Strategies for Strengthening Metallic and Intermetallic Alloys at High temperatures

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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.
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:
    - $\text{AB}_2$ phases (C14, C15 & C36) in ferritic steels
    - $\text{AB}_3$ phases ($\delta$, $\gamma'$ & $\gamma''$) 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 $\gamma$ in Ni-Nb-Fe-20Cr system

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

1. $\gamma + \mu \rightarrow \text{Cr}_2\text{Nb} + \text{Fe}_2\text{Nb}$
2. $\gamma + \text{Cr}_2\text{Nb} \rightarrow \text{Ni}_3\text{Nb} + \text{Fe}_2\text{Nb}$
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) → Ni$_3$Nb-$\delta$ → Fe$_2$Nb-$\varepsilon$ (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 $\gamma$ phase
Intermetallic-phase hardening: Summary

- Three stable two-phase fields exist in the Fe-Ni-Nb and Fe-Ni-Cr-Nb alloy systems
  \[ \gamma\text{-Ni}_3\text{Nb} \quad \gamma\text{-Fe}_2\text{Nb} \quad \alpha\text{-Fe}_2\text{Nb} \]
- 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

Solid Solution Hardening

Solid Solution + Carbide Hardening

Solid solution + carbides + intermetallic-phase Hardening
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-0.25Y₂O₃ alloy (12YWT) processed by mechanical alloying (MA).
- Surprisingly, these nanoclusters are stable even at 1300°C (2370°F)(=0.87 Tₘ)
- 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$_2$O$_3$)
  
  $O = 24\%$, $Ti = 20\%$, $Y = 9\%$ (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.

- 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

- **Microstructure Control Using** $\alpha$ to $\gamma$ **Phase Transformation**
Titanium aluminide alloys with fine lamellar structures show excellent mechanical properties

- Both yield strength and tensile elongation can be controlled by adjusting lamellar 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