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Isothermal Martensitic and Pressure-Induced (Delta) to (Alpha)' Phase Transformations in a Pu-Ga Alloy

A. J. Schwartz, M. A. Wall, D. L. Farber, K. T. Moore, K. J. M. Blobaum

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Plutonium Futures "The Science" 2008
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Isothermal Martensitic and Pressure-Induced δ to α′ Phase Transformations in a Pu-Ga Alloy

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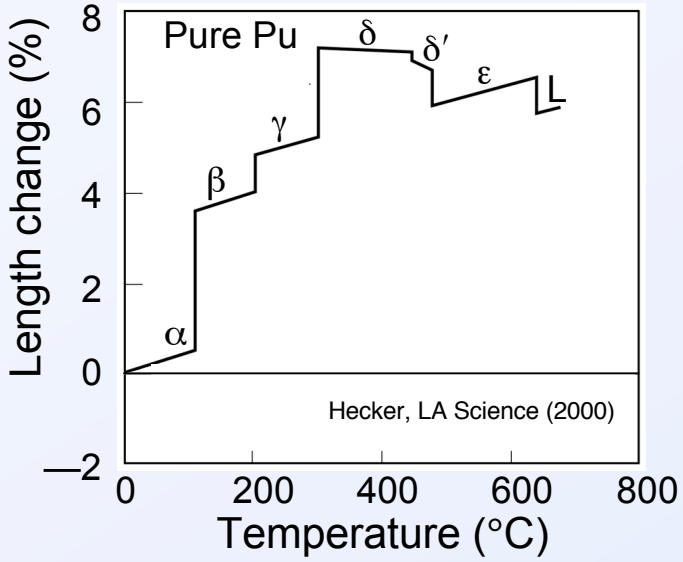
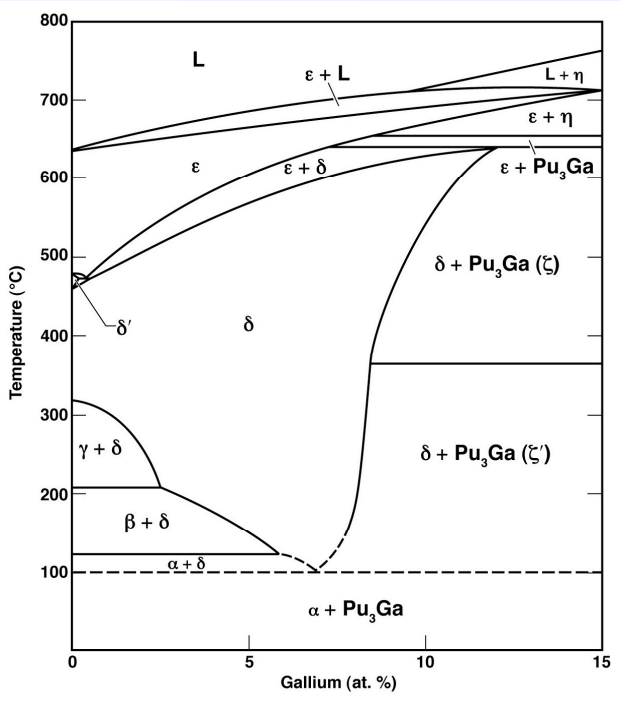
LLNL-CONF-xxxxxx

Understanding the phase transformations remains as one of the significant Pu metallurgical challenges

- Equilibrium phase diagram
- 5 allotropic phase transformations
- Phase transformations and phase stability
  - The δ → α′ isothermal martensitic transformation
  - The δ → α′ transformation under pressure



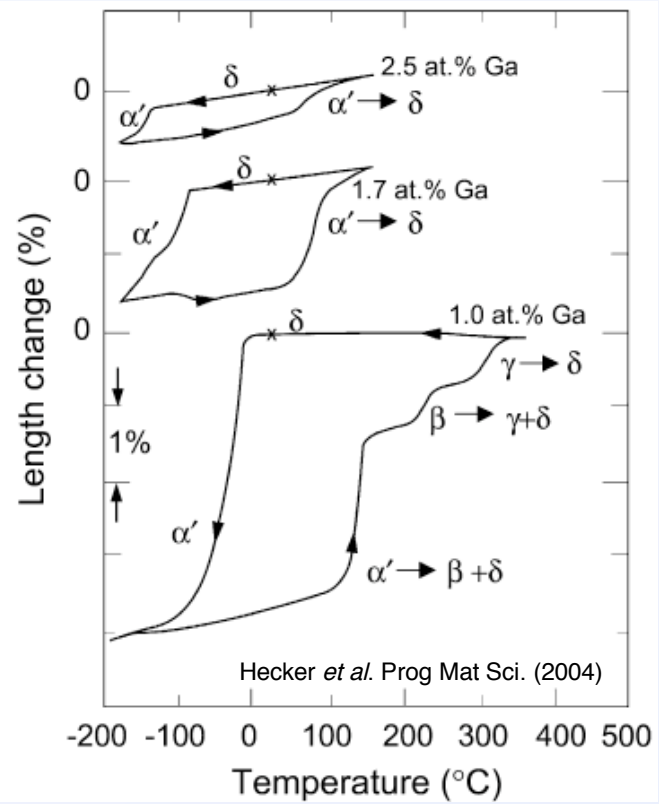


The δ-phase retained to room temperature is metastable

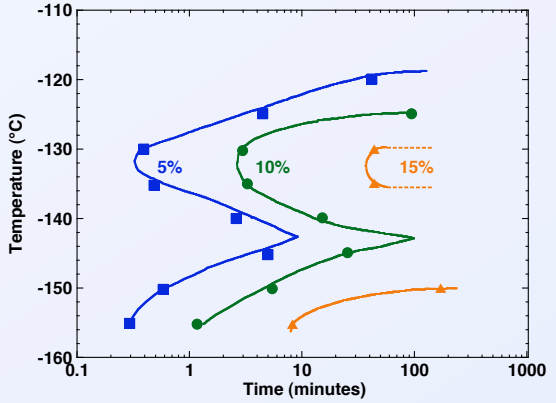
Timofeeva (2003) estimated 10,000 years to decompose

Upon cooling to sub-ambient temperatures, δ transforms to α′ via an isothermal martensitic transformation

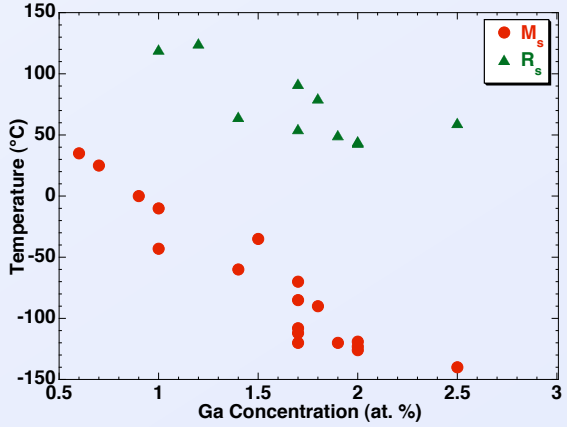
The δ → α′ isothermal martensitic transformation can be induced with continuous cooling experiments



The TTT curve for the isothermal δ → α′ transformation has double-C curve kinetics



The martensite start temperature, M_s is a function of Ga content

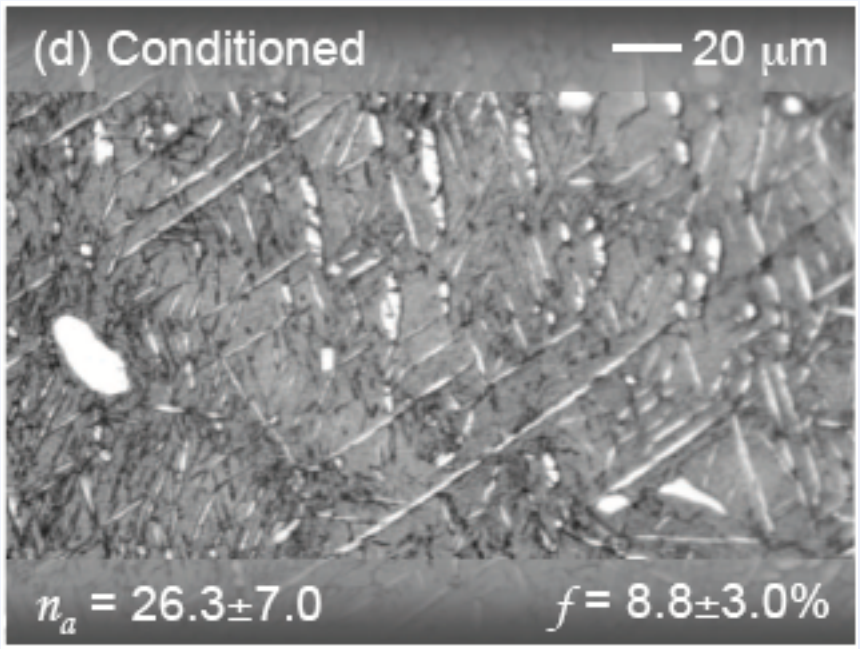


Like the δ-phase at room temperature, α′ is also metastable

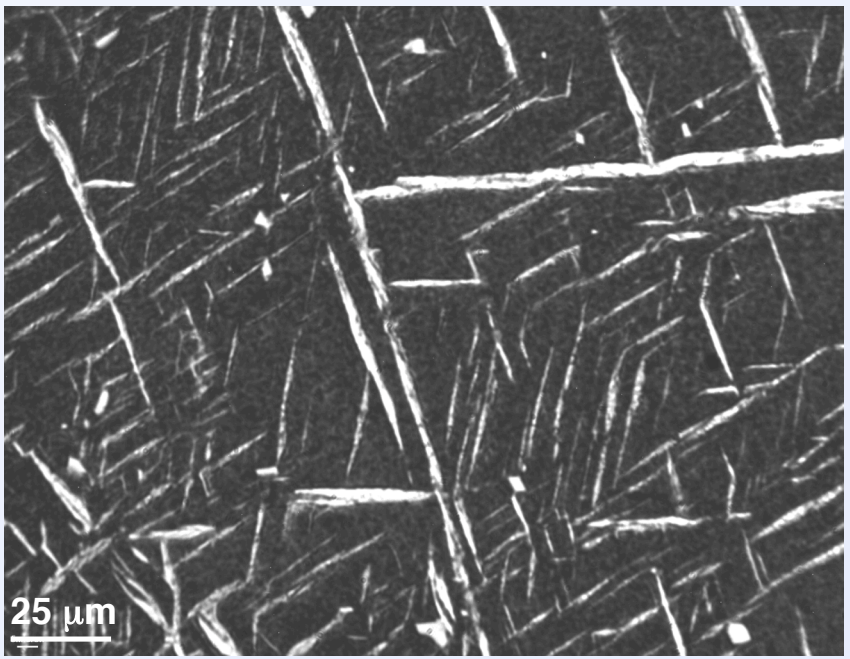
The α′ particles that form from the isothermal martensitic transformation appear as lathes in optical microscopy

Pu - 2.0 at.% Ga

-120°C/4 hours



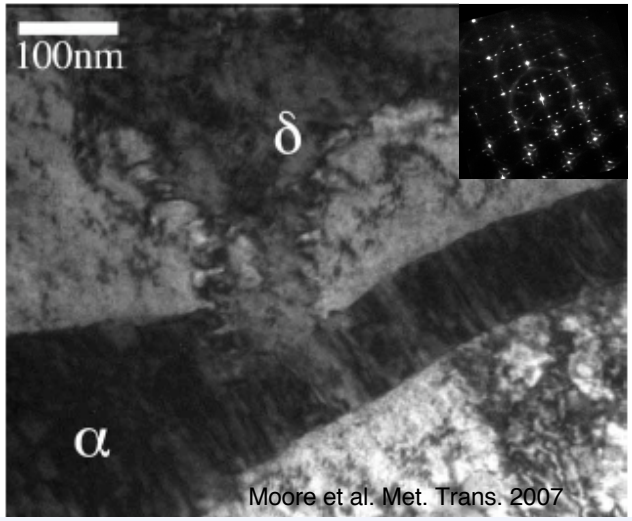
–155°C/4 hours

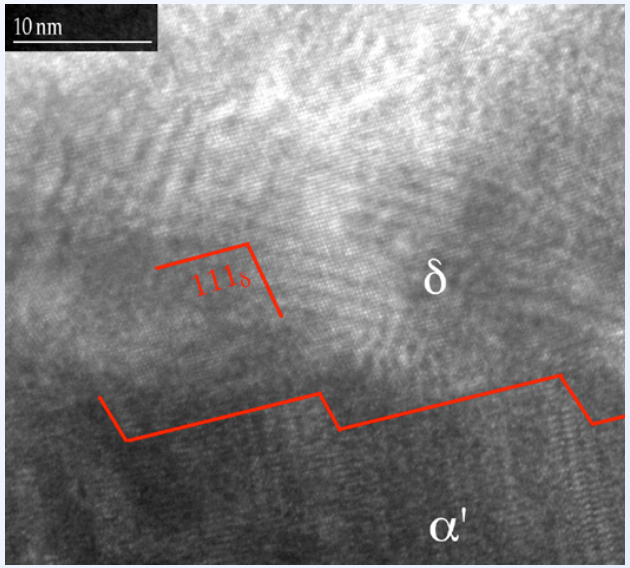


Partially transformed
(δ + α′ phases)

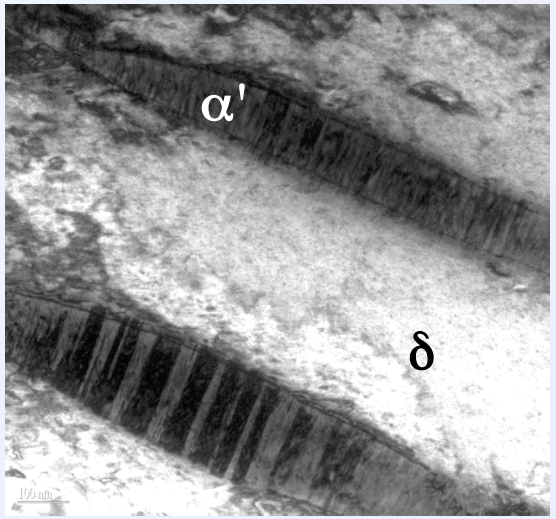
The δ → α′ isothermal martensitic transformation goes to ~ 25% completion

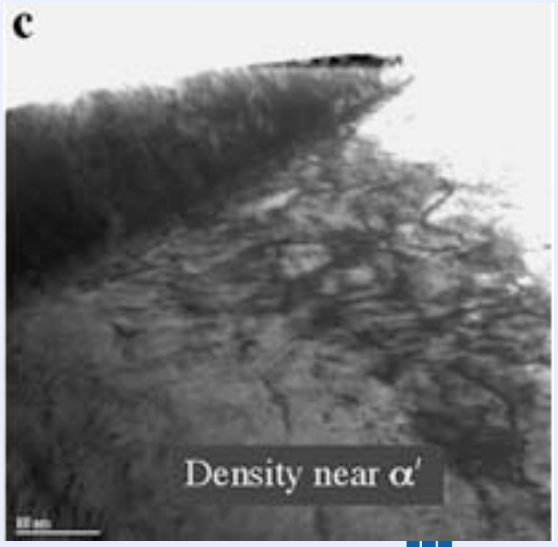
The crystallography and morphology of the δ → α′ transformation have been characterized with TEM



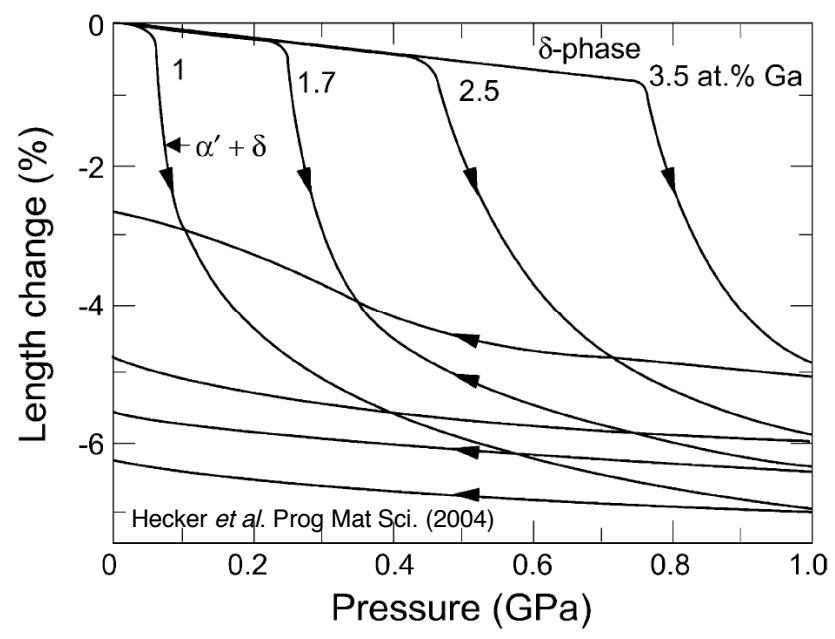


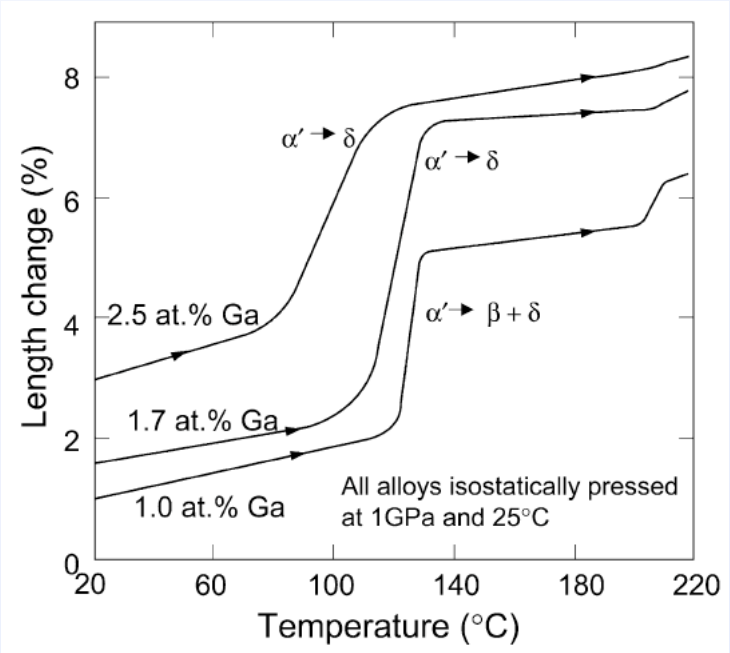
- The orientation relationship between α′ and δ is:
  $(111)_\delta \parallel (020)_{\alpha'}$
  $[-110]_\delta \parallel [100]_{\alpha'}$
  (Zocco *et al.* Acta Met. 1990)
- α′ particles consist of 2 variants rotated 60° around $<020>_{\alpha'}$
- TEM shows $(205)_{\alpha'}$ twinning as a lattice invariant deformation mode
- The α′–δ interface is composed of a terrace and ledge structure that is faceted on 111_δ
- The dislocation density is ~ an order of magnitude greater in the vicinity of α′ particles





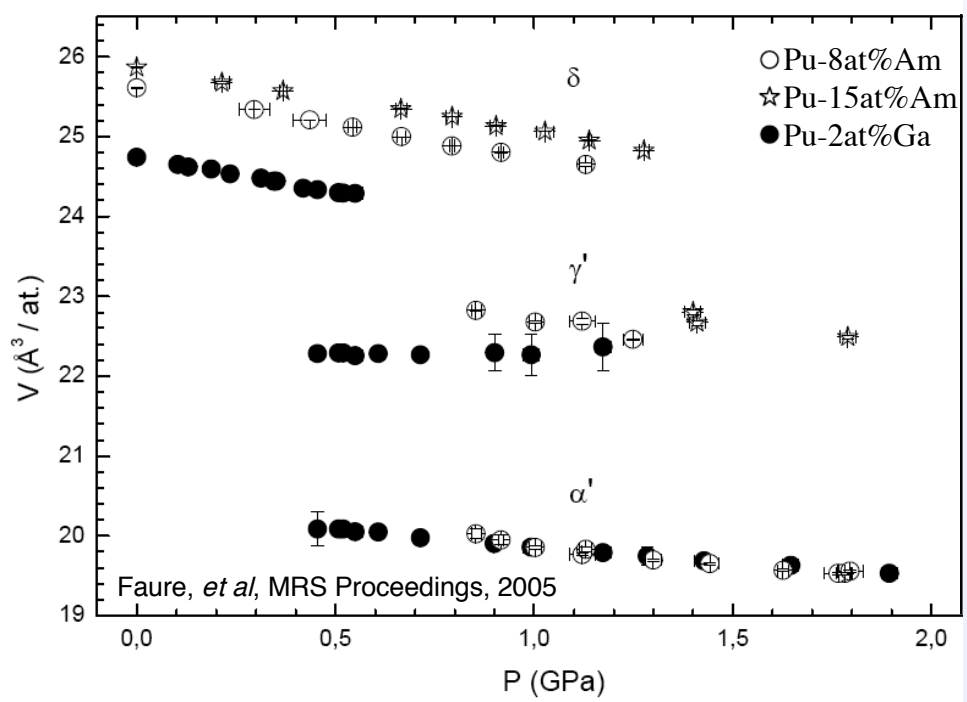
The δ → α′ transformation and reversion characteristics are a strong function of composition





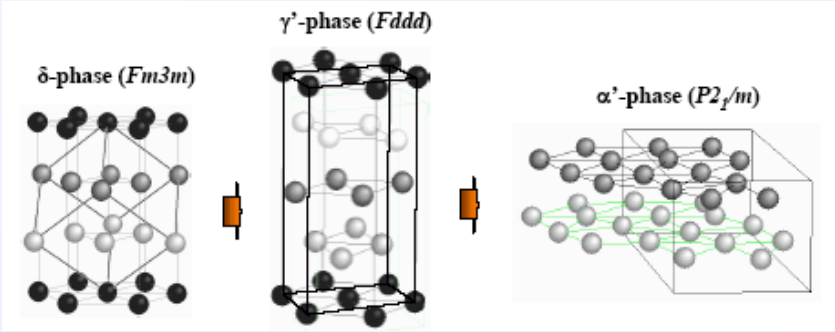
- **Under pressure, Pu - Ga alloys transform directly to α′ and undergo either a direct (α′ → δ) or indirect (α′ → β + δ → γ + δ → δ) reversion**
- **Reversion characteristics are similar to those in thermally-induced transformations**

Diamond anvil cell experiments on a Pu - 2 at.% Ga alloy reveal δ → γ′ → α′ transformation sequence



In the DAC, Pu - 2 at.% Ga transforms through the sequence δ → γ′ → α′

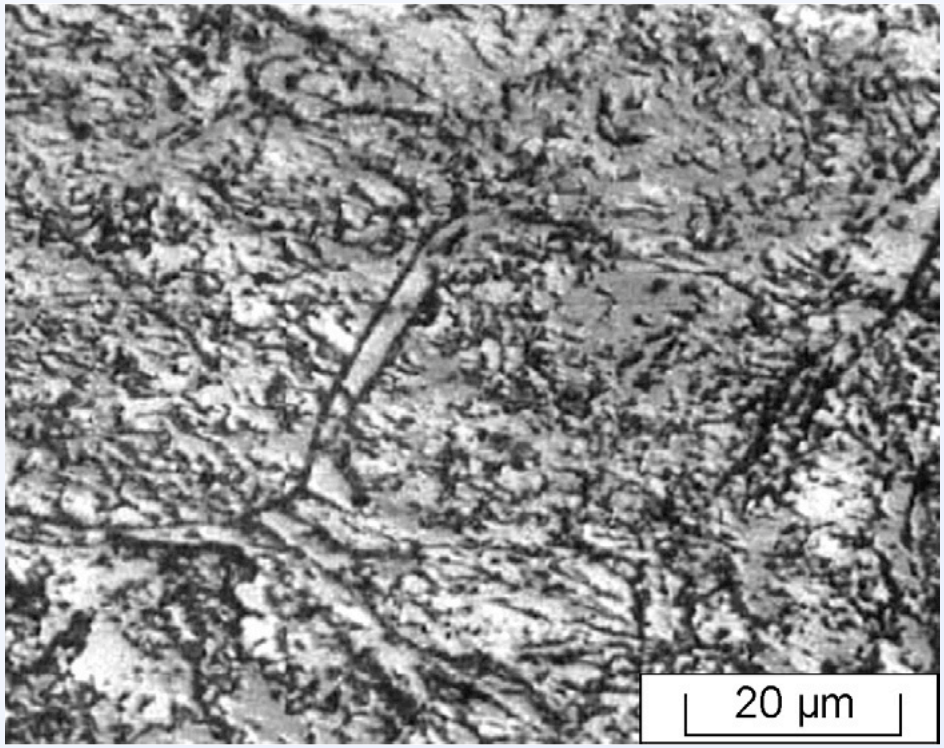
Zukas *et al.* (1981) report Pu - 2 at.% Al alloys transform through the sequence δ → β′ → α′



Faure *et al.* MRS Proceedings (2006)

Upon cooling, Harbur reported that a 0.68 at.% Ga alloy has a density intermediate between δ and α phases

Harbur, JALCOM (2007)



After compressing to 1 GPa

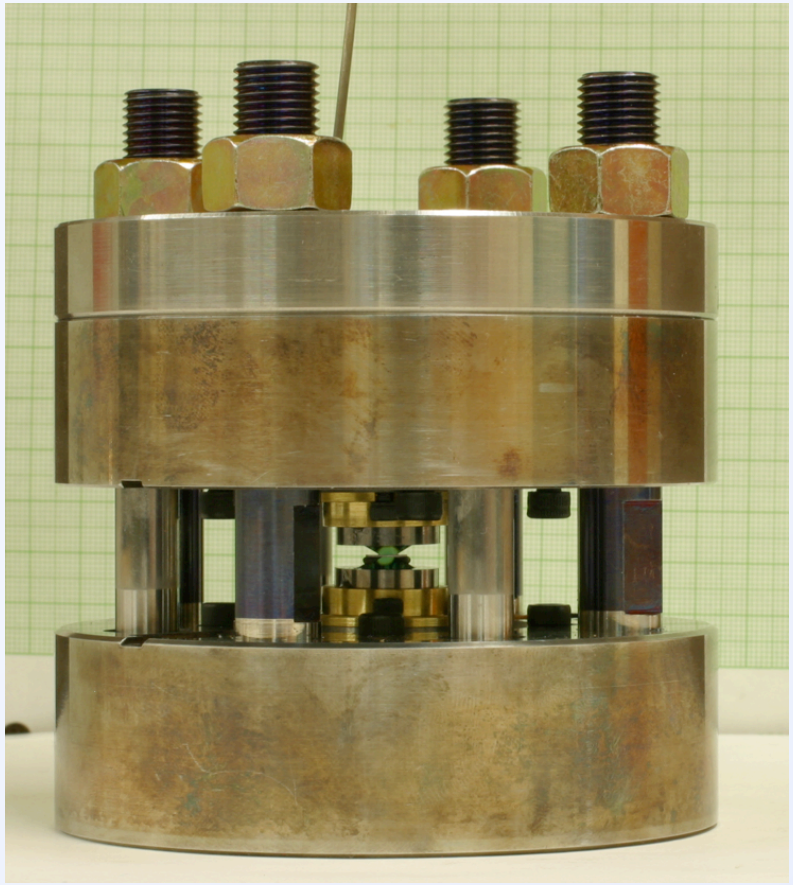
Alloy	% α′	% δ	% amorphous
1.0 at.% Ga	87	0	13
1.7 at.% Ga	66	0	34
2.5 at.% Ga	68	12	20

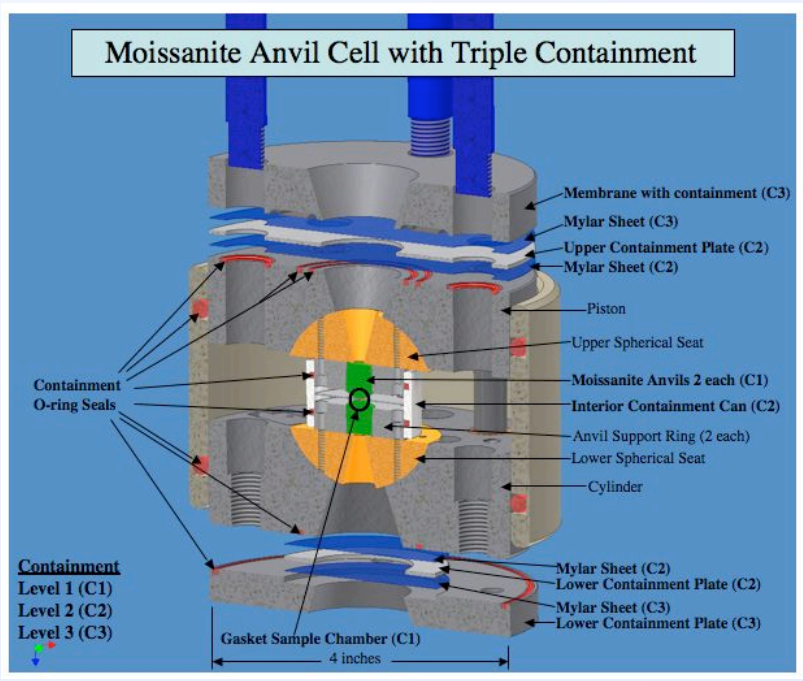
Harbur, JALCOM (2007)

Harbur proposes that the δ phase transforms to α′ + amorphous phase

- **on cooling low solute alloys**
- **under pressure**

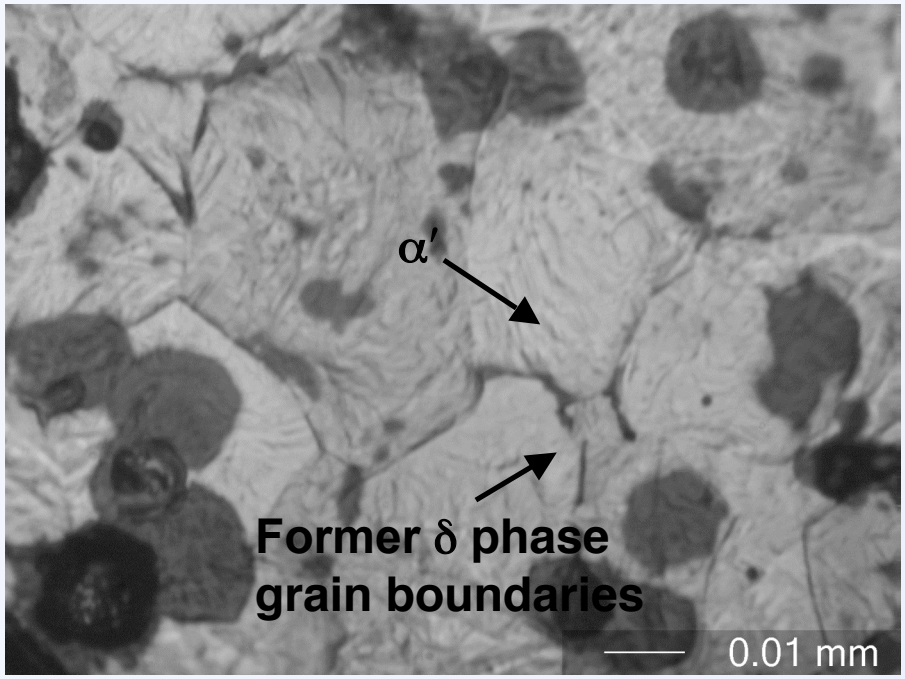
We are coupling low pressure recovery experiments with TEM to elucidate the mechanism and morphology

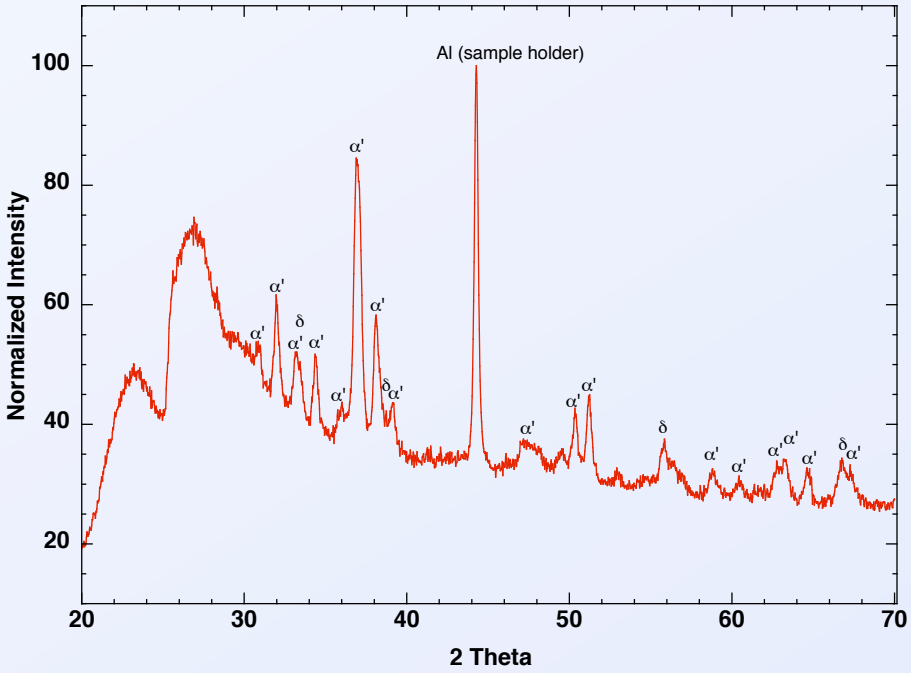




2.3 mm diameter specimens are slowly compressed to 1 GPa in the large volume moissanite anvil cell

Optical microscopy and x-ray diffraction of the compressed specimen reveals α′ and δ phases

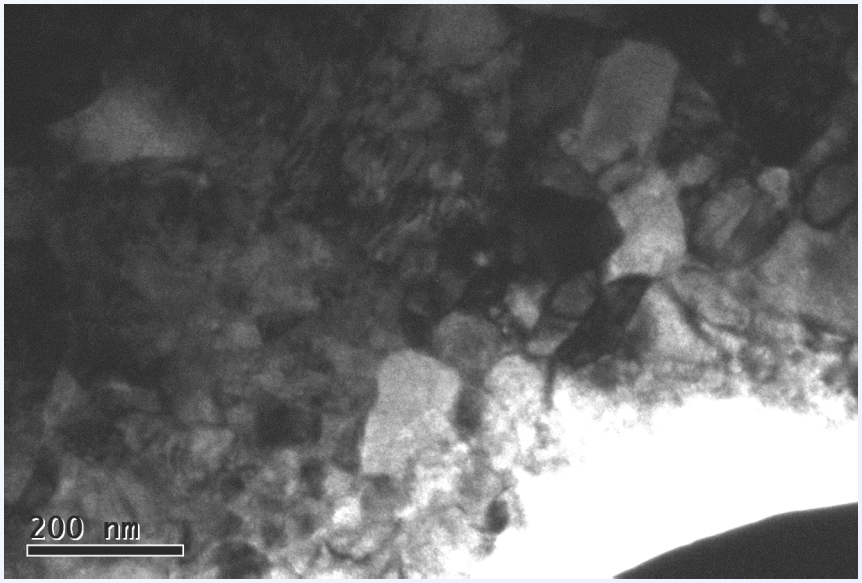


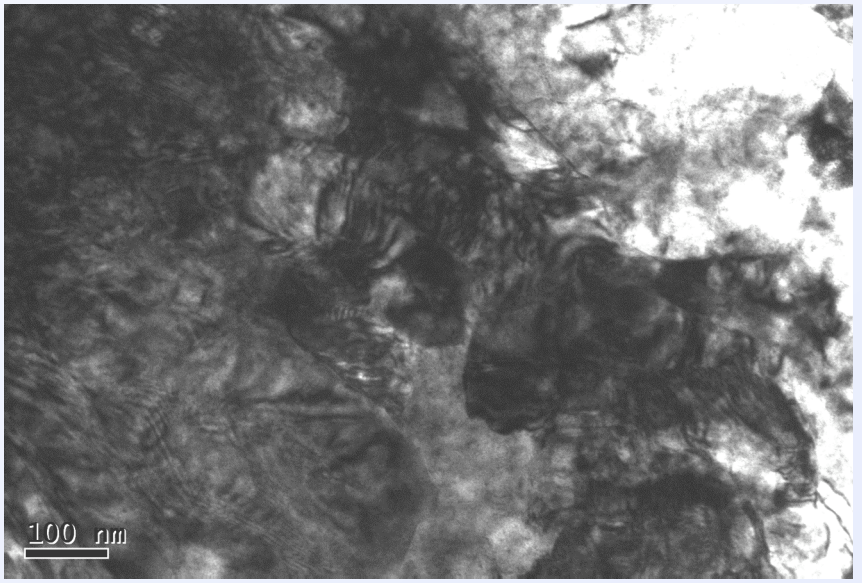


Optical microscopy does not have the resolution to differentiate between phases

X-ray diffraction experiments and simulations do not indicate the presence of an amorphous phase

The pressure-induced microstructure does not exhibit typical martensitic features





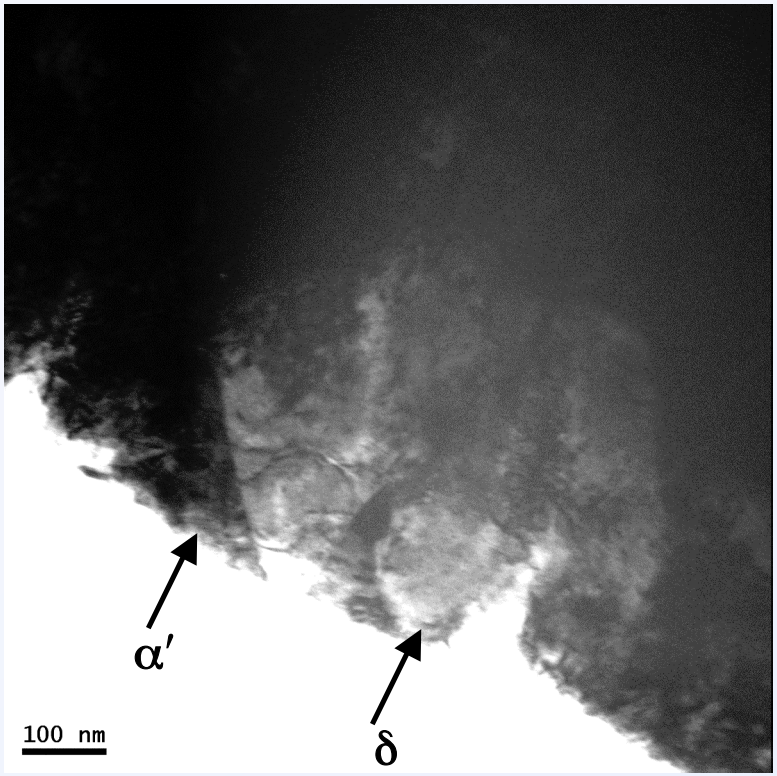
Pressure-induced δ → α′ transformation

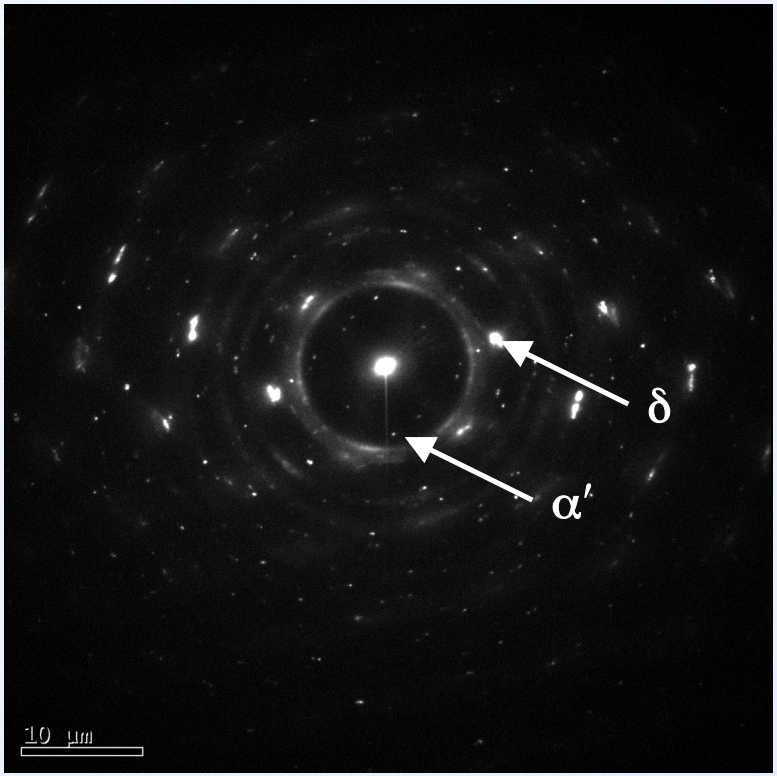
- **Average α′ grain size ~ 100s nm, 10 – 20% δ**
- **Implies nucleation-dominated mechanism**

Low-temperature-induced δ → α′ isothermal martensitic transformation

- **Average α′ particle size ~ 1000s x 10,000s nm**
- **Implies nucleation-limited mechanism (strain)**

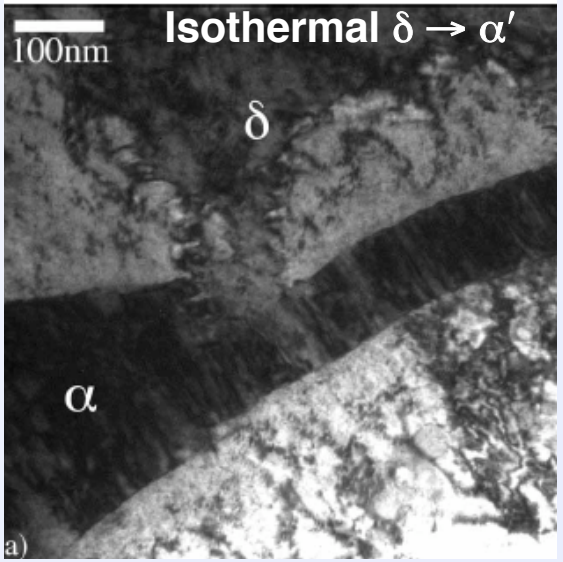
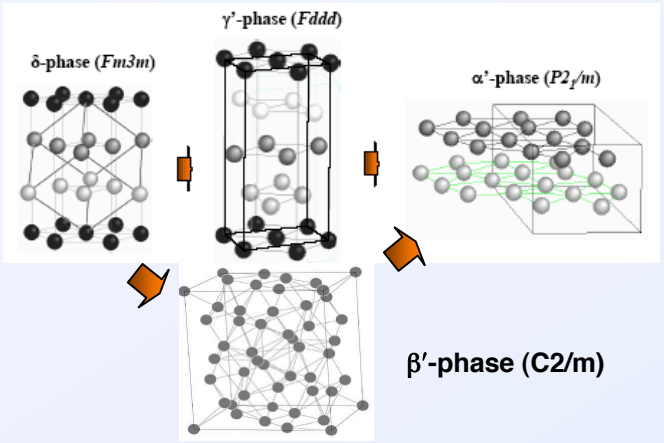
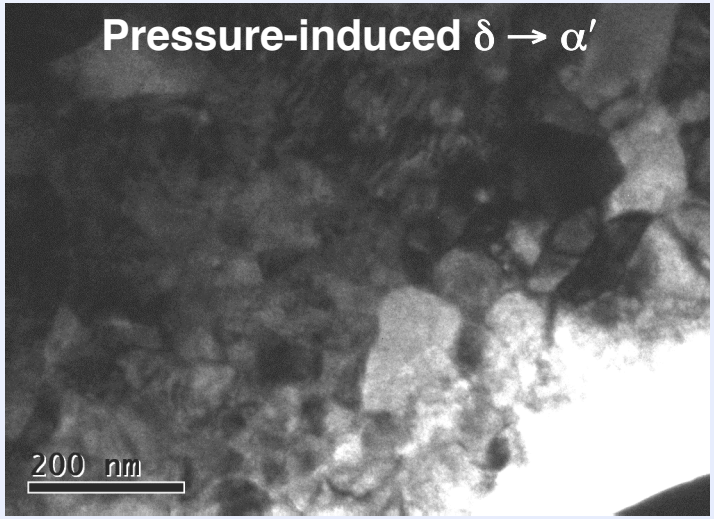
Preliminary TEM reveals fine-grained α′ and small amounts of δ – no evidence of an amorphous phase





10 – 20% δ phase is observed dispersed between the α′ grains

- **High dislocation density**
- **No apparent orientation relationship (yet)**

The isothermal martensitic and pressure-induced microstructures differ significantly

- **Low temperature isothermal δ → α′ transformation**
  - Nucleation is limited
  - Lath-shaped particles form
  - Intermediate phases are possible
- **Pressure-induced δ → α′ transformation**
  - Nucleation dominates
  - Very fine grain size results
  - No evidence of the amorphous phase
  - Intermediate phases are likely