Strategies for Strengthening Metallic and Intermetallic Alloys at High temperatures

C. T. Liu[1], M. Takeyama[2], I. G. Wright[1]
M. P. Brady[1], and P. J. Maziasz[1]
[1]Oak Ridge National Laboratory
[2]Tokyo Institute of Technology, Japan

17th Annual Conference on Fossil Energy Materials
Baltimore, MD, April 22-24, 2003

DOE currently sponsors several major power generation initiatives that require HT materials

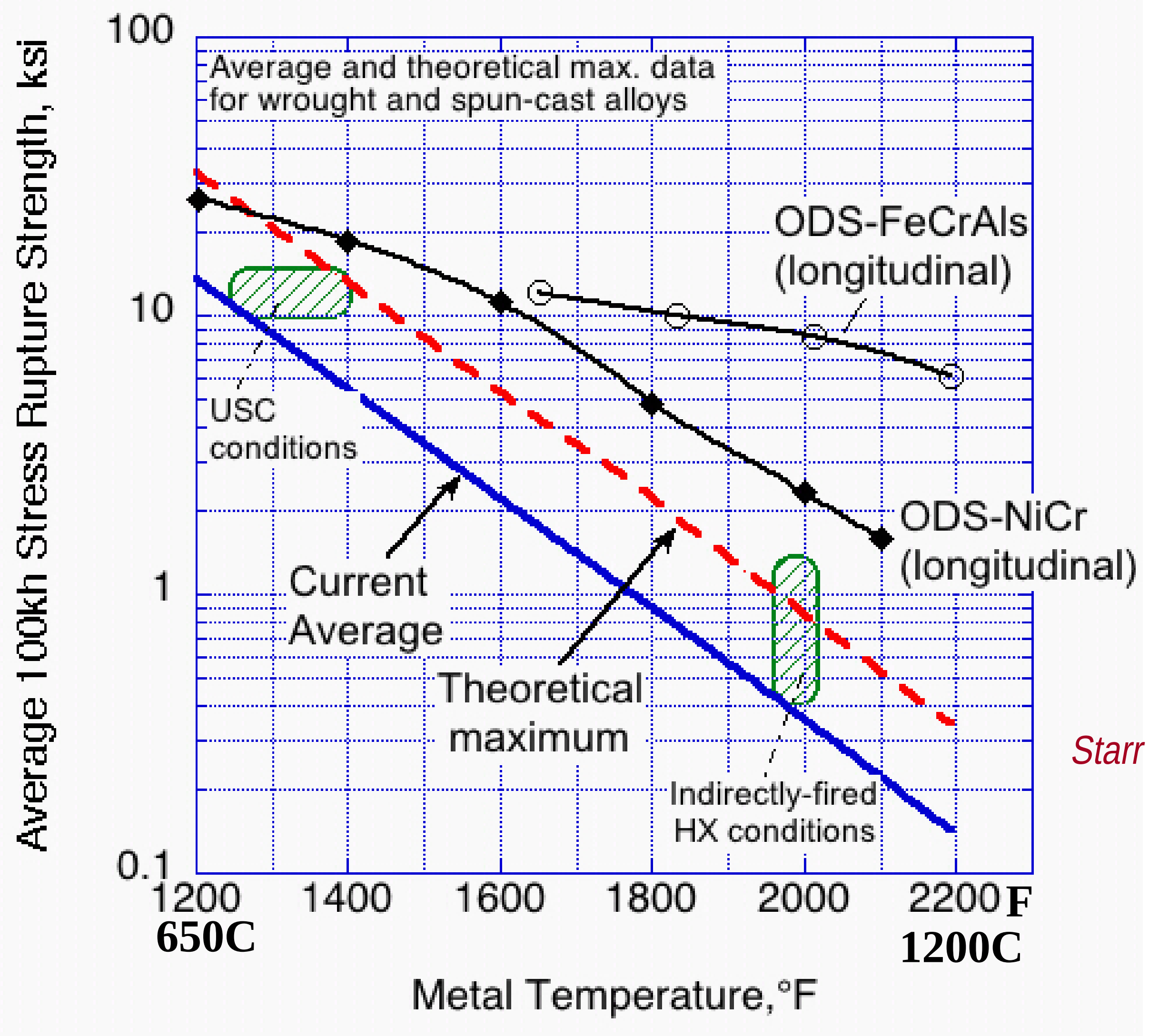
- **Power Generation Initiatives**
  - **Vision 21**
  - **Clean Coal Technologies**
  - **FutureGen**

- **Successes of these initiatives rely greatly on processing and development of materials with improved high temperature capabilities**

Temperature targets of next-generation structural materials imposed by DOE/ARM Programs

- **Ferritic steels (Fe-base): up to 750°C (~1400°F)**
- **Austenitic steels [(Fe,Ni) base): up to 850°C (1560°F)**
- **Multiphase alloy systems: >850°C**
  - **ODS alloys**
  - **High temperature intermetallic alloys**

Conventional, wrought alloys are marginal for next-generation applications



Starr & Tariq, 2002

Material development

- **The temperature requirements imposed by DOE/ARM programs are at the limits of the strength capabilities of current structural alloys**
- **It would be prudent from the outset to examine the possibilities for developing new materials with higher-temperature capabilities**
- **This paper summarizes the strategies used for strengthening metallic and intermetallic alloys at high temperatures**

Strategies used for strengthening metallic and intermetallic alloys at elevated temperatures

- **Solid solution hardening: large atomic size difference between solute and host atoms**
- **Particle strengthening : Dense precipitation of fine and stable particles**
- **Slow kinetic processes: high melting point, low vacancy concentration, low solubility limit**
- **Coarse grain structures**

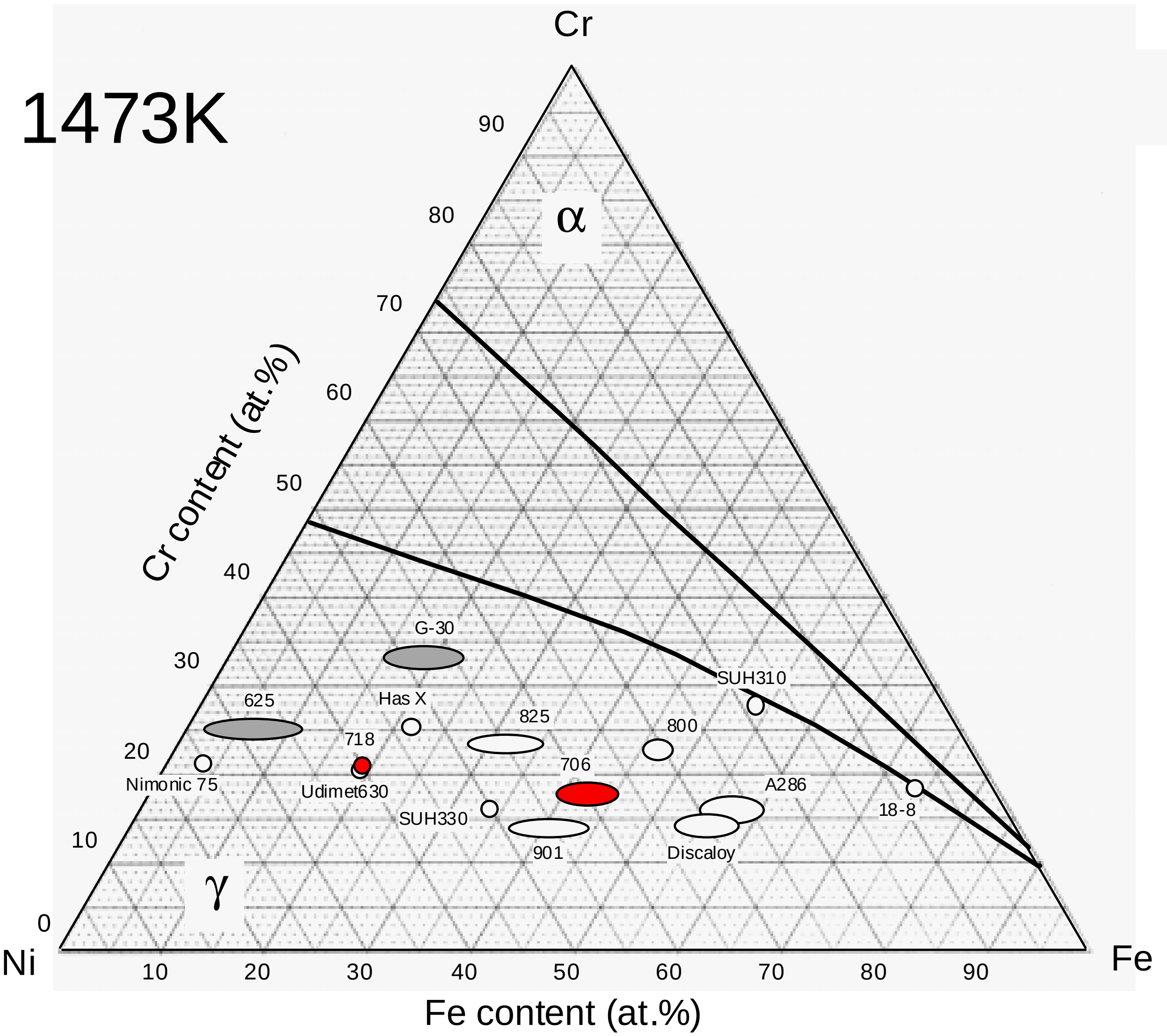
Strengthening of ferritic and austenitic steels

- **Solid solution hardening: Mo, W**
- **Particle strengthening**
  - **Carbide particles: complex MC carbides containing Nb, Ti & V elements**
  - **Intermetallic particles:**

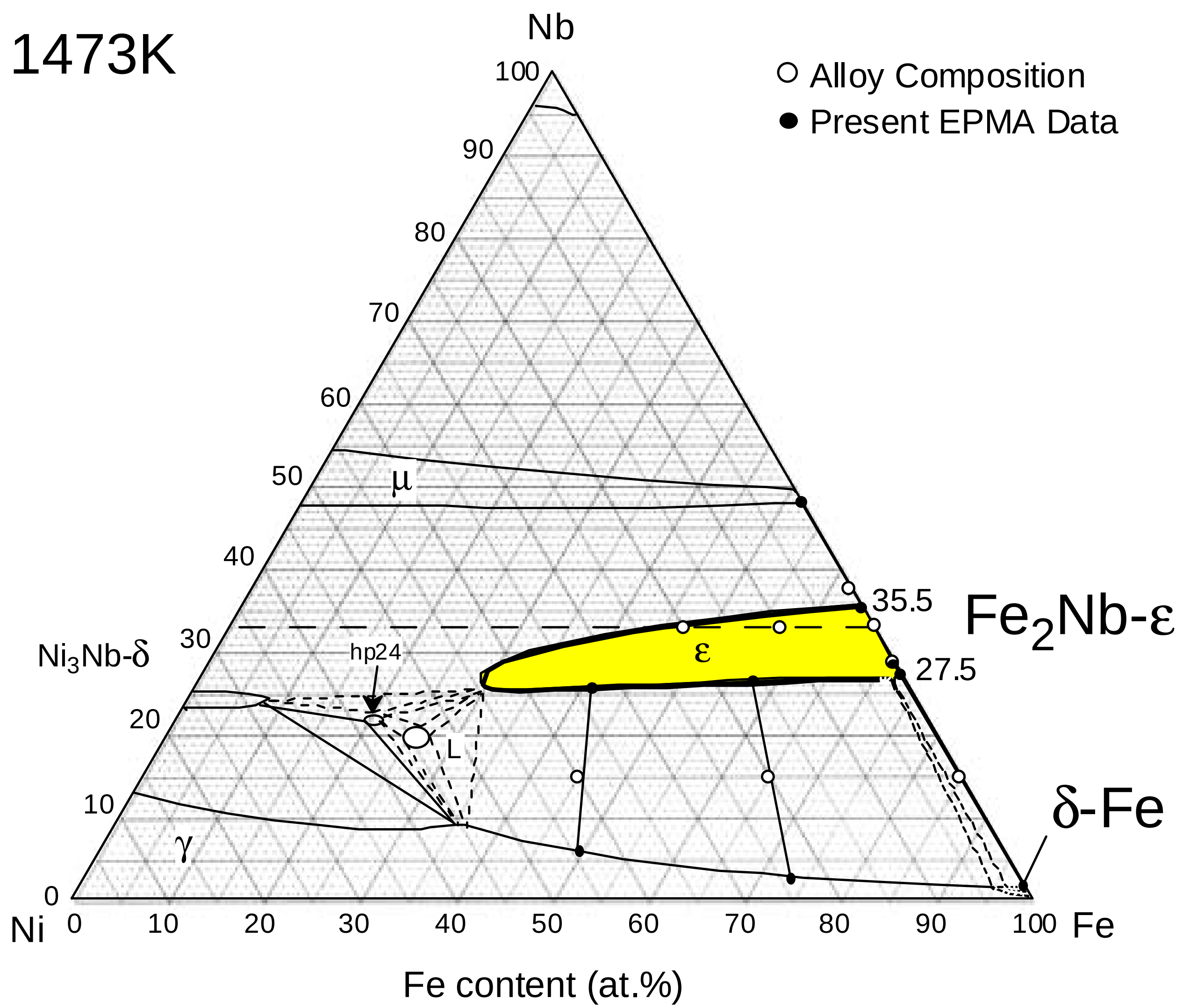
    AB_2 phases (C14, C15 & C36) in ferritic steels

    AB_3 phases (δ, γ' & γ'') in austenitic steels
- **Slow diffusion processes: slow precipitation and coarsening kinetics**

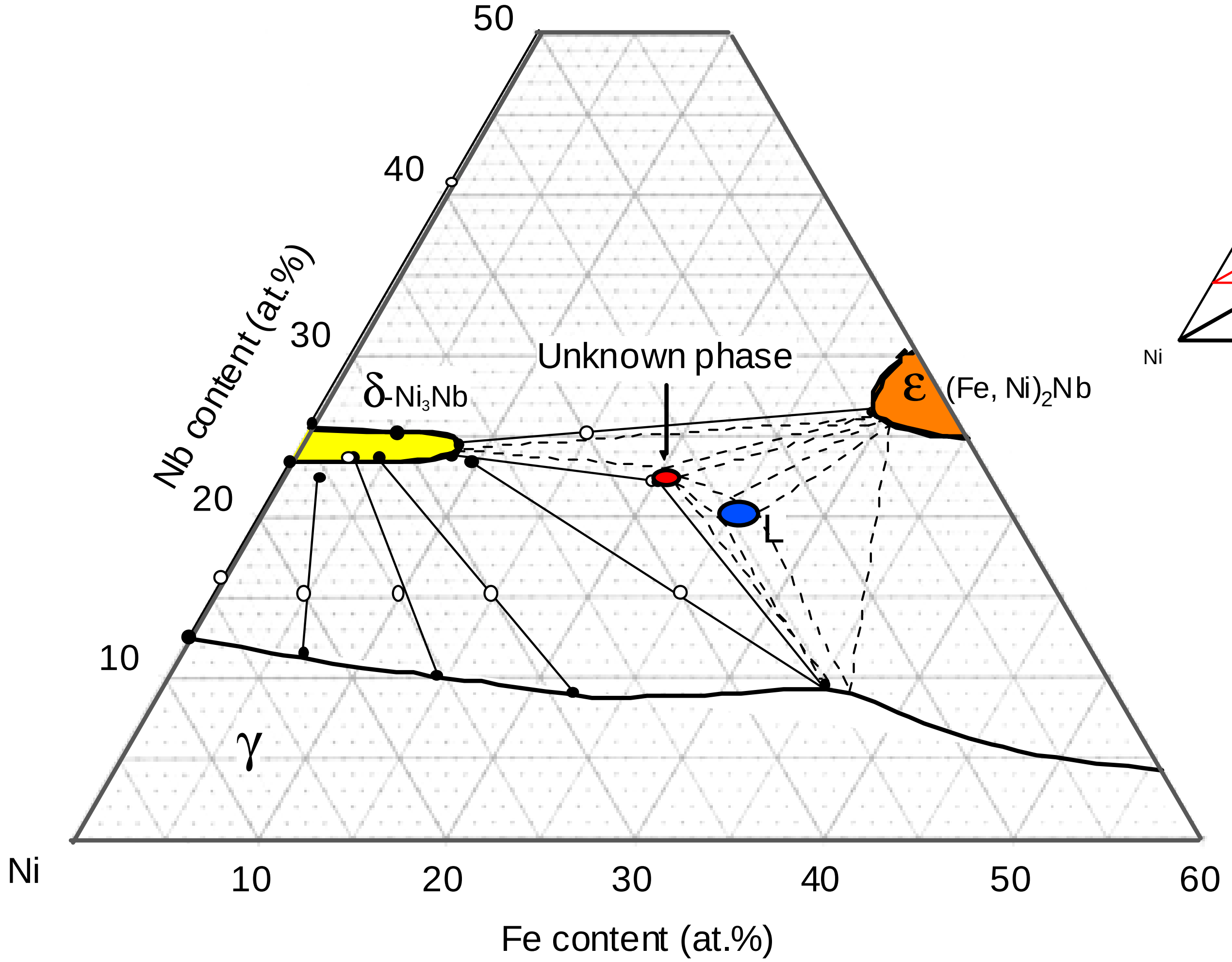
Many commercial alloys are based on the Cr-Ni-Fe alloy system

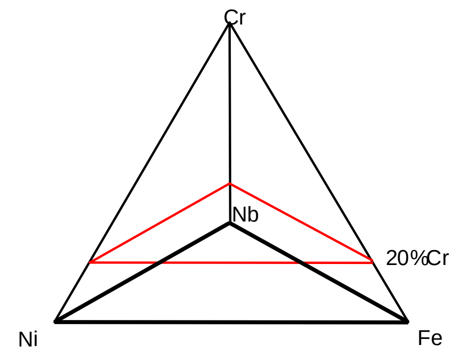


Newly published phase diagram of the Ni-Fe-Nb system at 1200°C (2190°F)

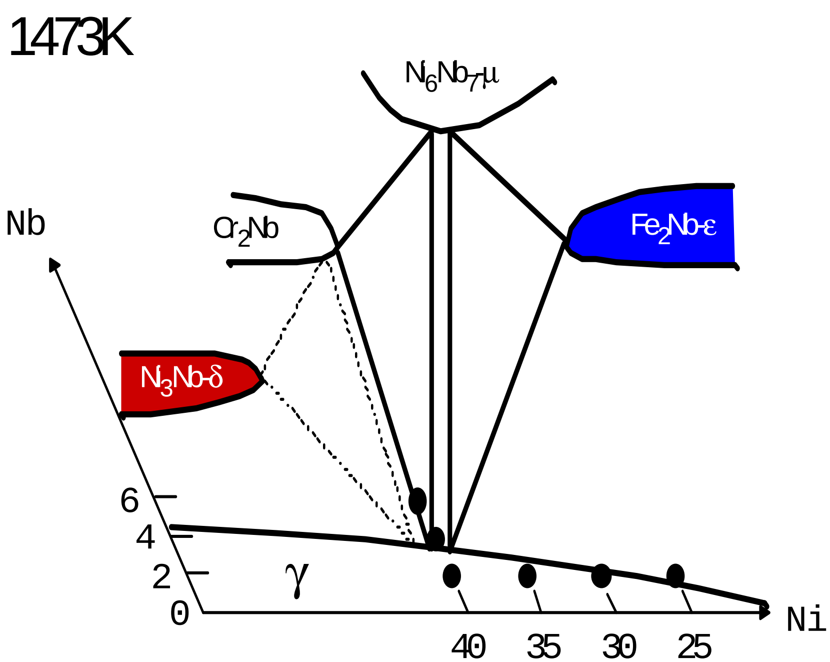


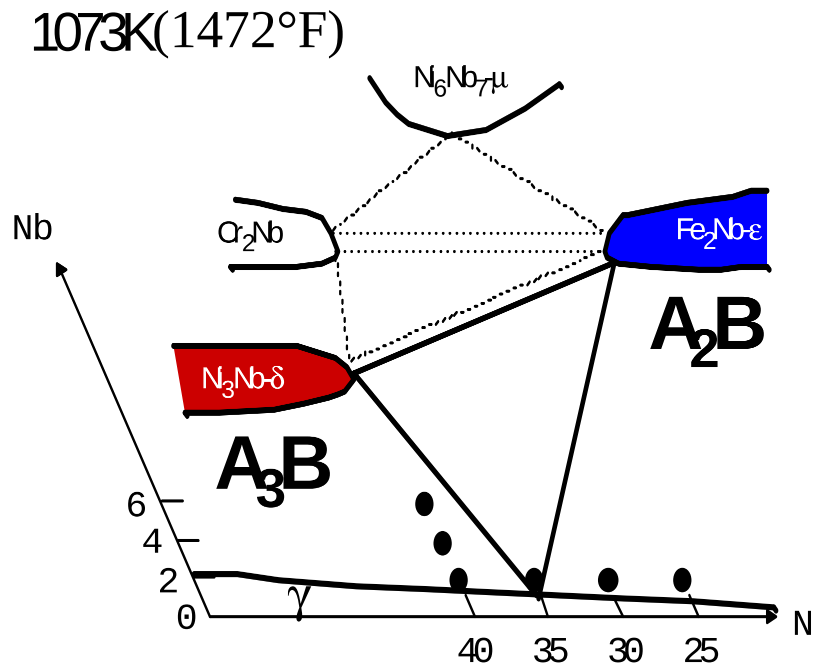
Isothermal section of Ni-rich Ni-Fe-NB system at 1200°C (2190°F)





Intermetallic phases in equilibrium with γ in Ni-Nb-Fe-20Cr system

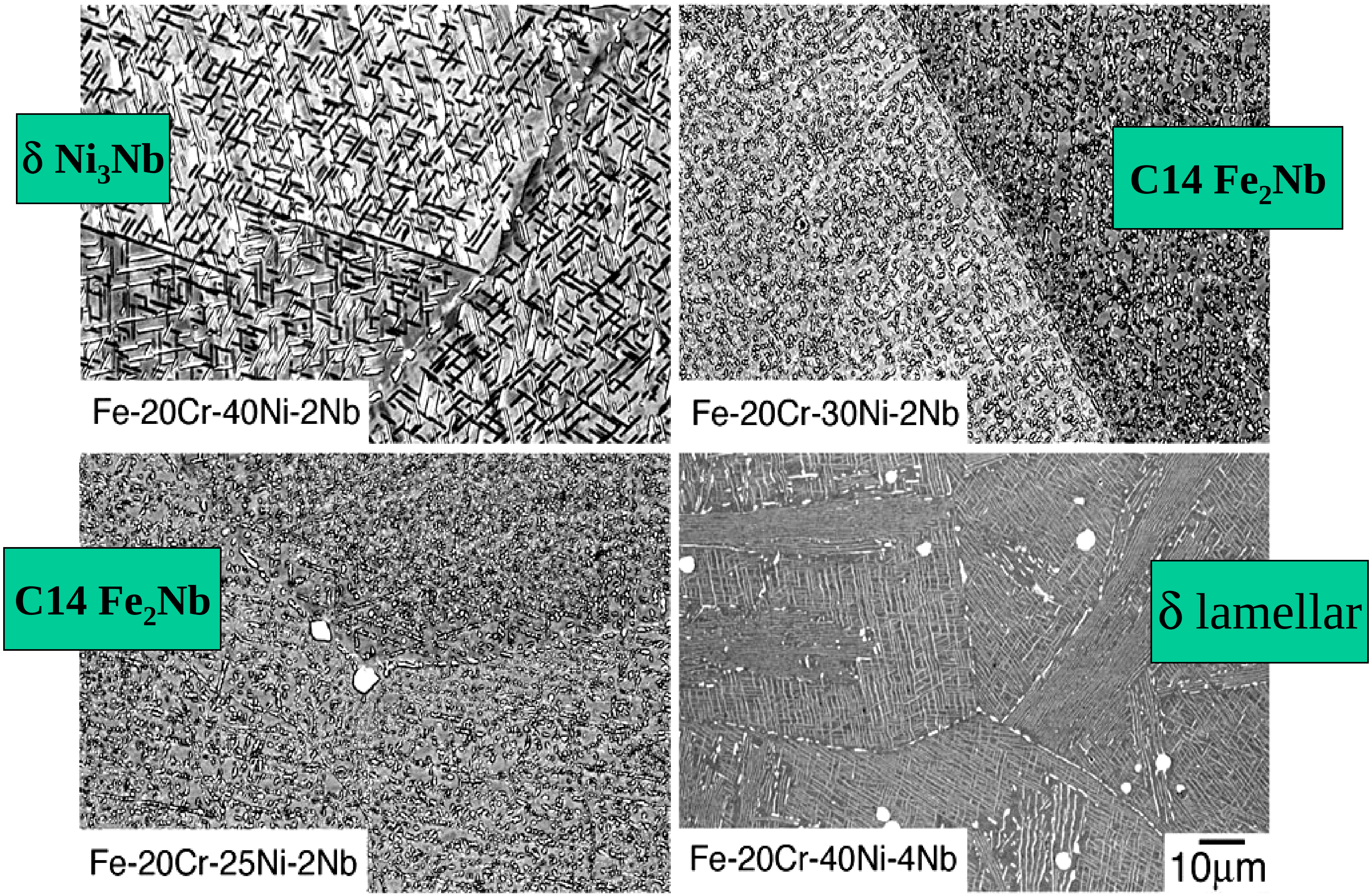




Two transition peritectiod reactions below are responsible for the phase equilibria change:

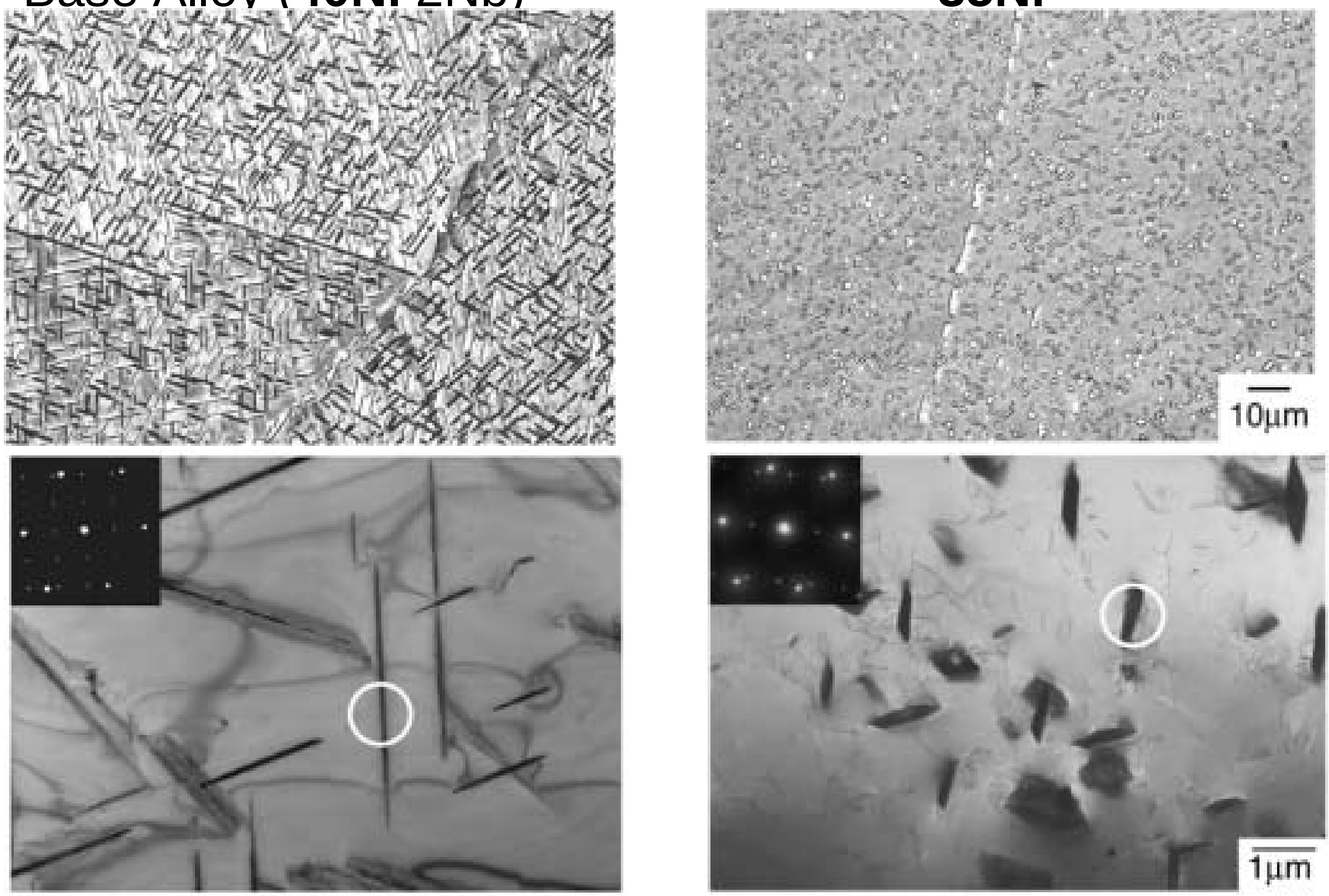
(1) $\gamma + \mu$ $\quad$ $Cr_2Nb + Fe_2Nb$ $\qquad$ (2) $\gamma + Cr_2Nb$ $\quad$ $Ni_3Nb + Fe_2Nb$

The Ni content strongly affects the morphology & alloy phase in the Fe-20Cr-Ni-Nb system at 800°C (1472°F)



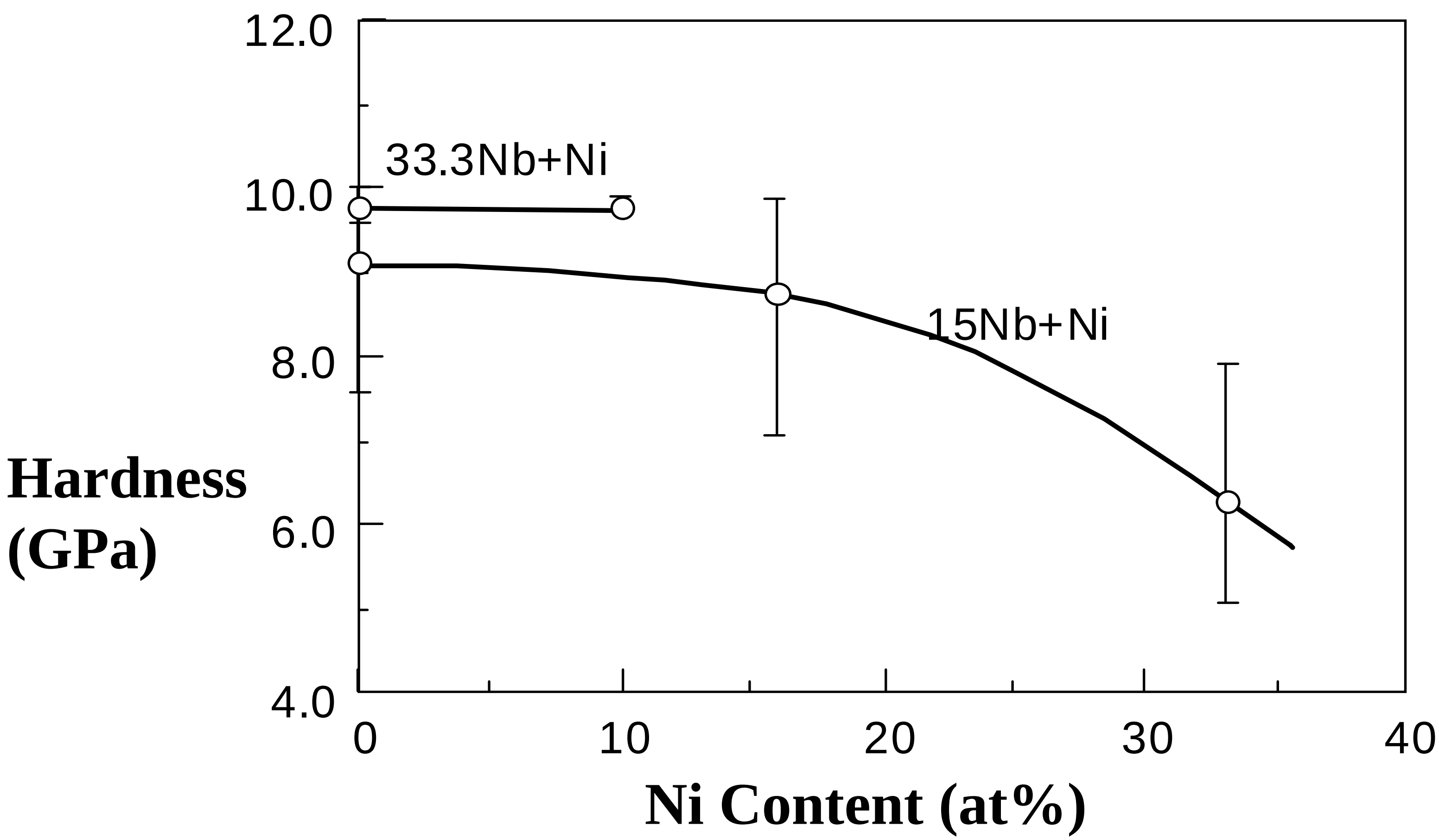
The Ni content strongly affects the microstructure & phases in Fe-20Cr-Ni-2Nb at 800°C (1470°F)

Base Alloy (**40Ni** 2Nb) **35Ni**



Ni_3Nb-δ ⟶ Fe_2Nb-ε (C14)

The Ni content affects the hardness of Laves phase



•The hardness decrease is due to the lowering of the amount of C14 precipitates in γ phase

Intermetallic-phase hardening: Summary

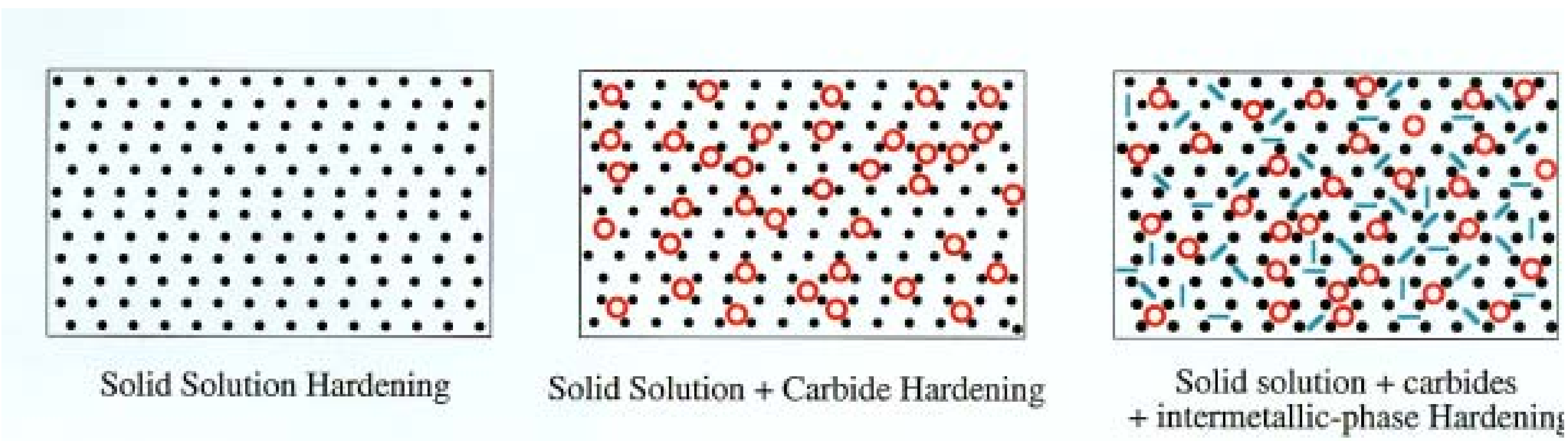
- **Three stable two-phase fields exist in the Fe-Ni-Nb and Fe-Ni-Cr-Nb alloy systems**

  γ-Ni_3Nb γ- Fe_2Nb α- Fe_2Nb

- **The Ni content strongly affects the amount and morphology of intermetallic-phase precipitates**
- **Microstructural features greatly affect the hardening behavior of the two-phase alloys**
- **It is possible to develop new ferritic and austenitic with improved high temperature capabilities by precipitation of intermetallic phases**

A sketch to show the strategies for strengthening ferritic and austenitic alloys

Solid solution + Carbides + Intermetallic-phase



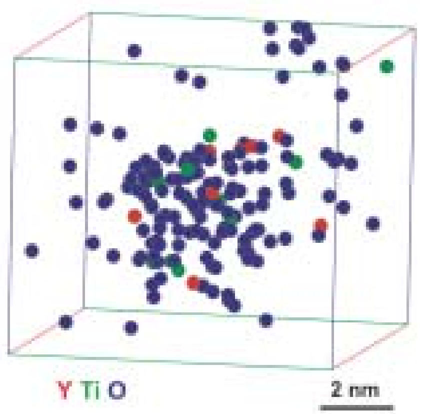
Innovative Approach:
Strengthening of ferritic steels by nanoclusters at elevated temperatures

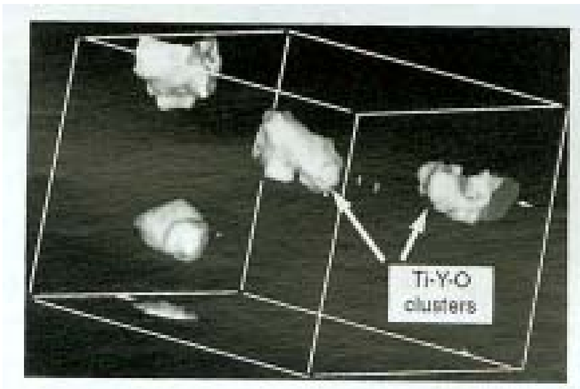
- Recent studies at ORNL show that nanoclusters (2-5 nm) are formed in Fe-12Cr-3W-0.4Ti-0.25Y_2O_3 alloy (12YWT) processed by mechanical alloying (MA)
- Surprisingly, these nanoclusters are stable even at 1300°C (2370°F)(=0.87 T_m)
- These clusters effectively strengthen the alloys at room and elevated temperatures
- Creep tests show that the clusters reduce the creep rates at 650-900°C by six orders of magnitude

These nanoclusters are extremely stable at high temperatures

- Atom probe analyses indicate that the nanoclusters are enriched with O, Ti and Y in 12YWT alloy (Fe-12Cr-3W-0.4Ti-0.25Y_2O_3)

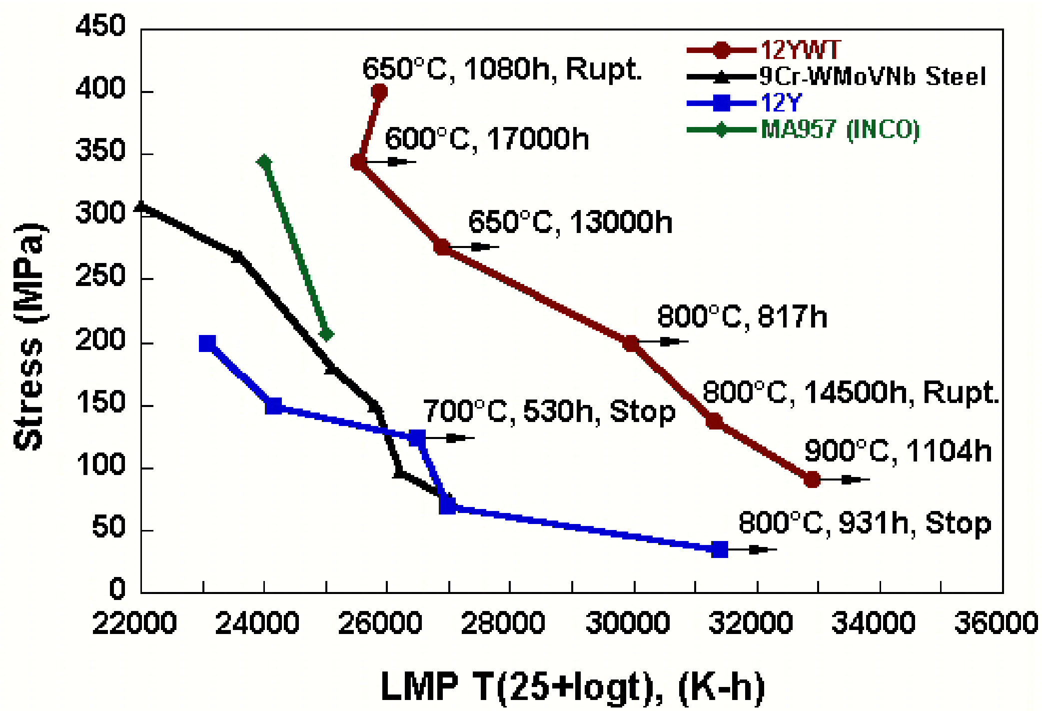
  O = 24%, Ti = 20%, Y = 9% (at. %)



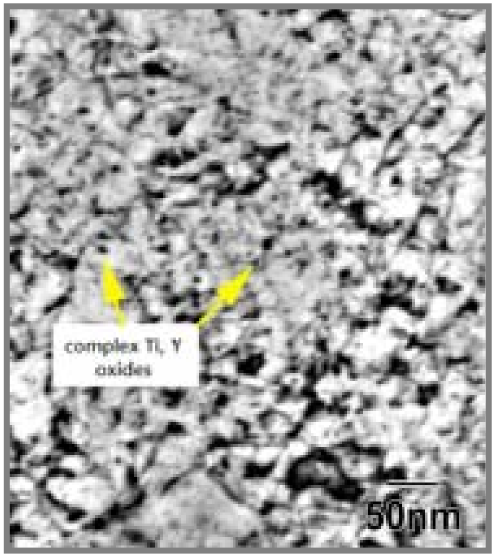


- Cluster density: $10^{24}/m^3$
- No appreciable coarsening after creep testing for 14,000 h at 800°C or annealing for 10 h/1300°C

The nanoclusters dramatically improve the creep resistance of the MA ferritic alloy



12YWT

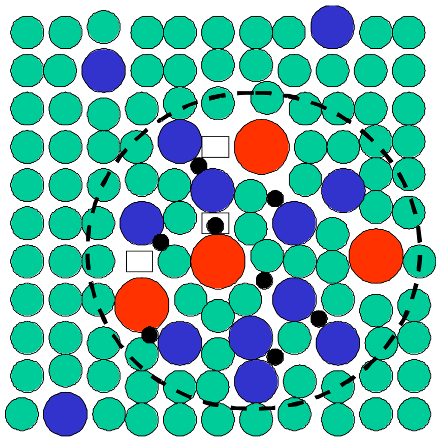


- **Comparison of the creep rupture properties of 12YWT ferritic alloy with other commercial ferritic alloys**

Future studies of nanoclusters in ferritic steels

- **Atomic arrangement**
- **Interfacial structure**
- **Formation mechanism**
- **Unusual thermal stability**
- **Innovative processing**

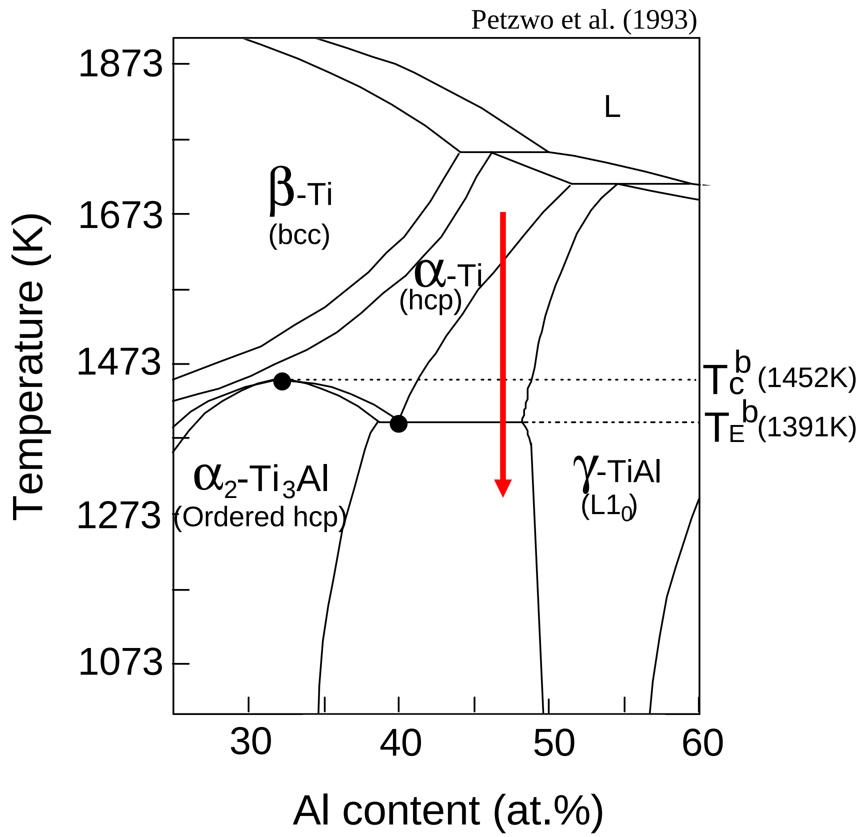
  (other than mechanical alloying)

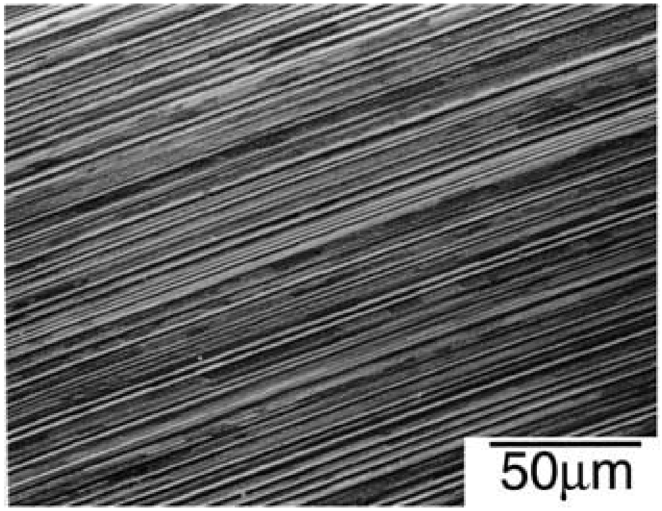


Multiphase Intermetallic Alloys for High Temperature Use:

Titanium aluminide alloys

In situ lamellar structures can be readily produced in titanium aluminide alloys

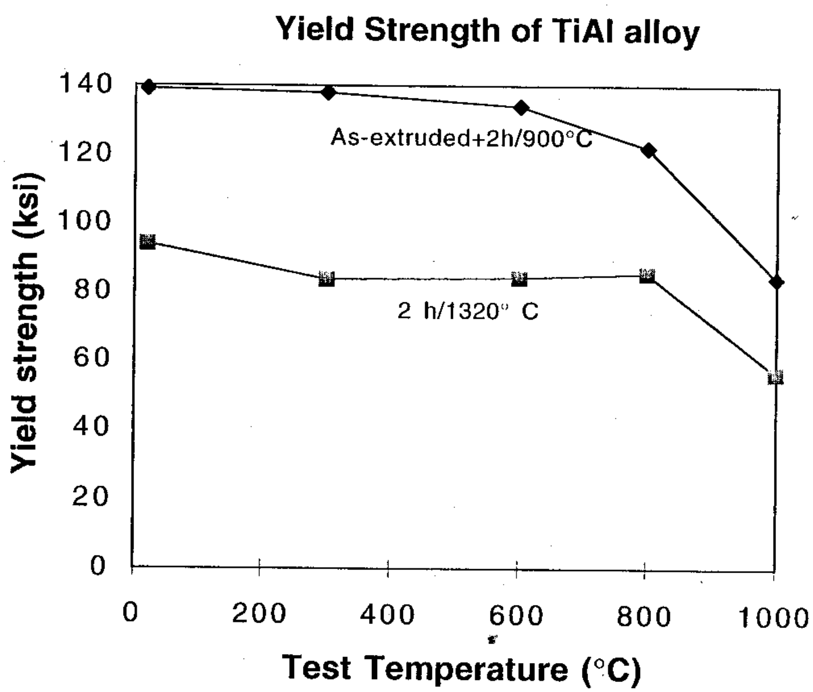


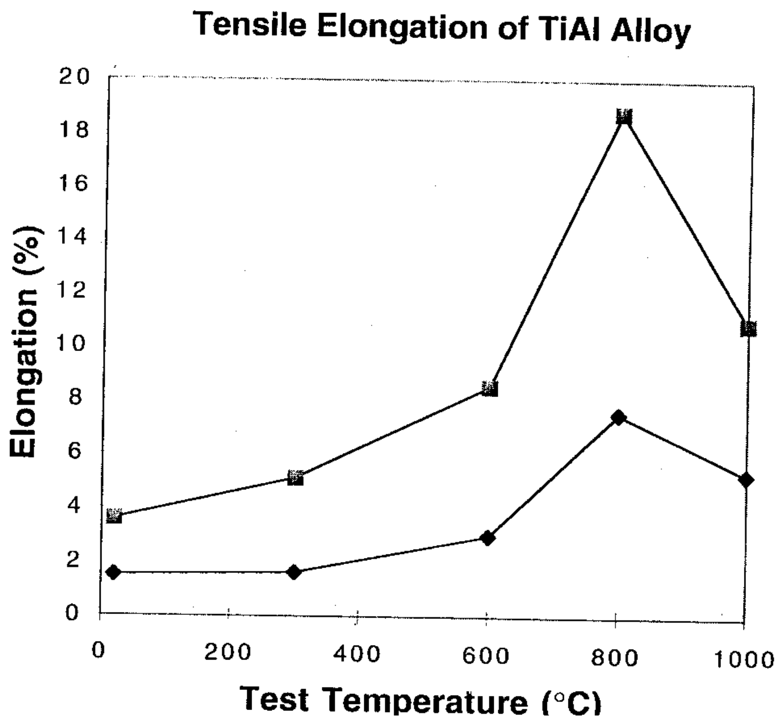


Fine lamellar structure

- **Microstructure Control Using α to γ Phase Transformation**

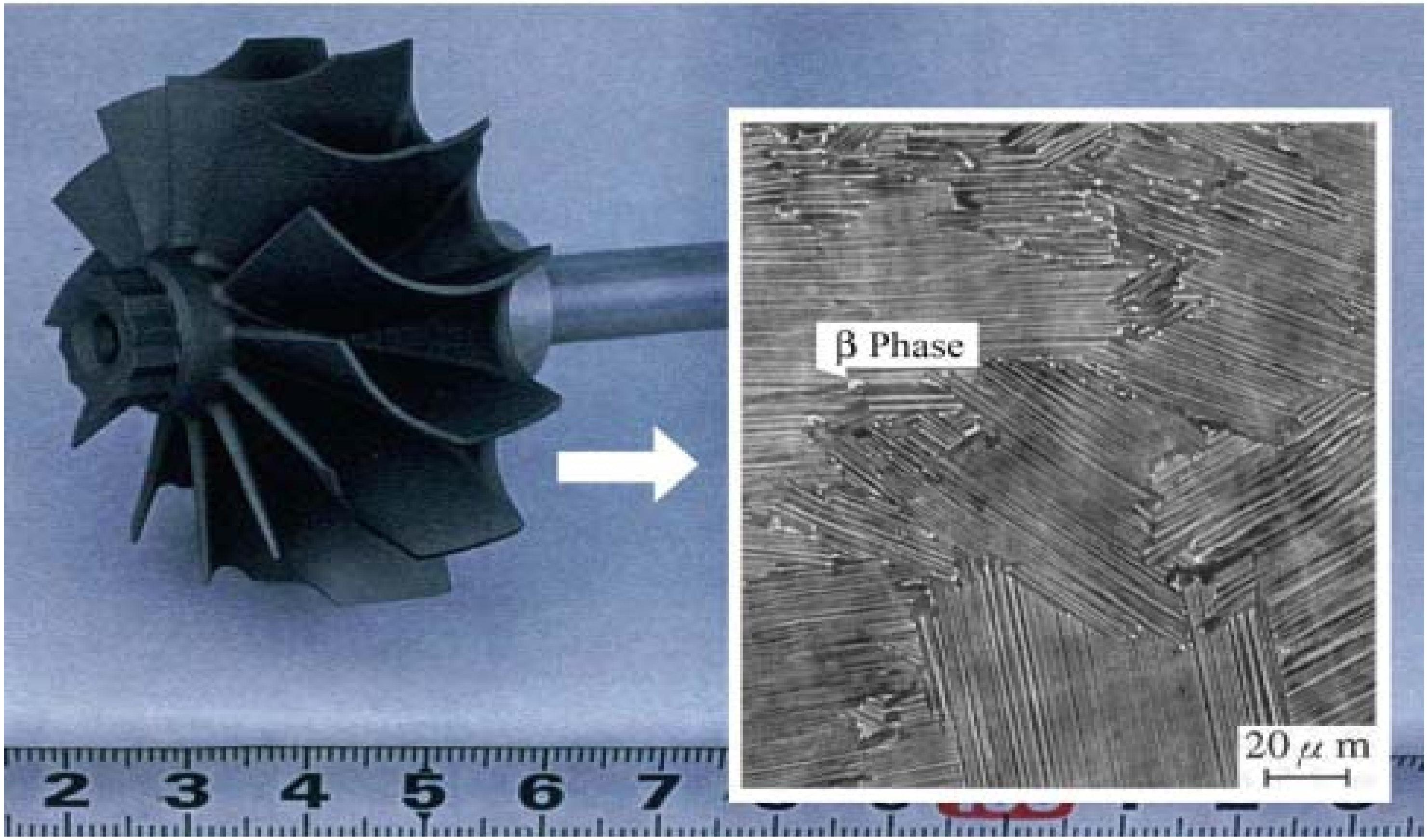
Titanium aluminide alloys with fine lamellar structures show excellent mechanical properties





- **Both yield strength and tensile elongation can be controlled by adjusting lemellar spacing and grain size via heat treatment**

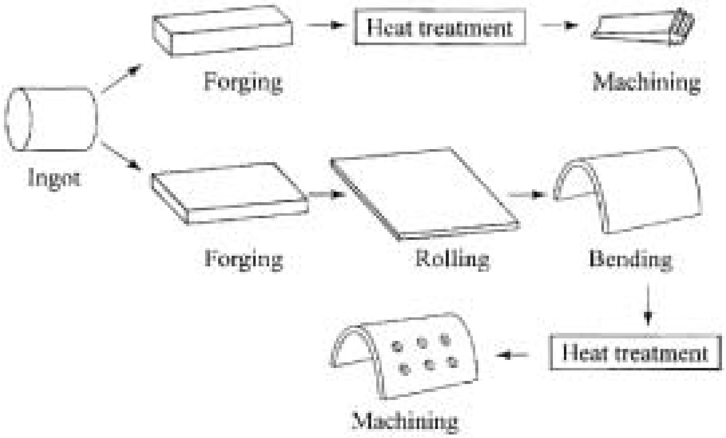
Cast turbocharger rotor made from a Titanium aluminide alloy in Japan



Ti-46Al-7Nb-1Cr

Manufacturing processes for wrought TiAl alloy turbine blade

LP Turbine Blade



- Tesui and Takeyama et al., Scripta Materialia 47 (2002) 399