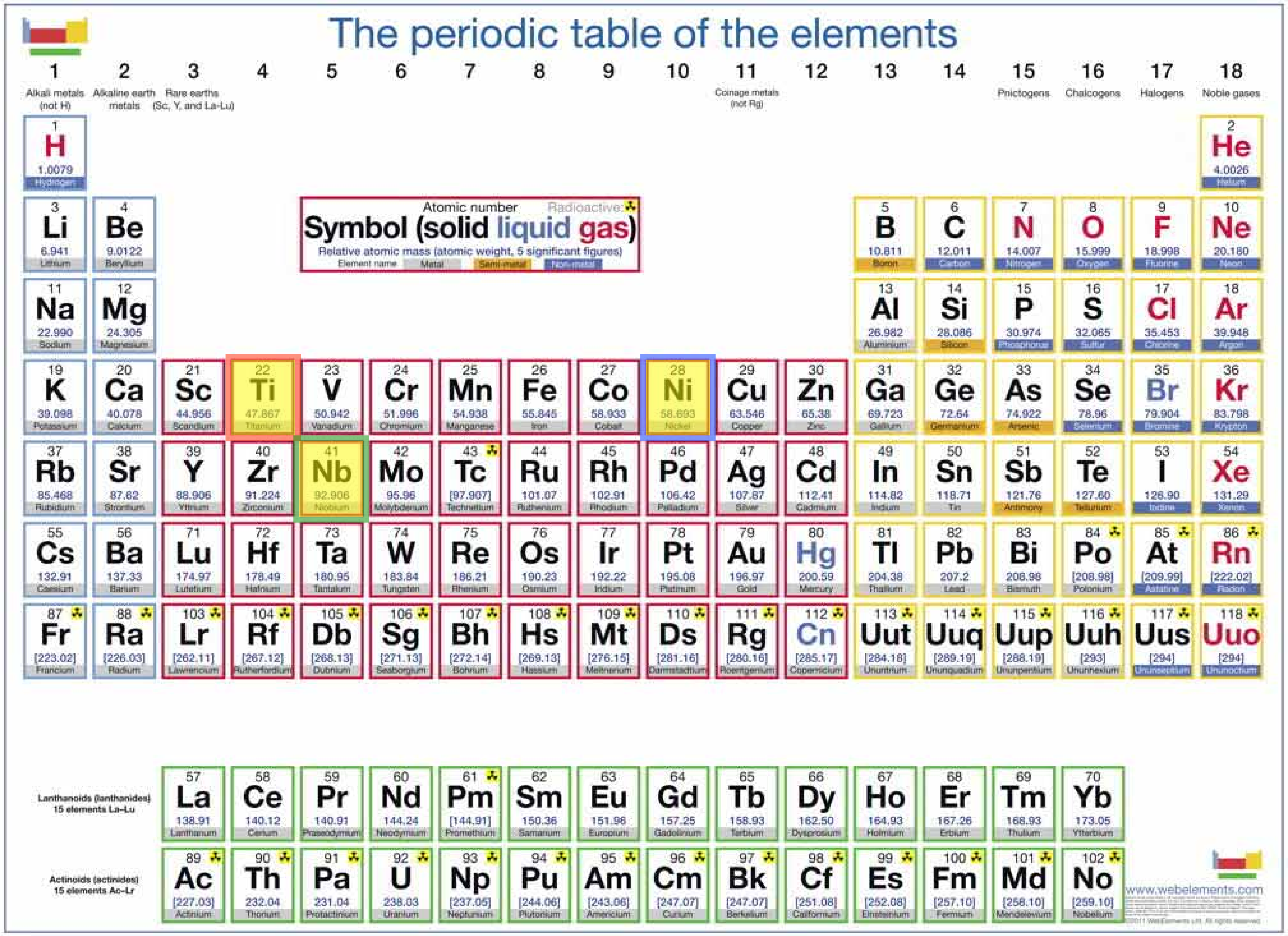
Technological Barrier Overcome

Long-standing difficulty:

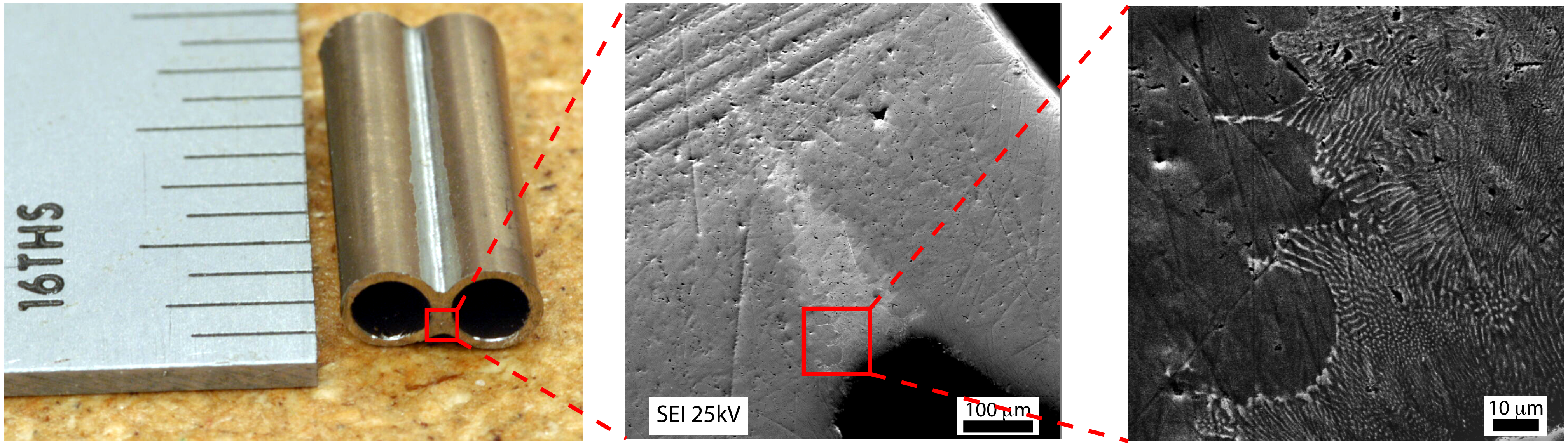
- Joining NiTi to itself or anything else
- Usually requires mechanical attachment/crimping
- Gluing is a very low strength option

Metallurgical bonds:

- Sensitive to interstitial contaminants (C, O, N).
- Laser welding in inert gas
  - Tricky (& proprietary), but some recent success.
  - Requires line-of-sight access.
- Soldering
  - Requires very aggressive fluxes to remove Ti-oxides.
  - Low strength
- Nb-reactive bonding (our process)
  - Discovered in 2004
  - Self-fluxing
  - Strong, ductile joints
  - Vanadium also works well


The periodic table of the elements
Atomic number
Radioactive
Symbol (solid liquid gas)
Relative atomic mass (atomic weight, 5 significant figures)
Element name
Metal
Semi-metal
Non-metal
Lanthanoids (lanthanides) 15 elements La–Lu
Actinoids (actinides) 15 elements Ac–Lr
www.webelements.com

Discovery of a Nb-based braze for joining wrought NiTi

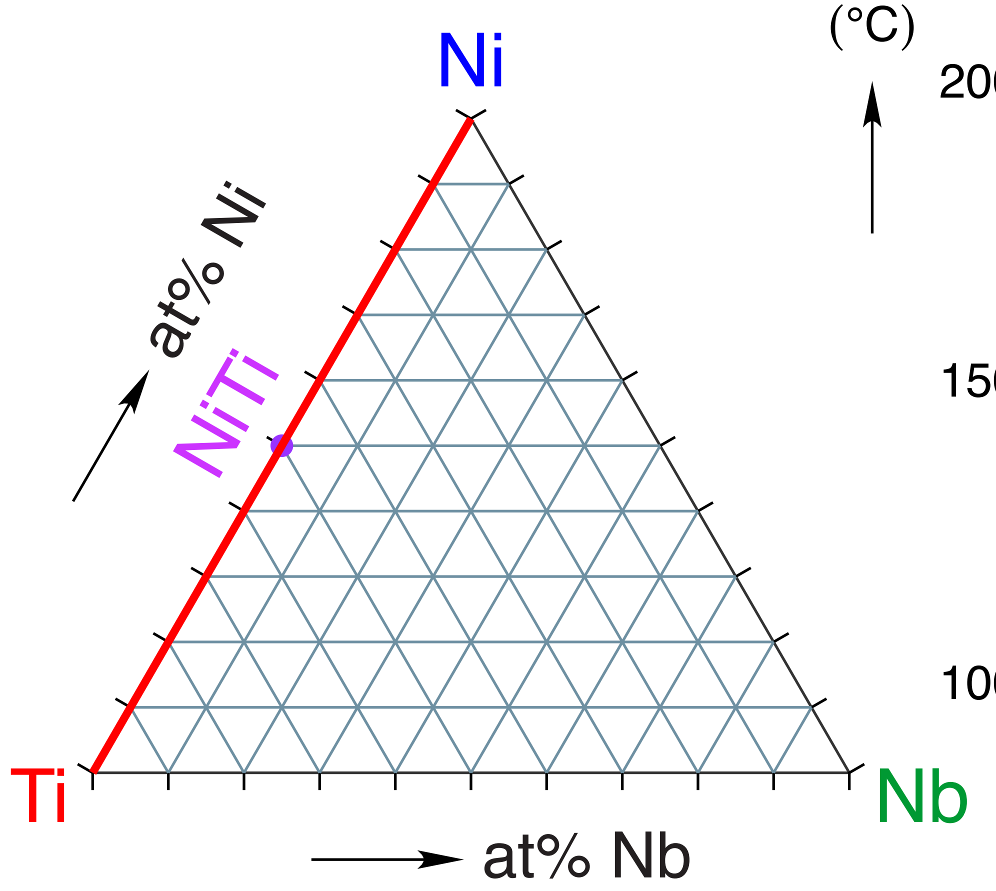


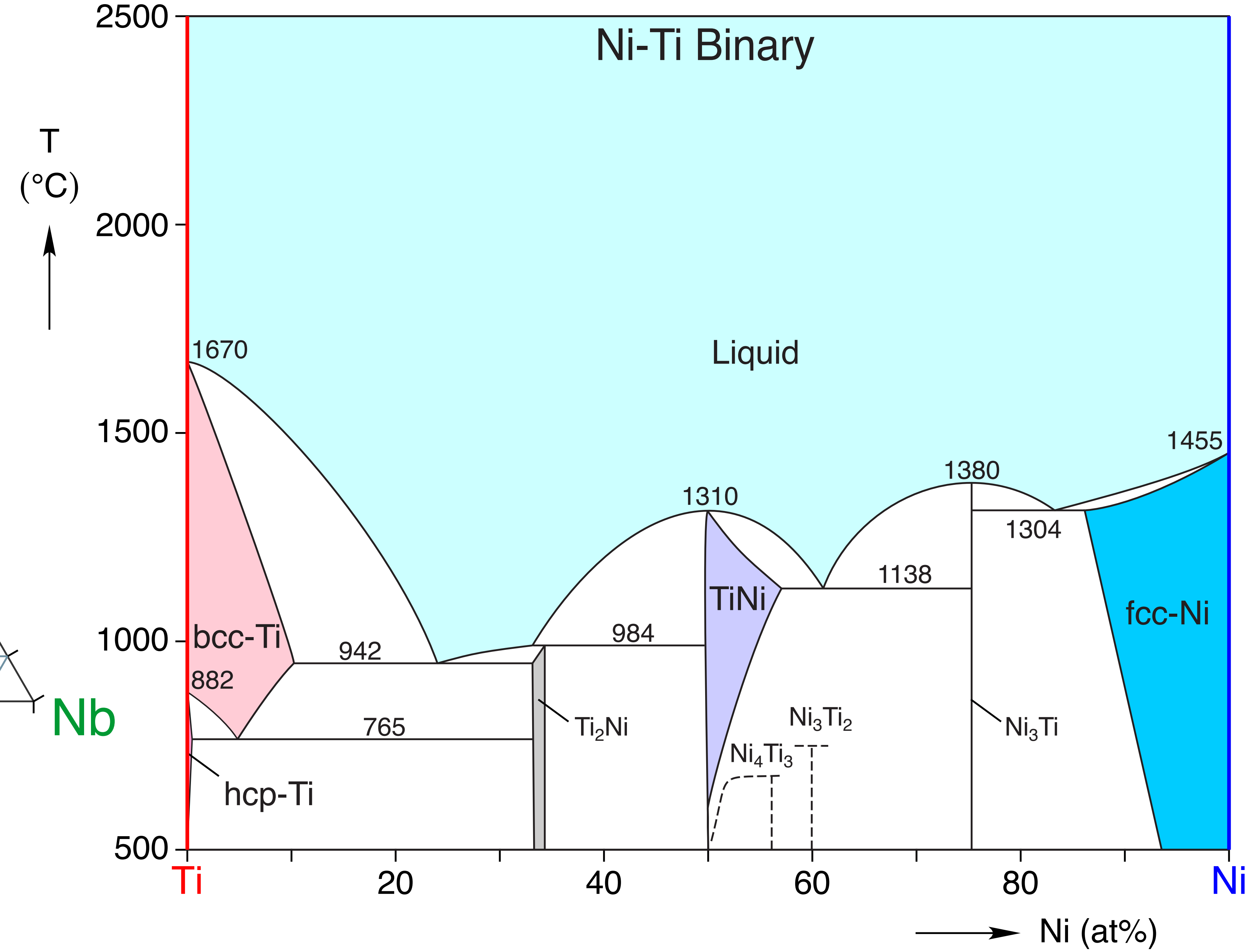
[Shaw/Grummon (UM/MSU) U.S. patent 7,896,222, issued March 1, 2011]

60 NiTi-tube array (32 % dense)

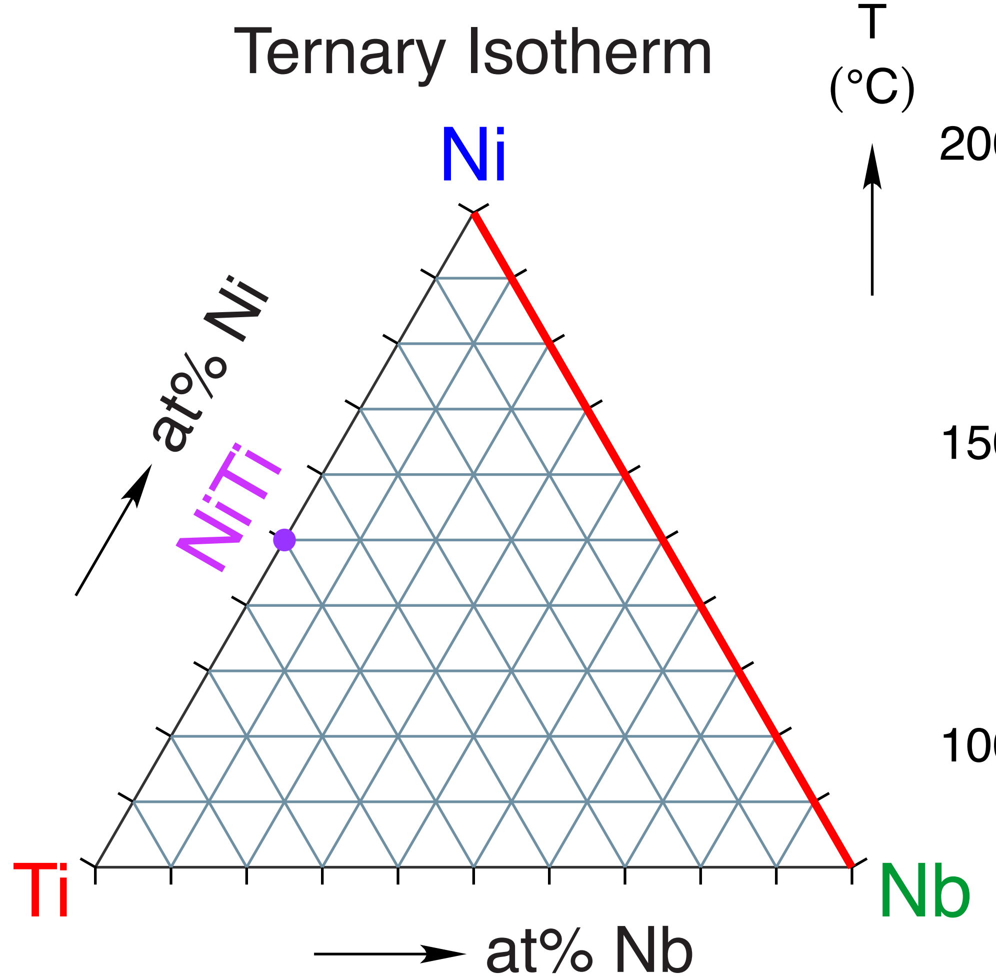
Some Metallurgy

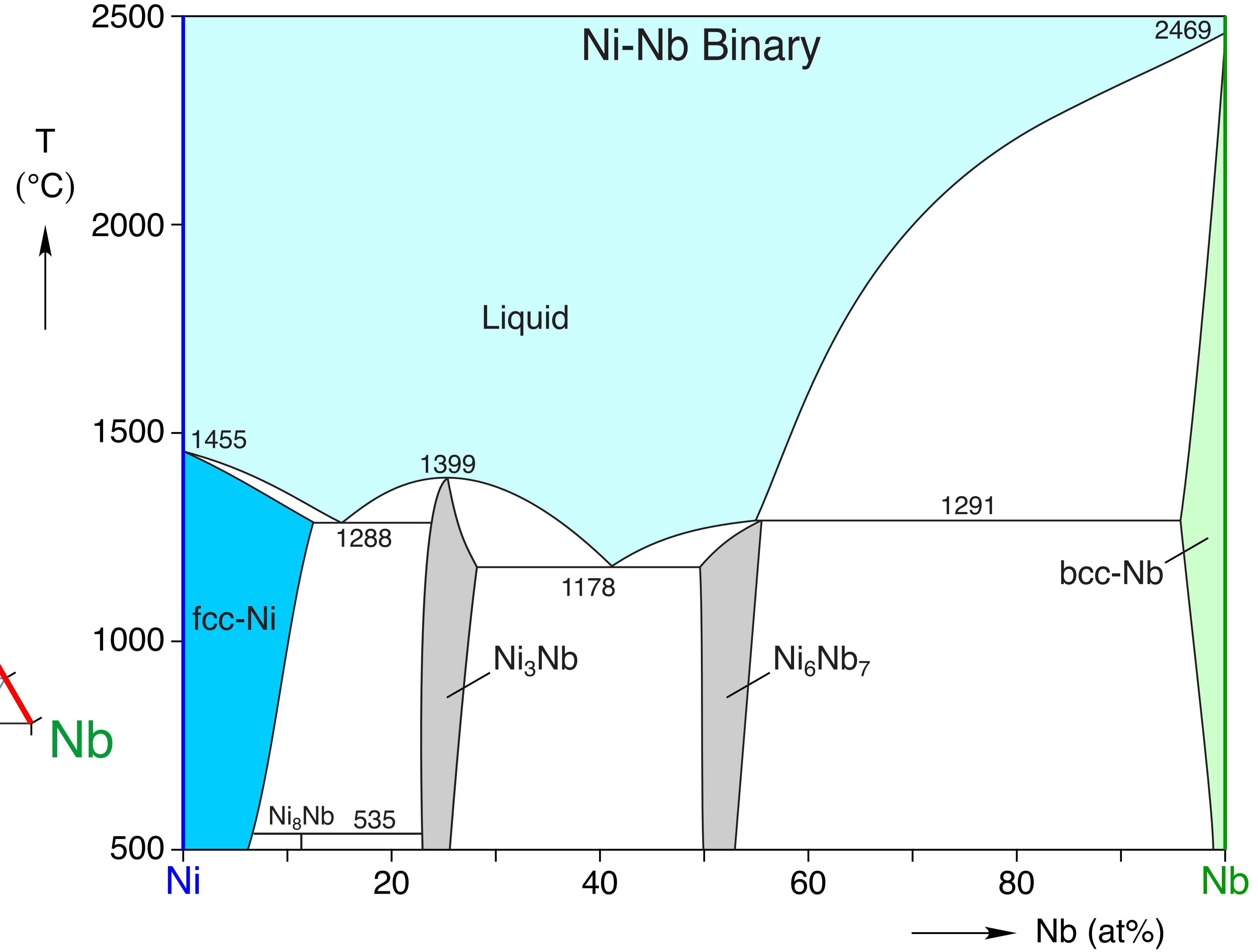
Ternary Isotherm

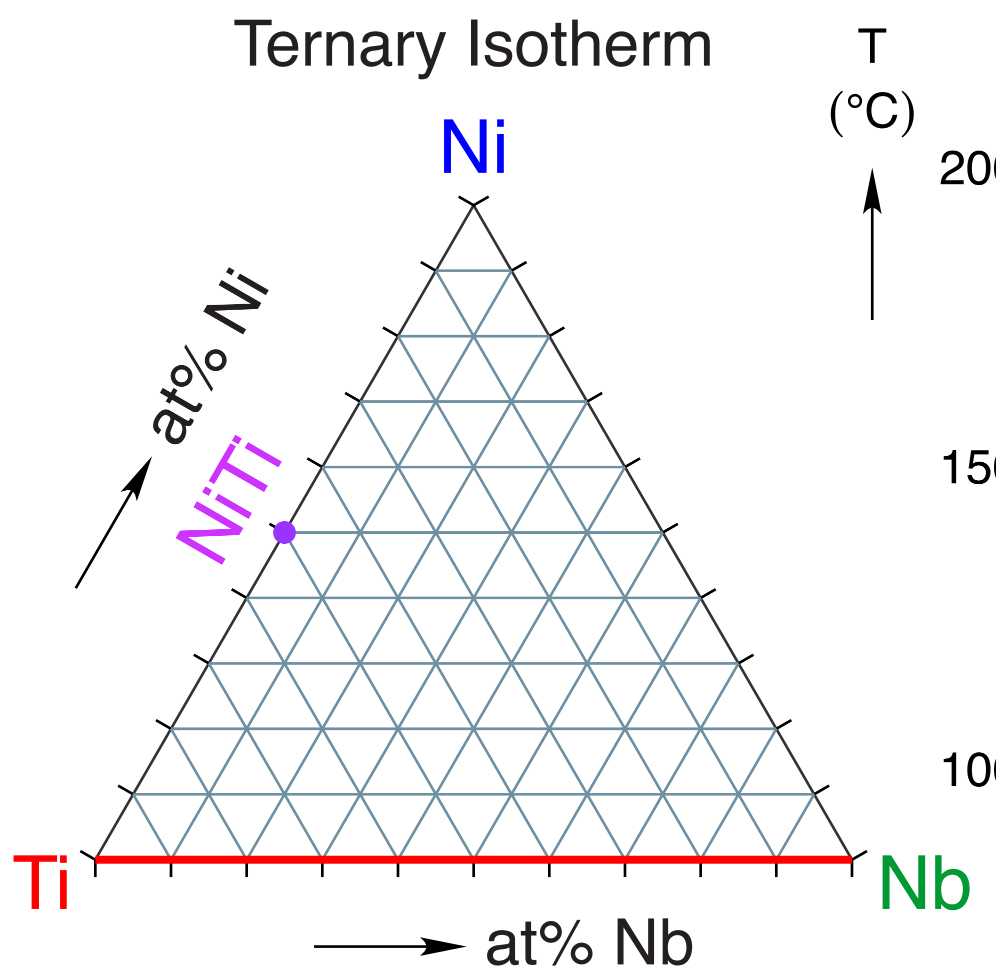


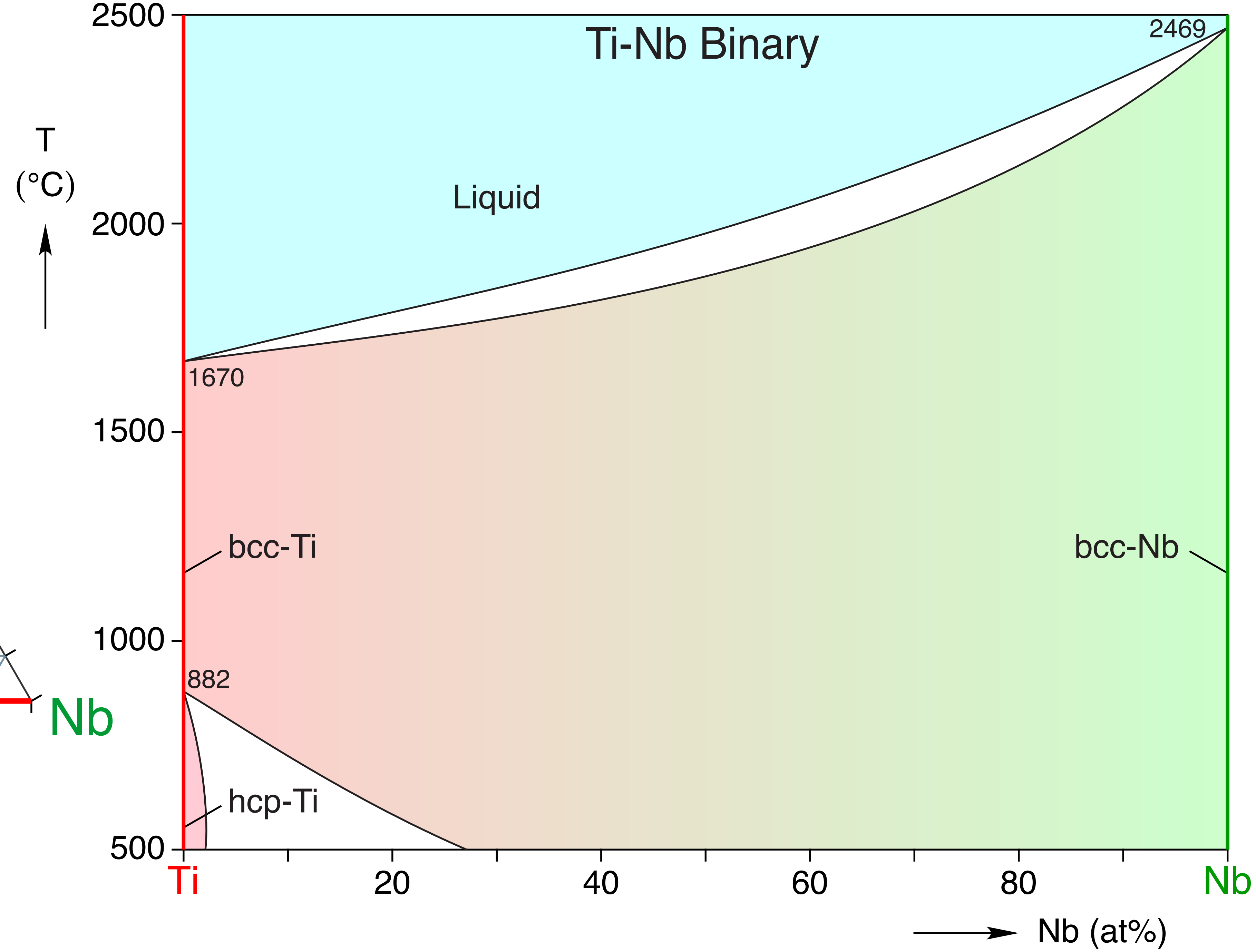


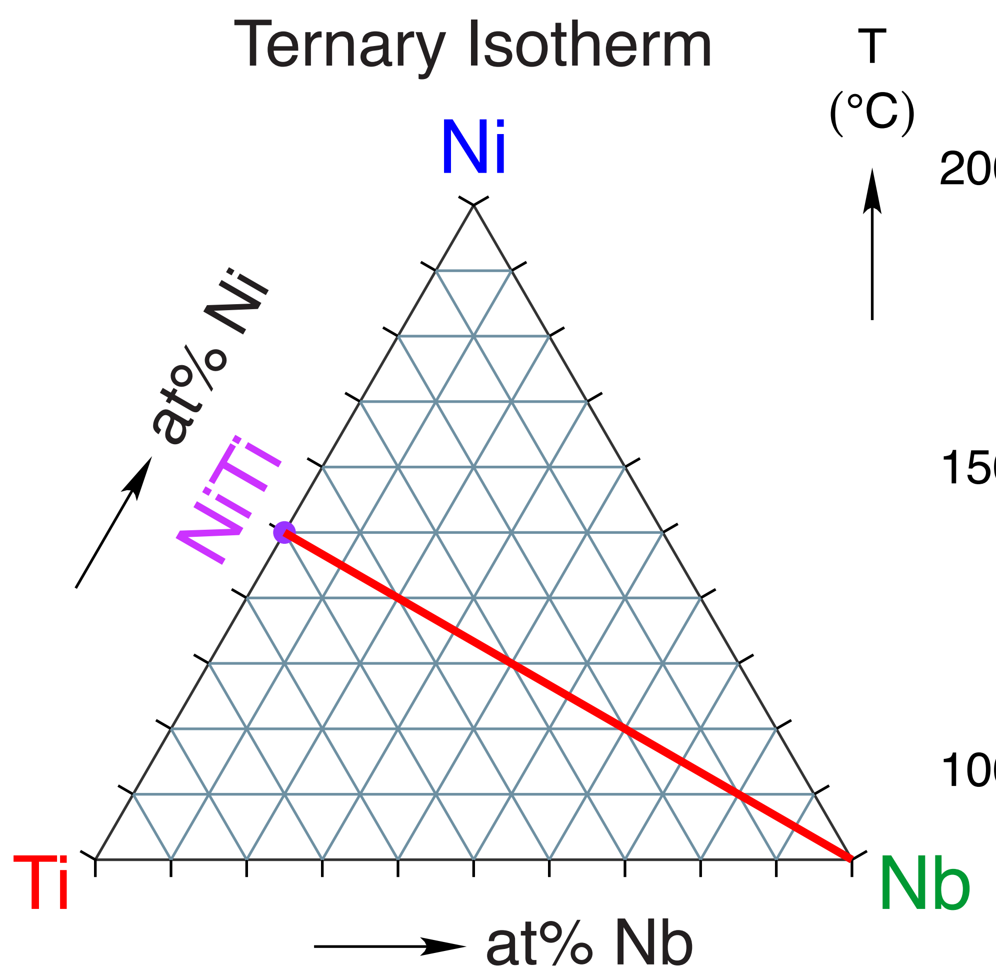
Some Metallurgy

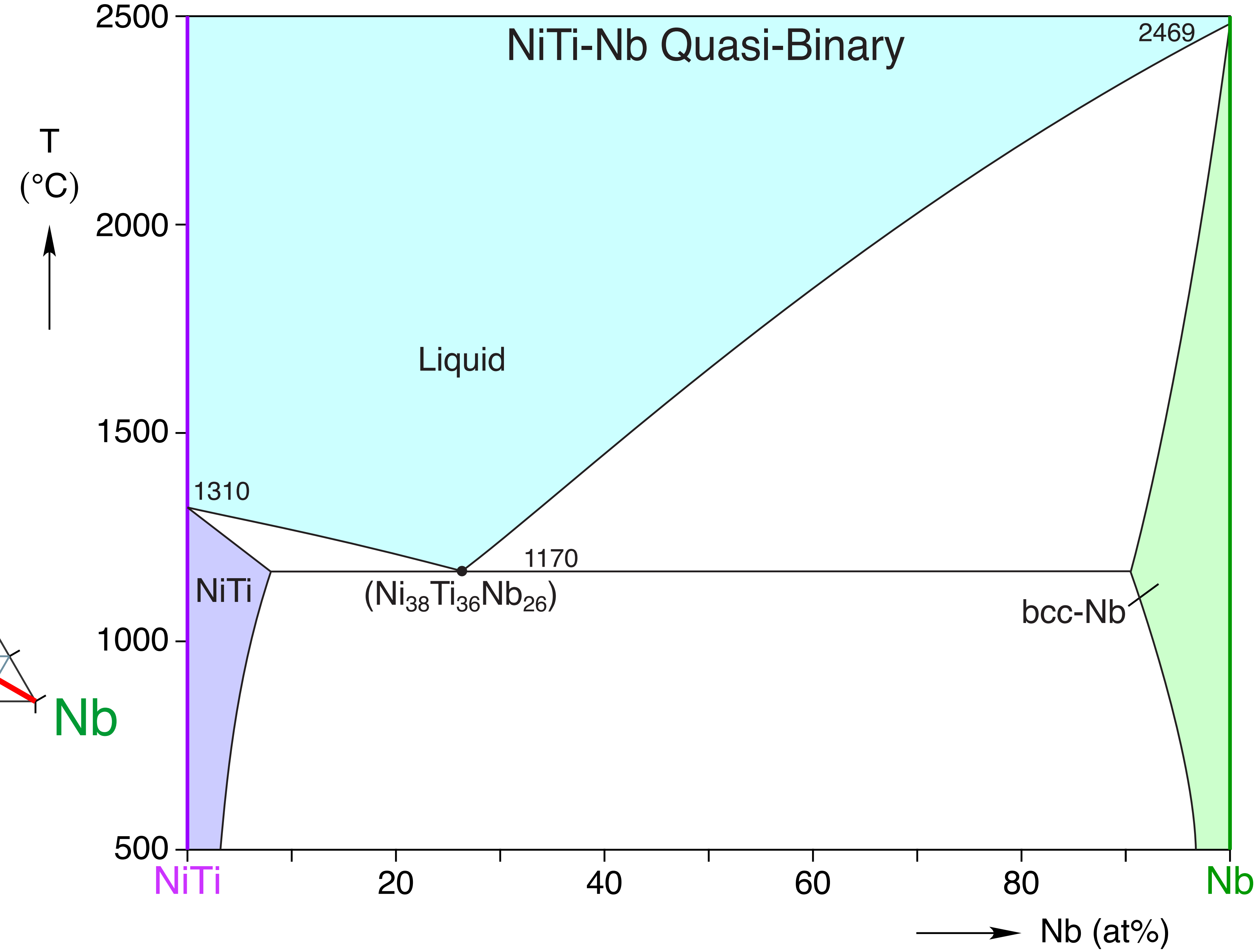




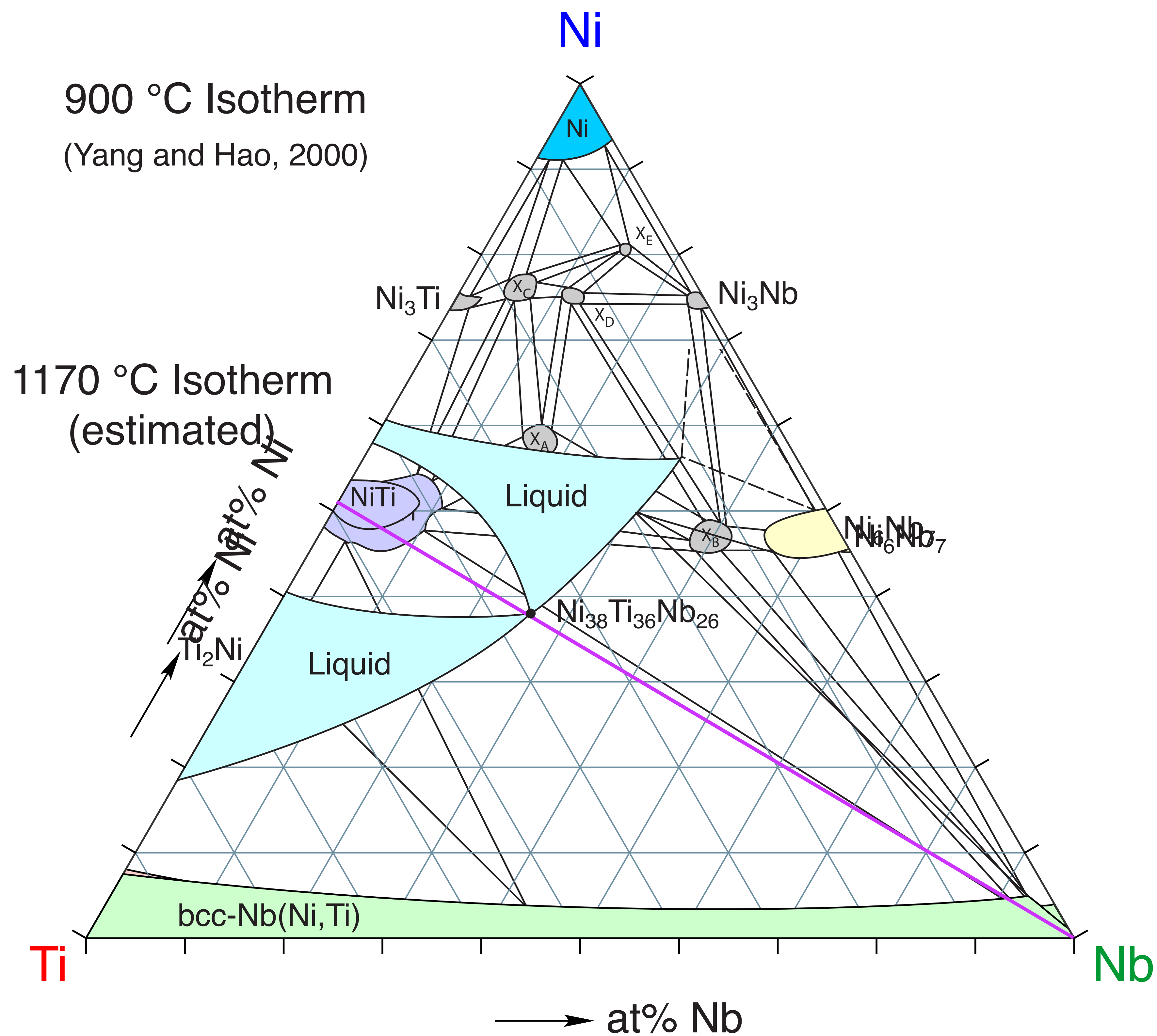

Ternary Isotherm
Ni
at% Ni
NiTi
Ti
Nb
at% Nb


Ti-Nb Binary
T
(°C)
2500
2000
1500
1000
500
2469
Liquid
1670
bcc-Ti
bcc-Nb
882
hcp-Ti
Ti
20
40
60
80
Nb
Nb (at%)

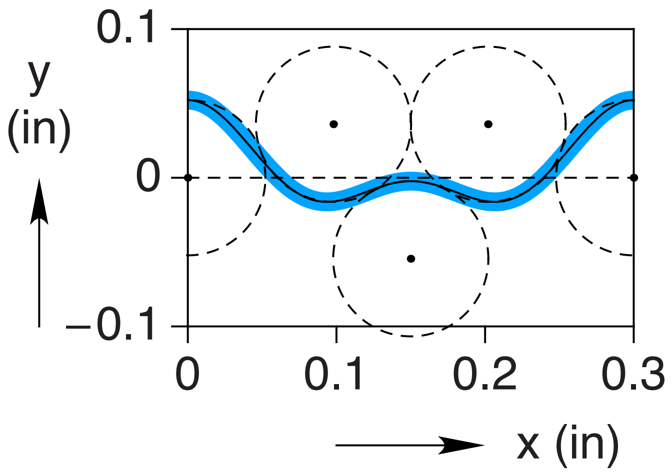

Ternary Isotherm
Ni
at% Ni
NiTi
Ti
Nb
at% Nb


NiTi-Nb Quasi-Binary
T
(°C)
2500
2000
1500
1000
500
2469
Liquid
1310
1170
NiTi
(Ni38Ti36Nb26)
bcc-Nb
NiTi
20
40
60
80
Nb
Nb (at%)

Quasi-binary Eutectic



Fabrication Procedure

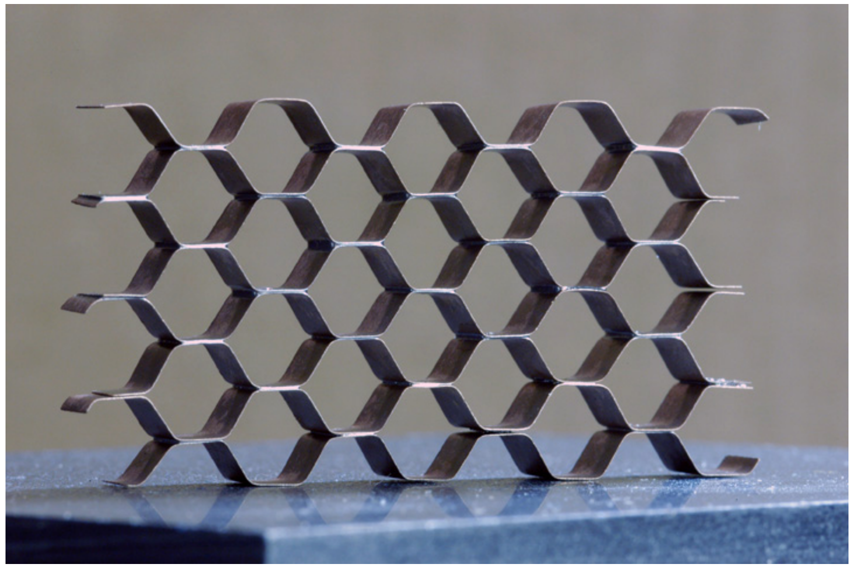


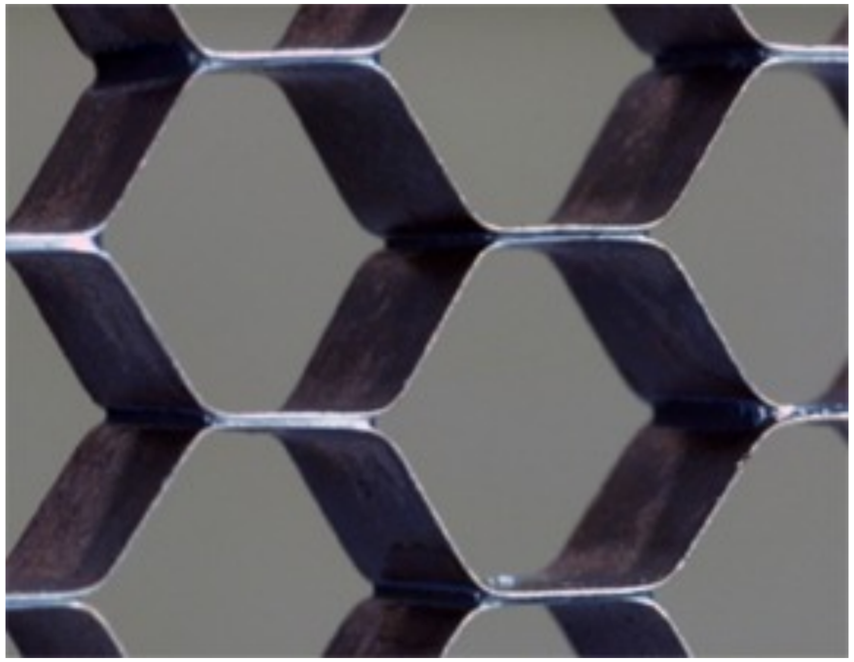
Shape-set of corrugated strips (500 °C)

1. Corrugate SMA strips at 500 °C by shape set die
2. Lay up corrugation layers & Nb foils
3. Vacuum furnace at 1170 °C, 5 min
4. Age at 500 °C, 10 min

Low-density NiTi cellular specimens

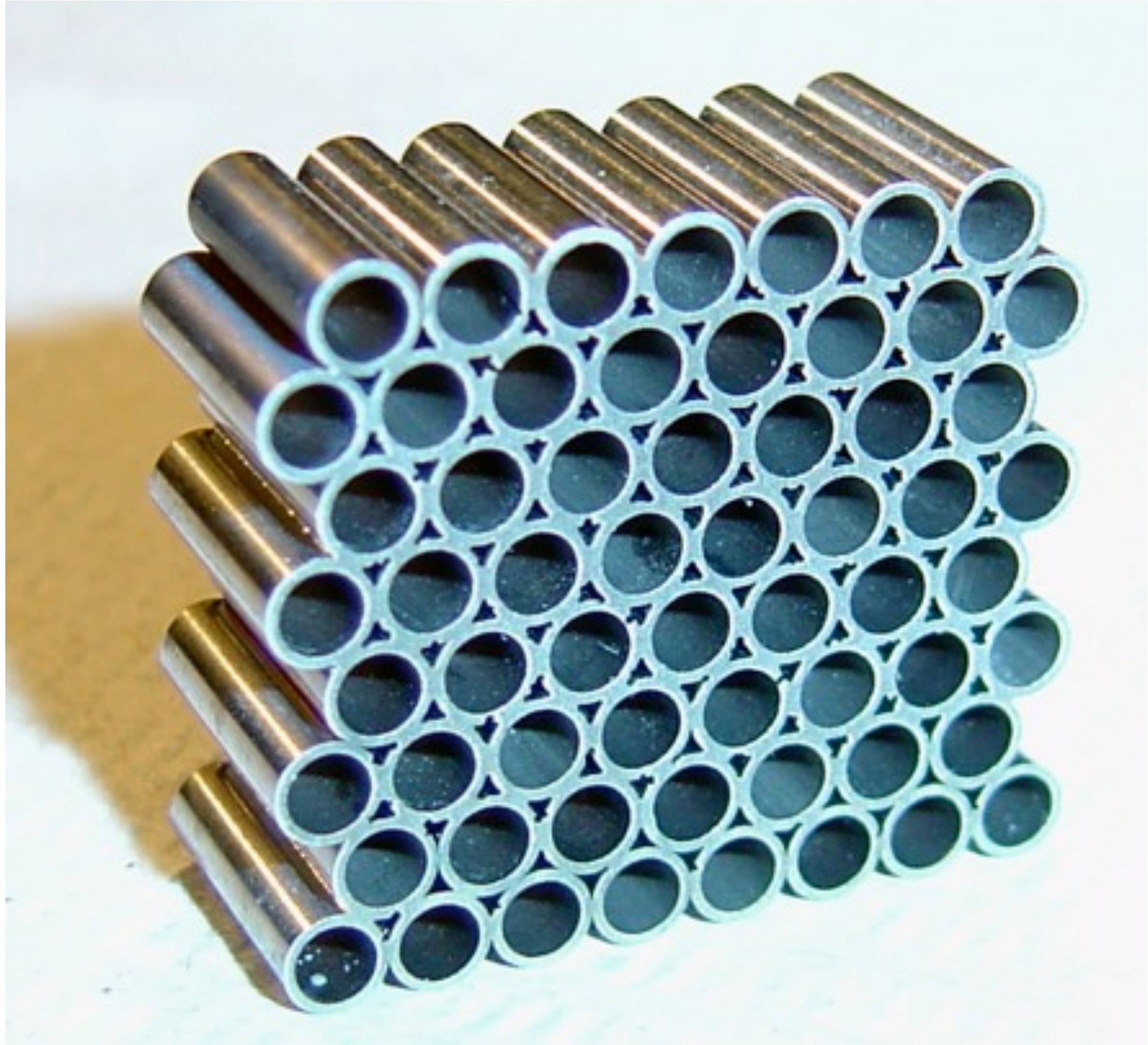
NiTi wavy corrugations

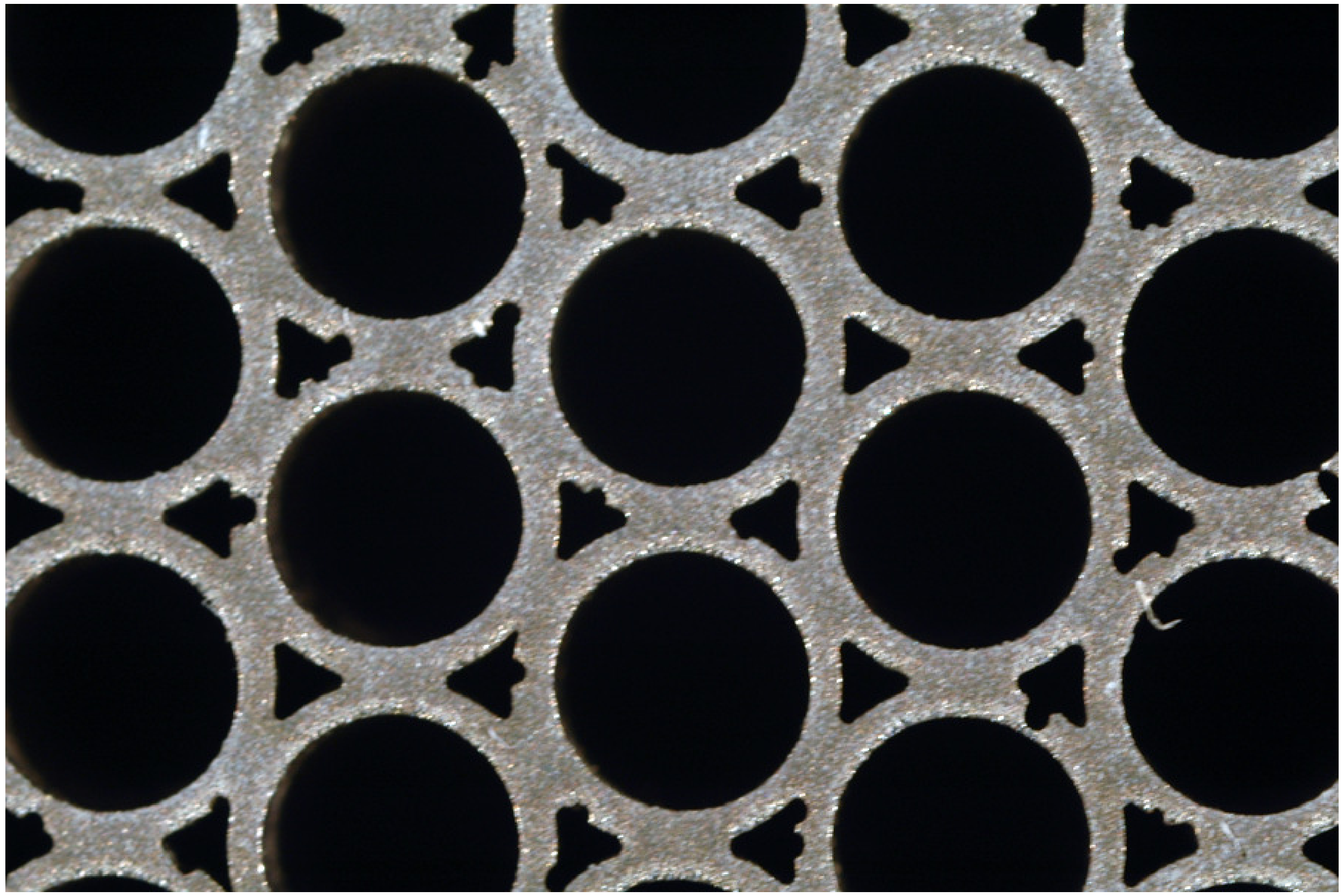




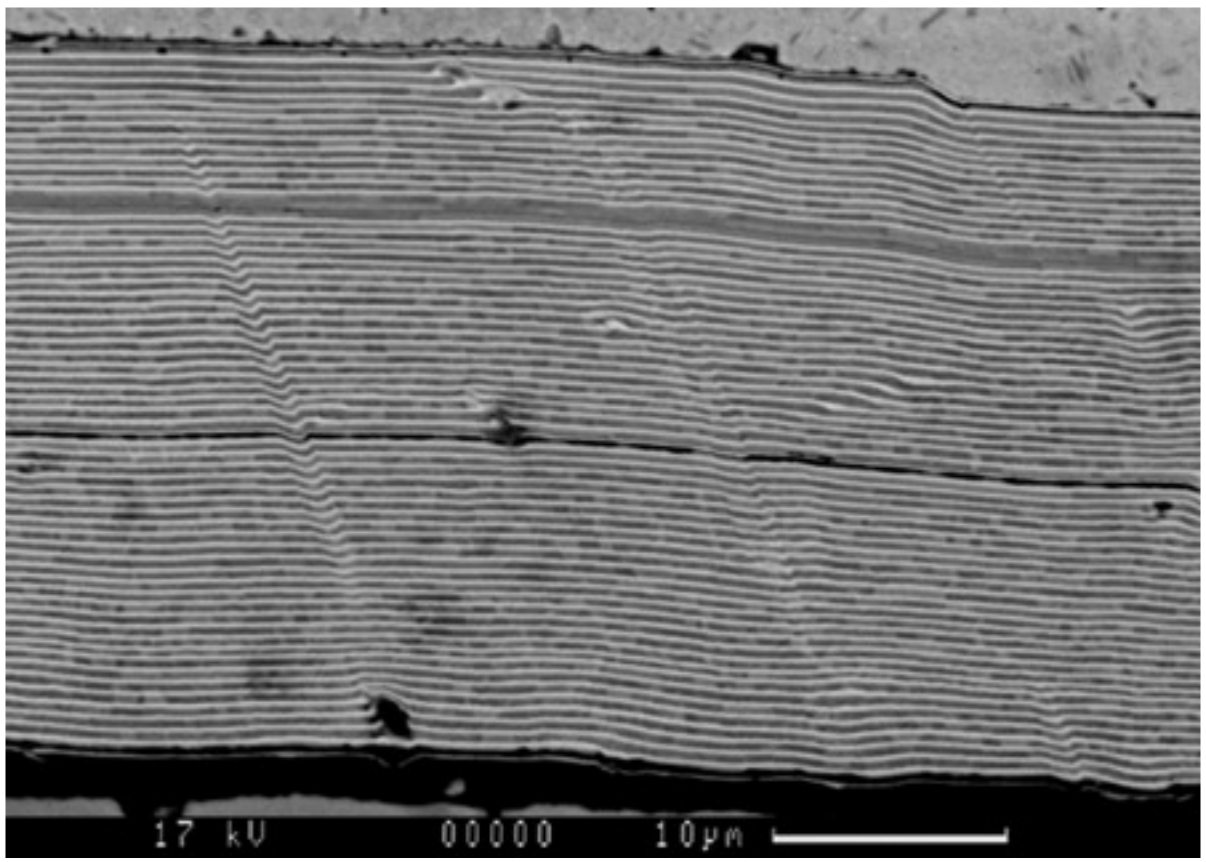
NiTi hexagonal honeycomb
(5.7% dense, 0.37 g/cc)

Aggressive Reaction

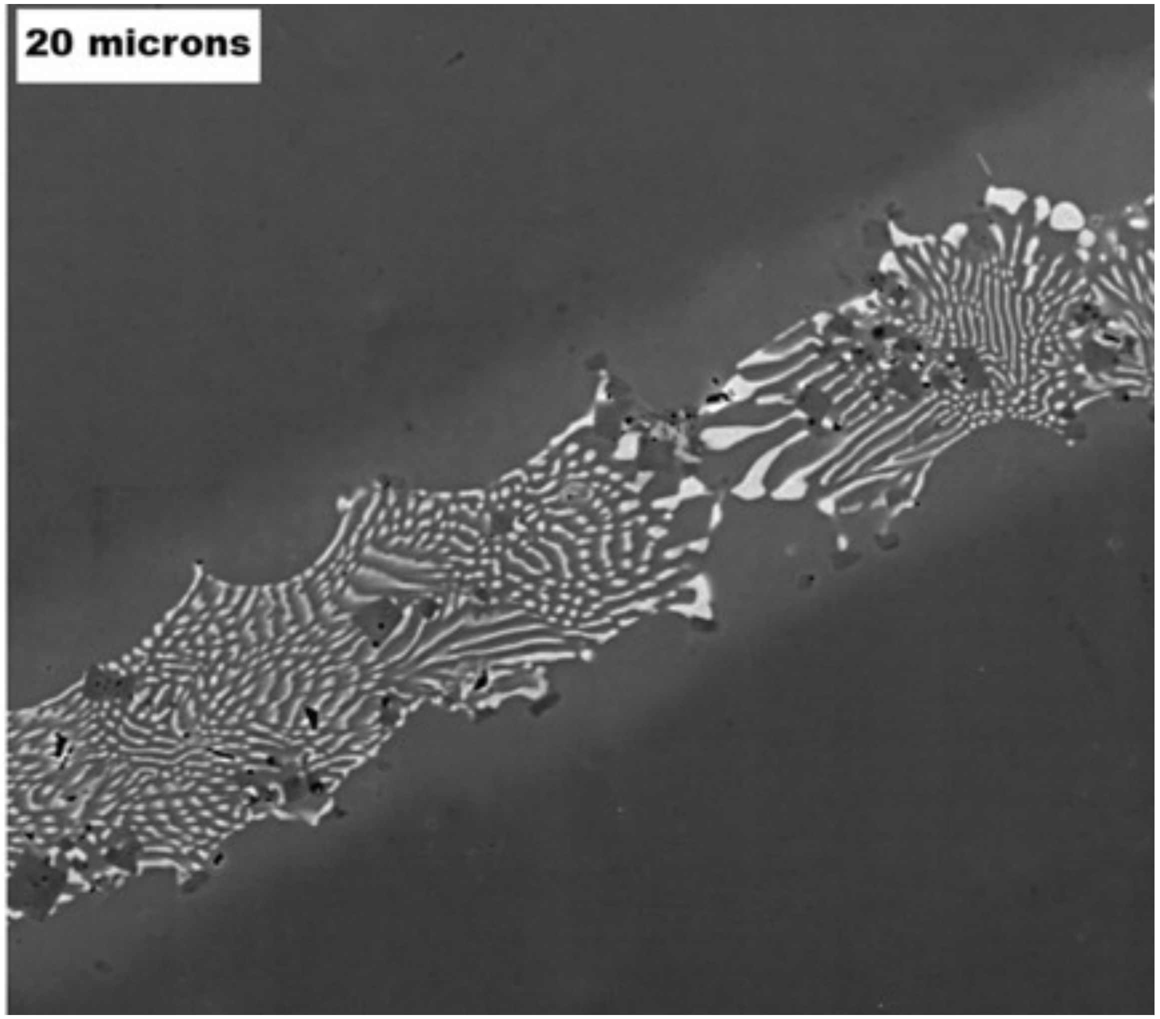




Advanced Braze Process Development

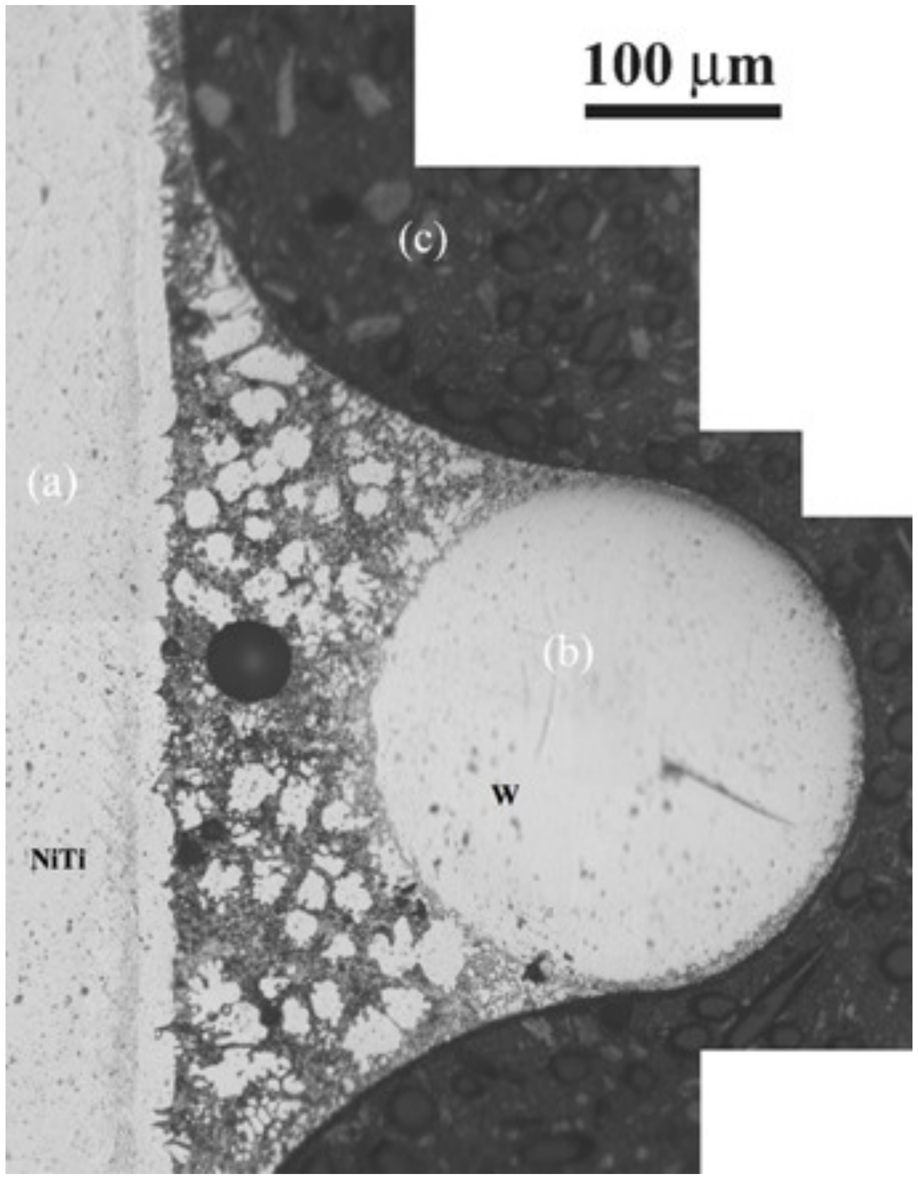


NiTi-Nb multilayer braze foil cross-section
(127 layers, 34 micron thickness total)

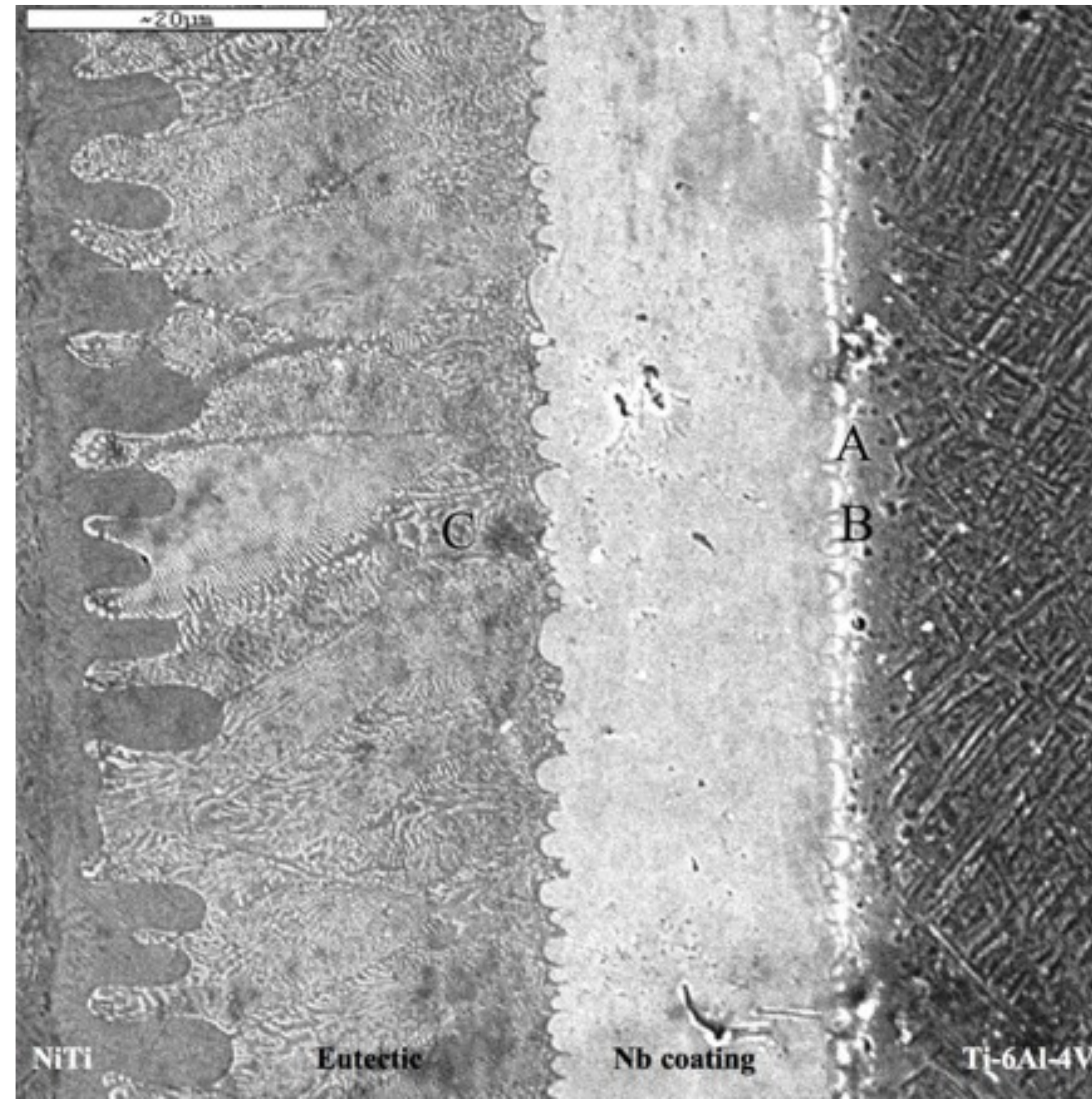


Braze microstructure using
multilayer foil

Other Heterobonds with NiTi

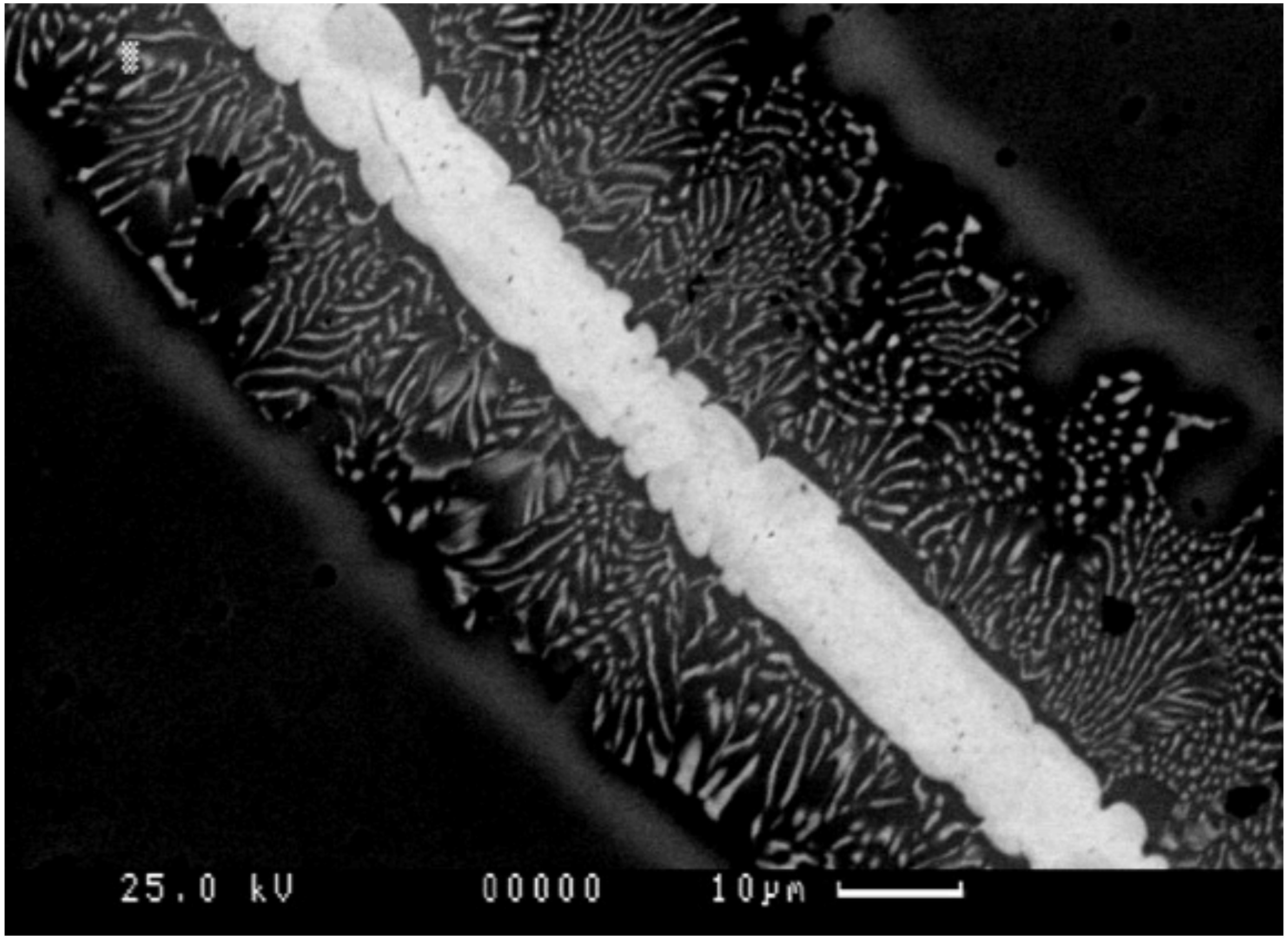


Pure tungsten (W) wire bonded to NiTi alloy



Sputtered Nb layer bonded between NiTi and Ti-6Al-4V

Possible Braze for High-temperature SMAs



Braze Joint between two wrought pieces of a $Ni_{24.5}Pd_{25}Ti_{50.5}$ HTSMA
(HTSMA from R. Noebe's group, NASA Glenn Research Center)

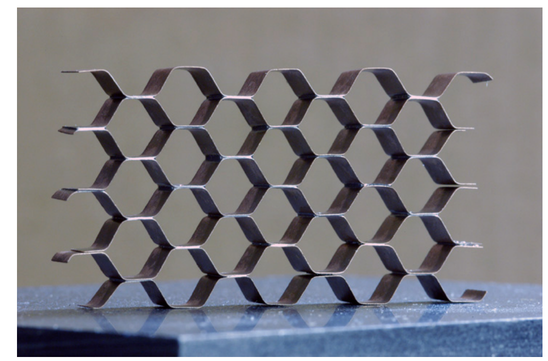
Fabrication of SMA cellular structures

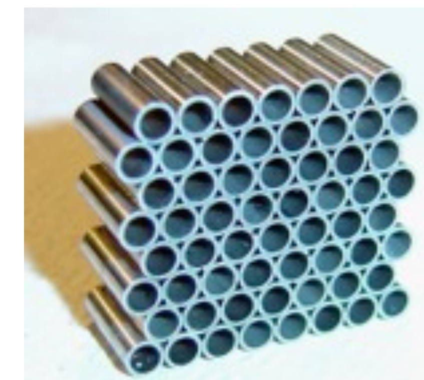
APPROACH:

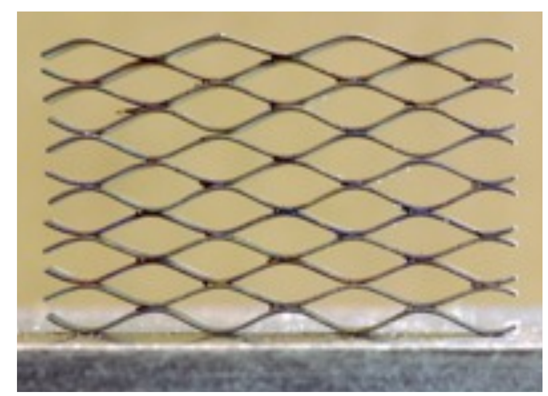
- Built-up, low density SMA corrugated structures
- Commercially-available wrought NiTi materials
- Nb-based brazing process

ACCOMPLISHMENTS:

- Fabricated NiTi SMA specimens:
  - hexagonal honeycombs (~ 5% dense)
  - wavy corrugations (~ 5% dense)
  - close-packed tube array (~ 32 % dense)
- Demonstrated robust braze joints:
  - Up to ~800 MPa tensile strength (butt-joints)
- Preserved adaptive properties of NiTi base material
- Improved layup with self-indexing geometry
- Multi-layer foils improve control of braze stoichiometry
- Positive indications that braze process can be used to join other metal alloys and high-temperature SMAs







Possible topologies & geometries