# Status and Potential of Refractory Alloys for Ultrahigh Temperature Applications

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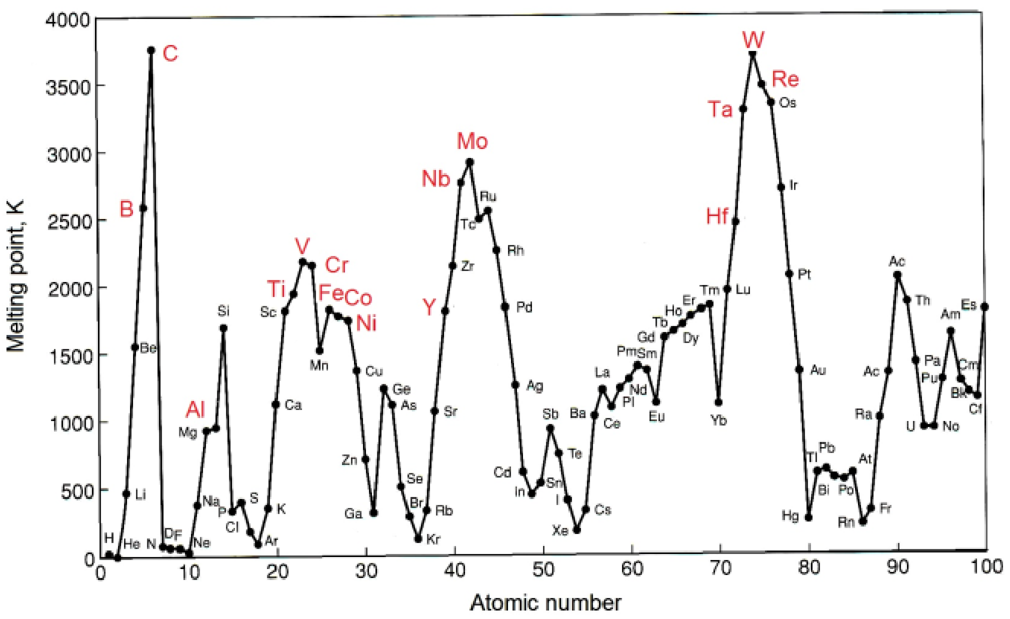
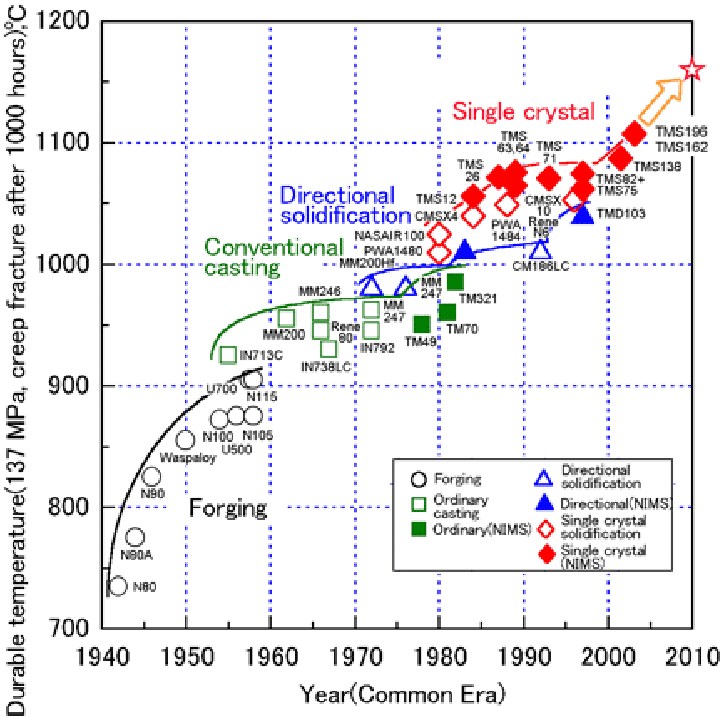
**APRA-E: Ultrahigh Temperature Materials for Energy Applications**
**Nov. 21-22, Seattle, WA**

# High Temperature Metals

## What do we have?




## Ni-base Superalloys in Jet Engines




- Superalloys limit temperature: 1300-1350C
- Refractory metals have higher temperature capabilities

# Refractory Metal Alloys

| Group | IVA | VA | VIA | VIIA | VIII |
|---|---|---|---|---|---|
| Element | Hf | Nb, Ta | Mo, W | Te, Re | Ru, Os, Rh, Ir |

- **Alloys for service temps beyond that of Ni- or Co-base superalloys**
- **$T_m$ > 1900C**

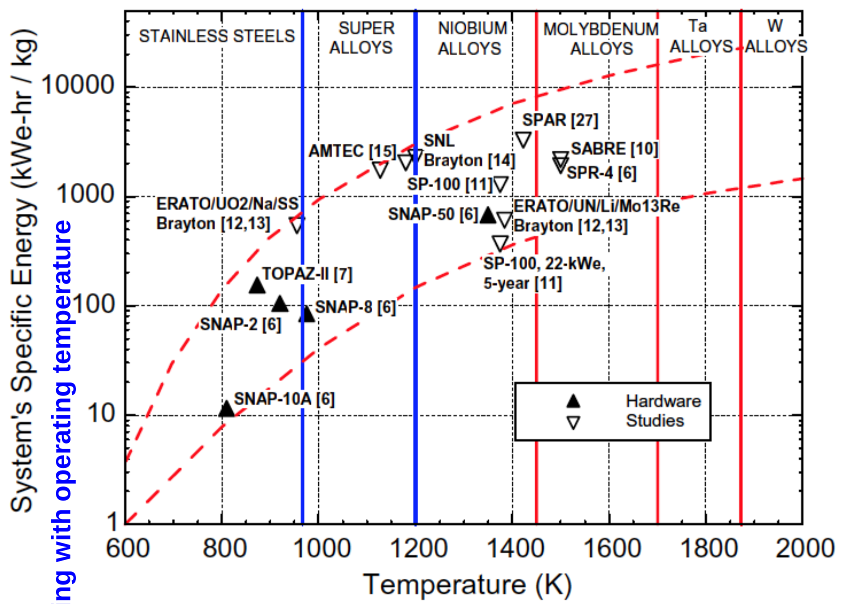
# Physical Properties of High Temperature Metals

| Physical properties | Unit | Refractory metals | | | | | Ni and Ni-based superalloy | |
|---|---|---|---|---|---|---|---|---|
| | | Nb | Ta | Mo | W | Re | Ni | MM-246** |
| Melting temperature | ℃ | 2468 | 2996 | 2610 | 3410 | 3180 | 1455 | 1315-1345 |
| Density [25℃] | $Mg/m^3$ | 8.56 | 16.65 | 10.22 | 19.3 | 21.4 | 8.90 | 8.44 |
| Coefficient of thermal expansion [R.T.] | $10^{-6}k^{-1}$ | 7.3 | 6.5 | 4.9 | 4.6 | 6.7 | 13.3(0-100℃) | 11.3(93℃) |
| Thermal conductivity [20℃] | W/m·k | 52.7 | 54.4 | 142 | 155 | 71 | 90.5 | 16.8(427℃) |
| Young's modulus [R.T.] | GPa | 103 | 185 | 324 | 400 | 469 | 204 | 205 |
| Ductile-brittle transition temperature | ℃ | -140 | -270 | 30 | 300 | - | - | - |

* Mainly from Rikagaku-Jiten(1998,Iwanami,Japan)
** INCO Catalog (High Strength Nickel Base Alloys (1977))

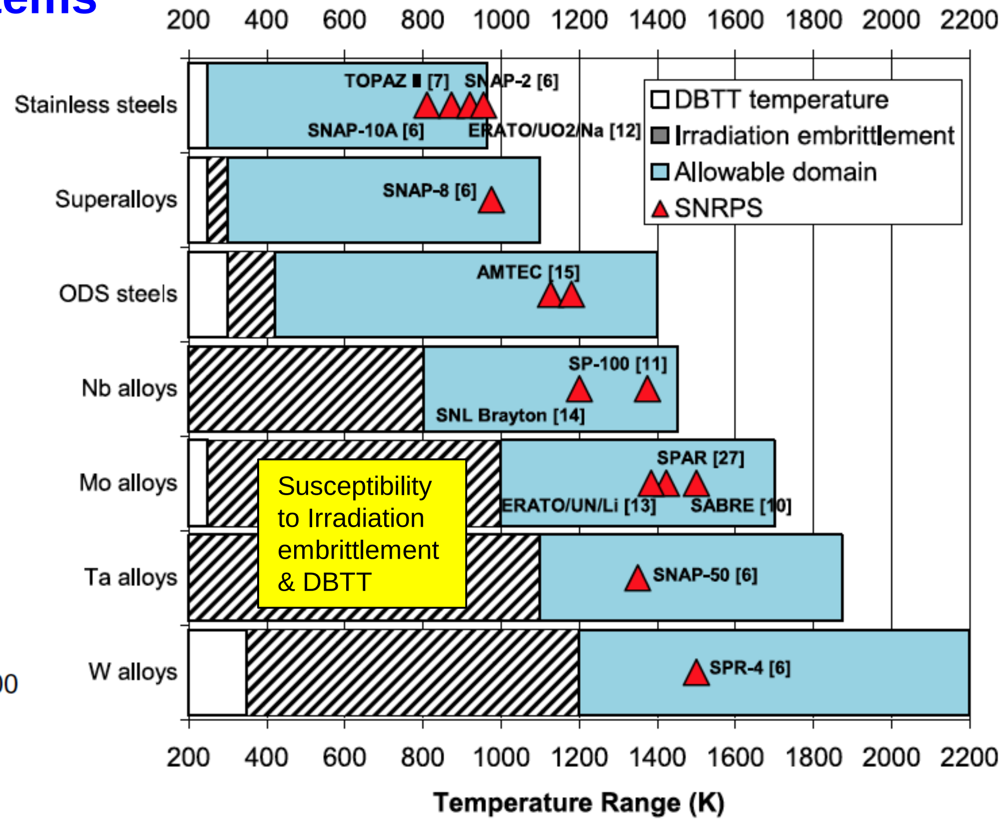
# Refractory Alloys from SNRPS Perspective

## Space nuclear reactor power systems



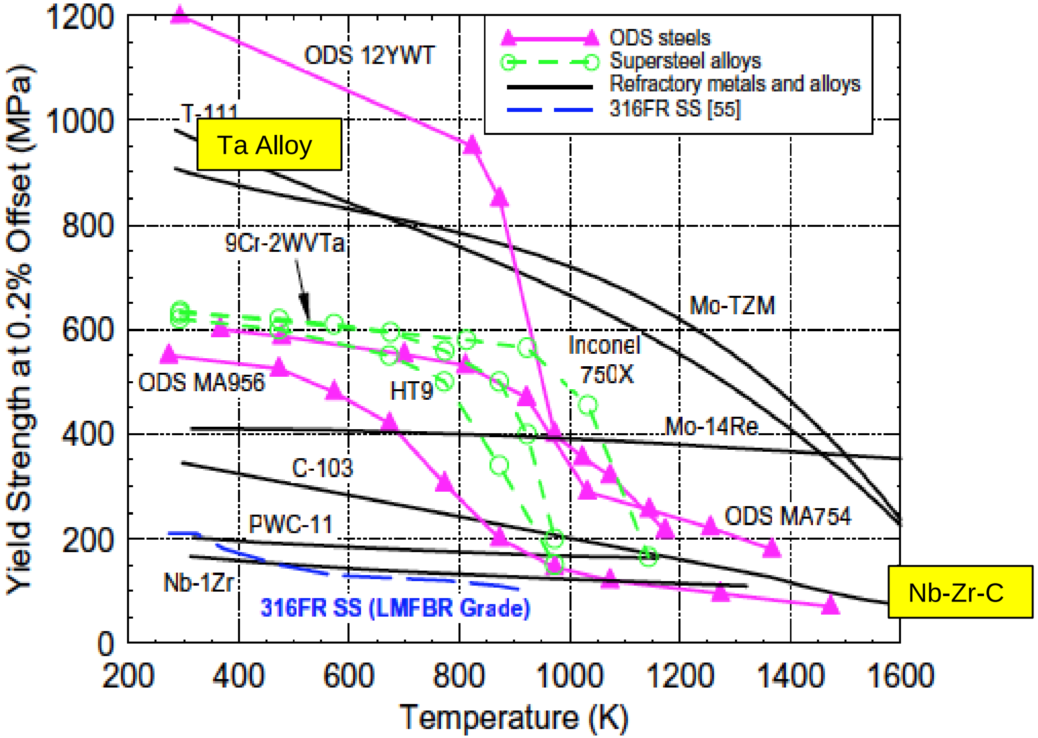

Scaling with operating temperature

Reactor outlet temperature



# Strength Capability of High Temperature Alloys

## Wrought alloys made in significant amounts

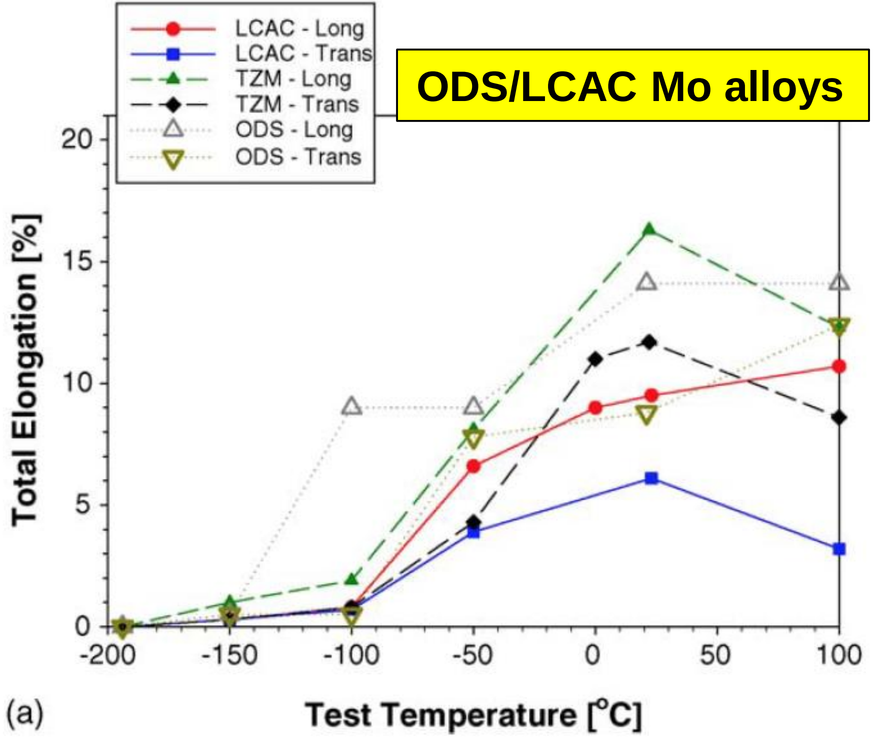


# Ductile-Brittle Transition Issues

- Ductile-to-brittle transition is a problem in some refractory alloys
- Interstitial effects on ductility is significant (Nb, Ta) exceptions

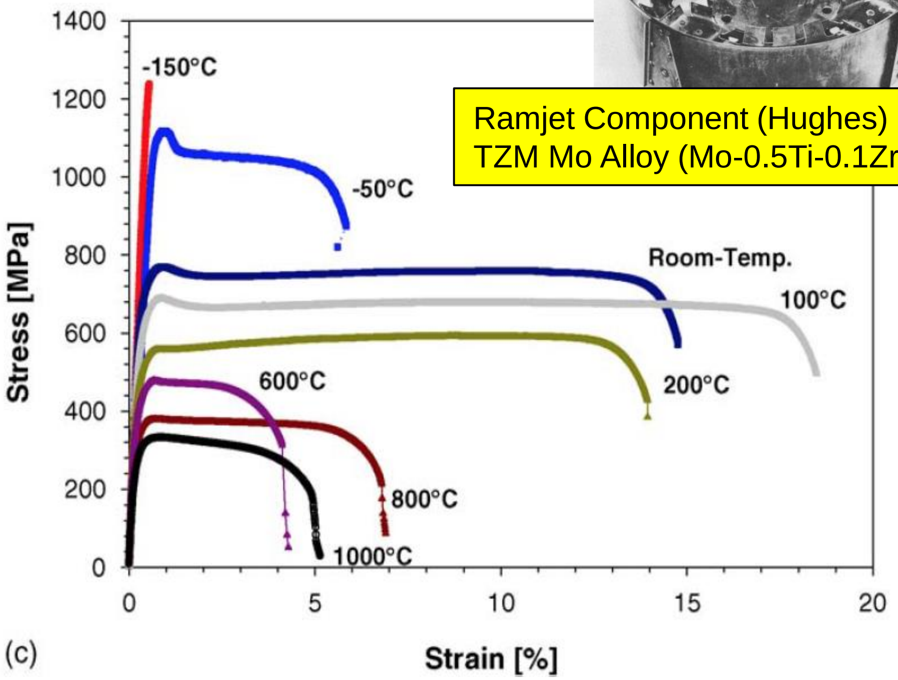
Fracture Toughness

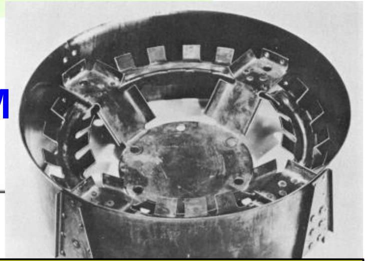
ODS/LCAC Mo alloys



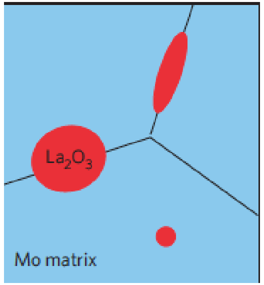
# ODS Molybdenum Alloys

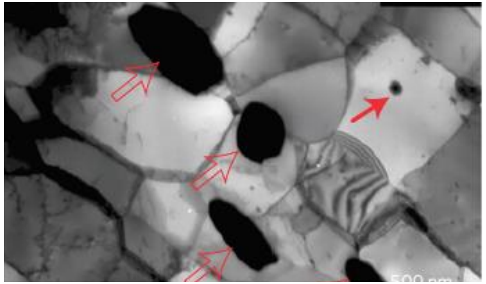
## Oxide dispersion strengthening of Mo vs. TZM

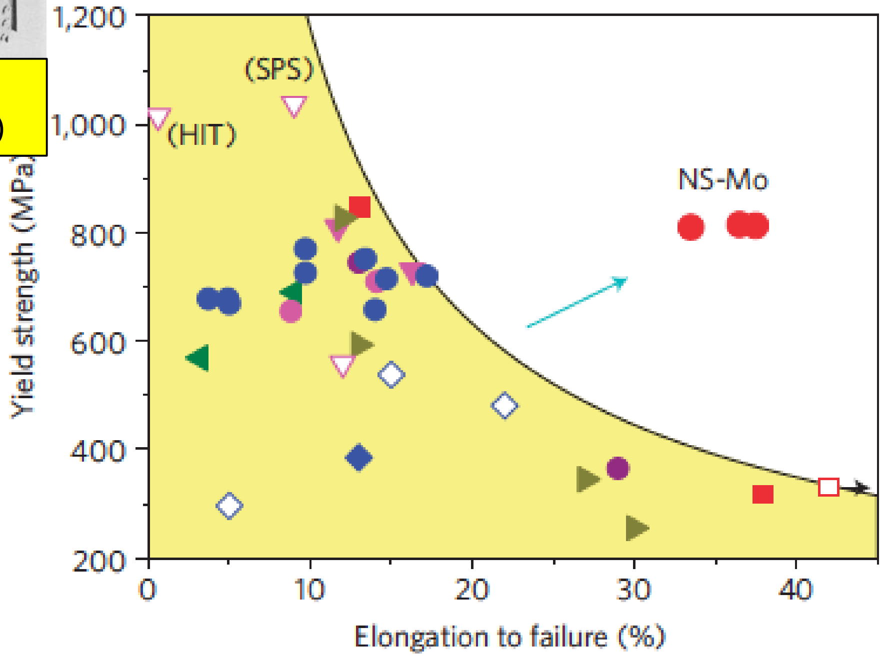


Ramjet Component (Hughes)
TZM Mo Alloy (Mo-0.5Ti-0.1Zr)

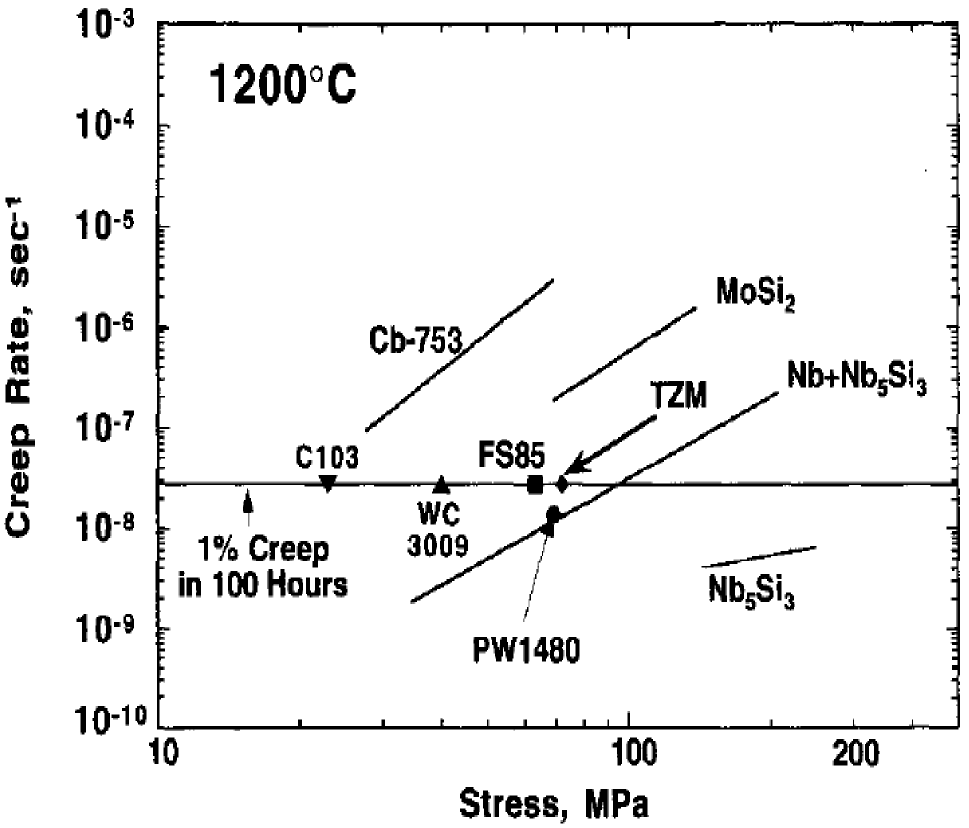


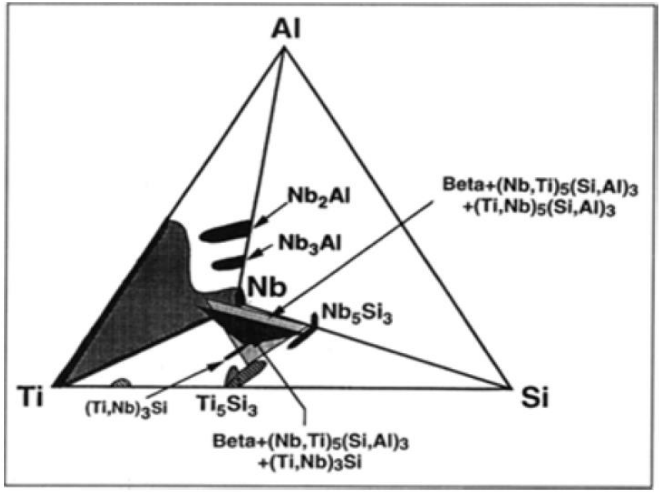



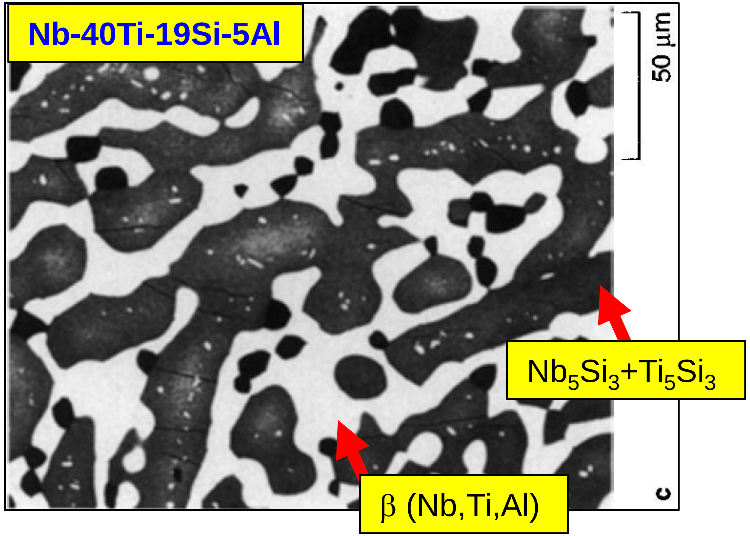


# Intermetallic Alloys Based on Niobium Silicide (1990s, AFRL)

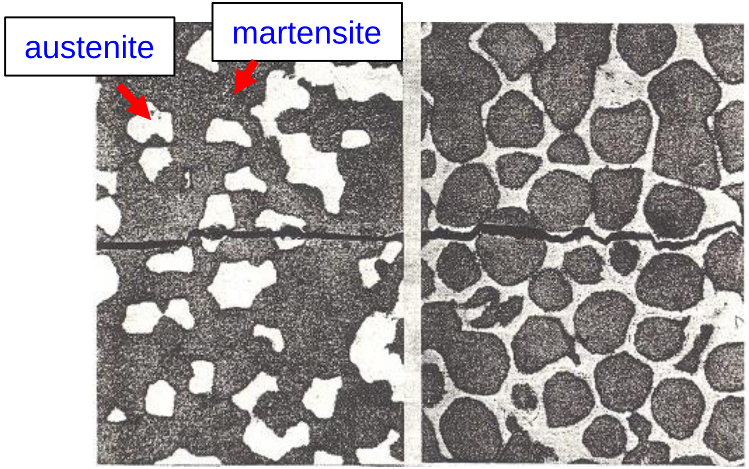
P. R. Subramanian, M. G. Mendiratta, and D. M. Dimiduk *JOM* 48, no. 1 (1996): 33-38.



# Toughening Intermetallic Alloys by Ductile Phases

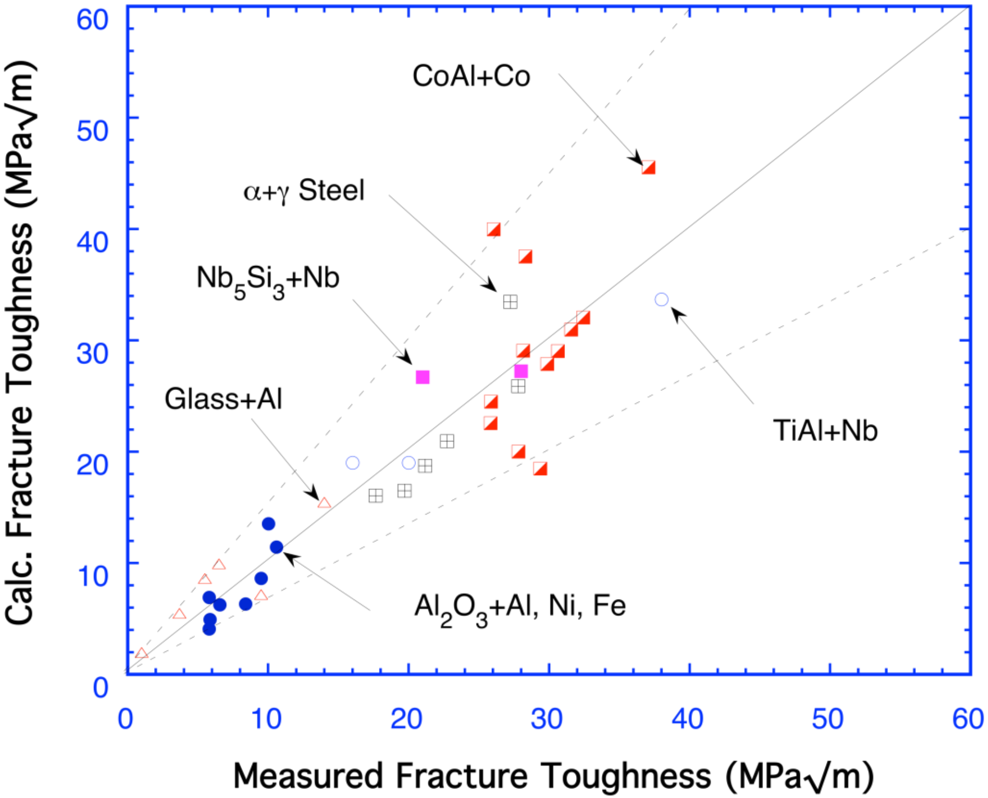



H. Fischmeister, et al *Z. Metallkd.* 80, no. 12 (1989): 8

$$K_{ic} = \sqrt{\frac{E_c(1-V_f)K_b(1-\nu_b^2)}{E_b(1-\nu_c^2)} + \frac{\beta V_f E_c \sigma_{eff,d}\, h_d}{(1-\nu_c^2)}}$$

Toughness of hard phase

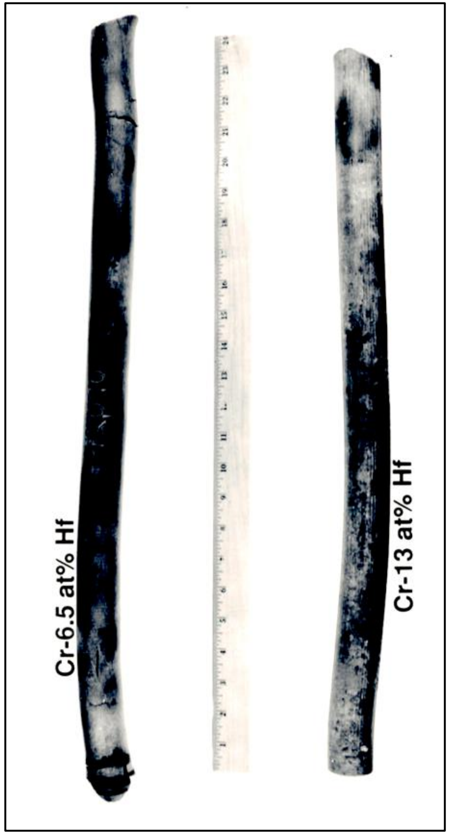
Toughness of ductile phase

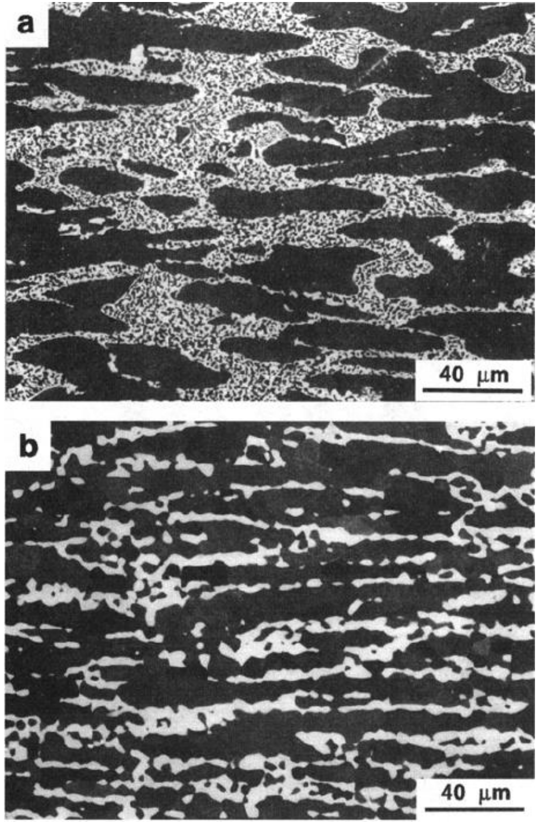


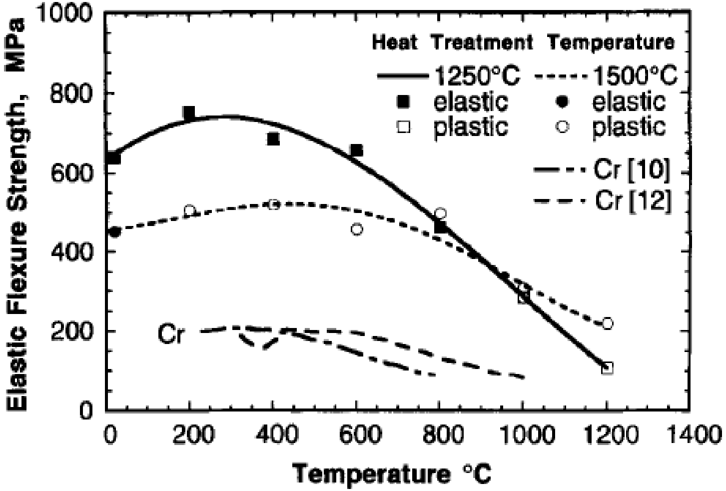


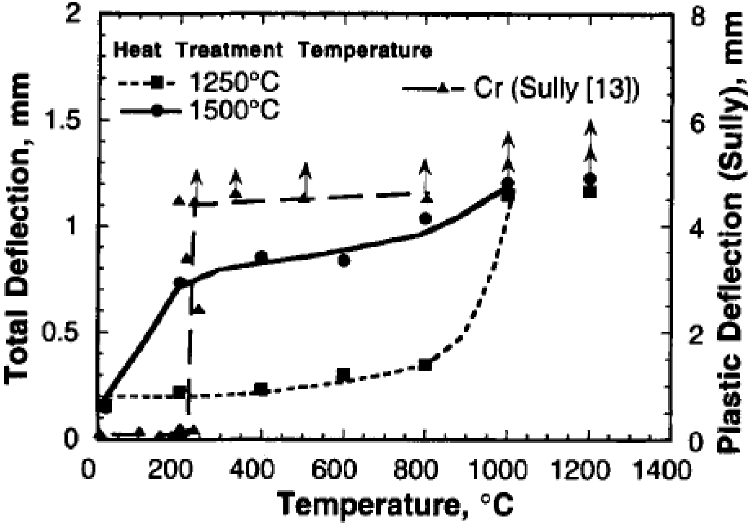
K. S. Ravichandran, "A survey of toughness in ductile phase composites." *Scripta Metall. Mater.;* 26 (1992).
K. S. Ravichandran, "Fracture toughness of two phase WC-Co cermets." *Acta Metall. Mater.;* 42, no. 1 (1994): 143-150.

# Cr-Hf / Cr-Nb  Intermetallic Alloys



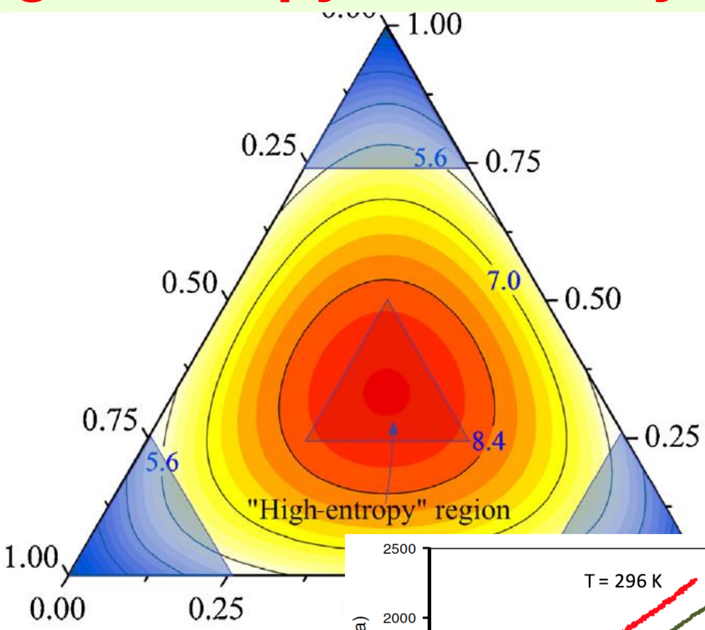



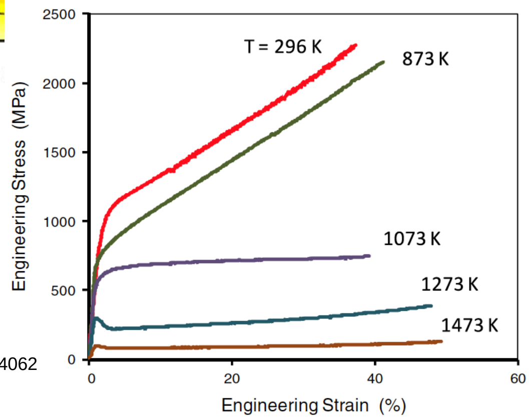




K. S. Ravi Chandran, D. B. Miracle, and M. G. Mendiratta, *Metall. and Mater. Trans. A* 27, no. 9 (1996): 2583

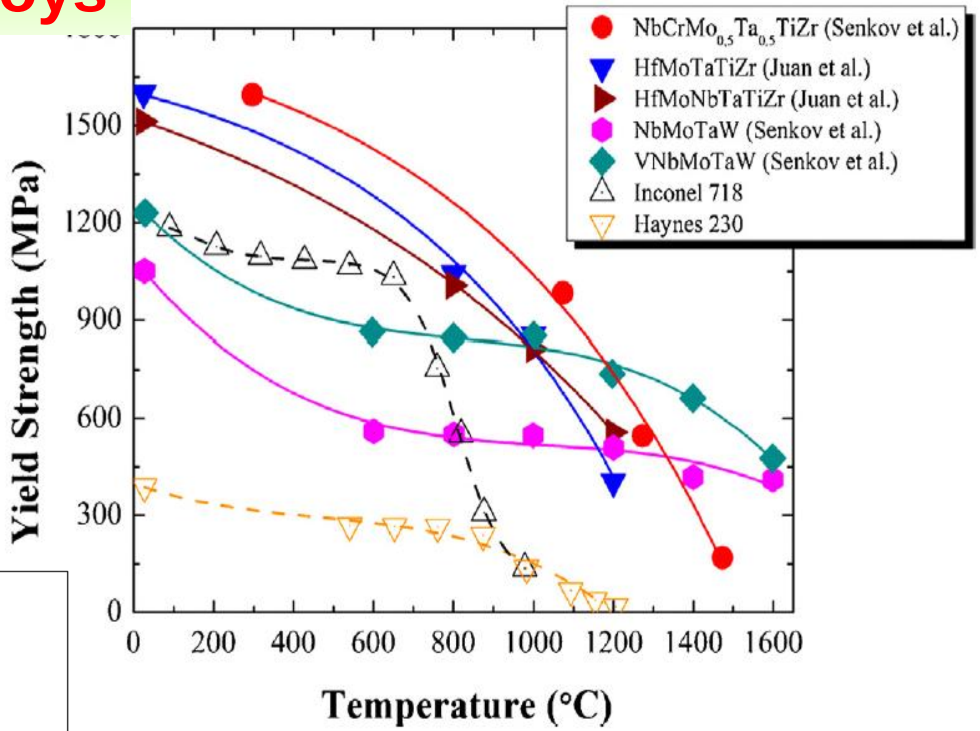
# High Entropy Refractory Alloys




Y. F. Ye et al., *Materials Today* 19, no. 6 (2016): 349



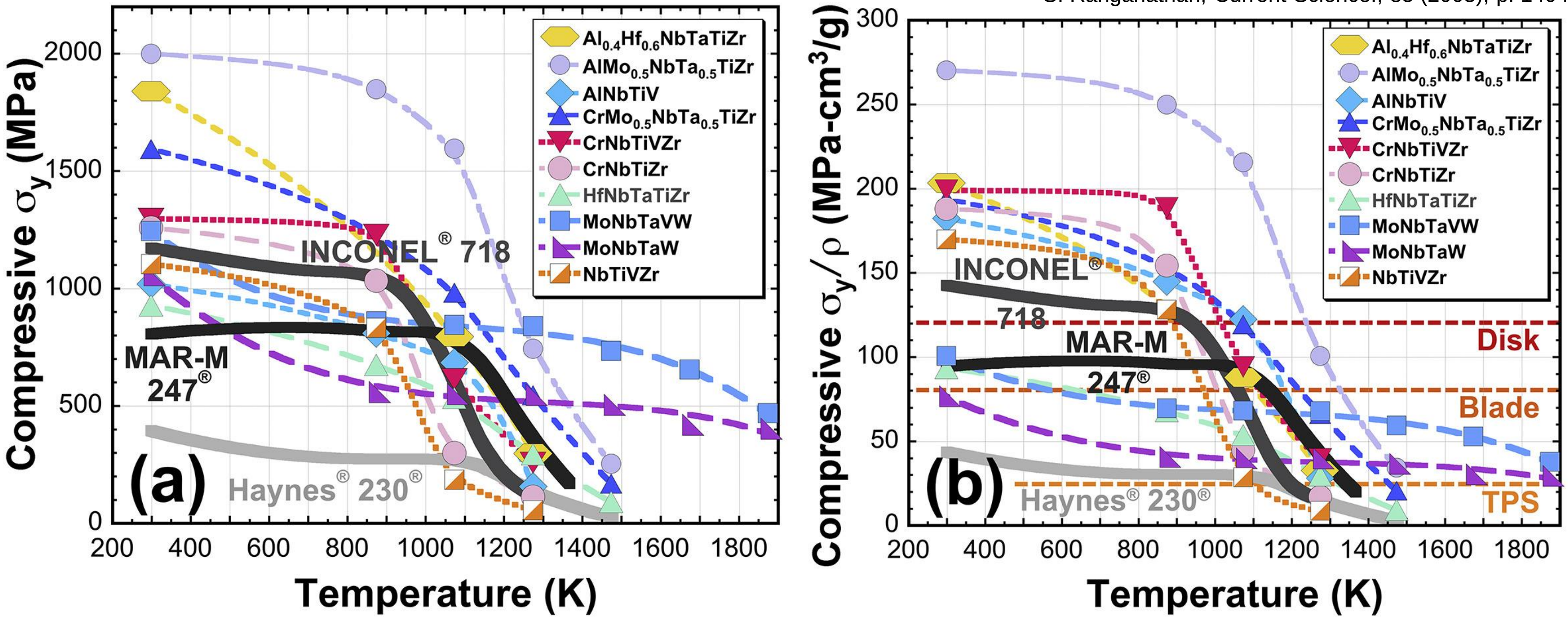

O. N. Senkov, et al., *J. Mat. Sci.* 47 (2012): 4062




- **RT tensile ductility not clear**
- **DBTT unknown**

# High Entropy Alloys—A Compilation

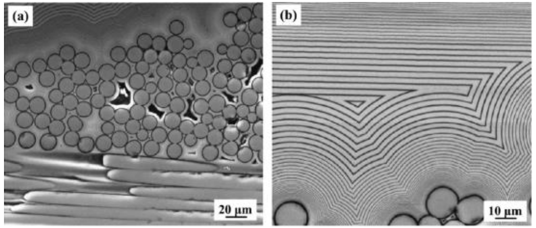
"Multielement Cocktails"
S. Ranganathan, Current Science., 85 (2003), p. 1404

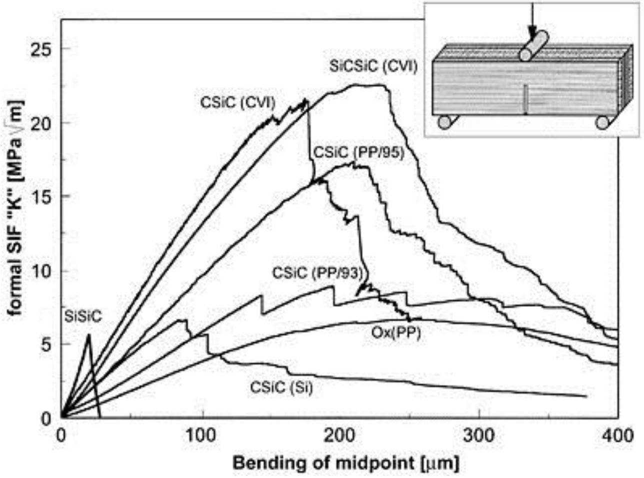


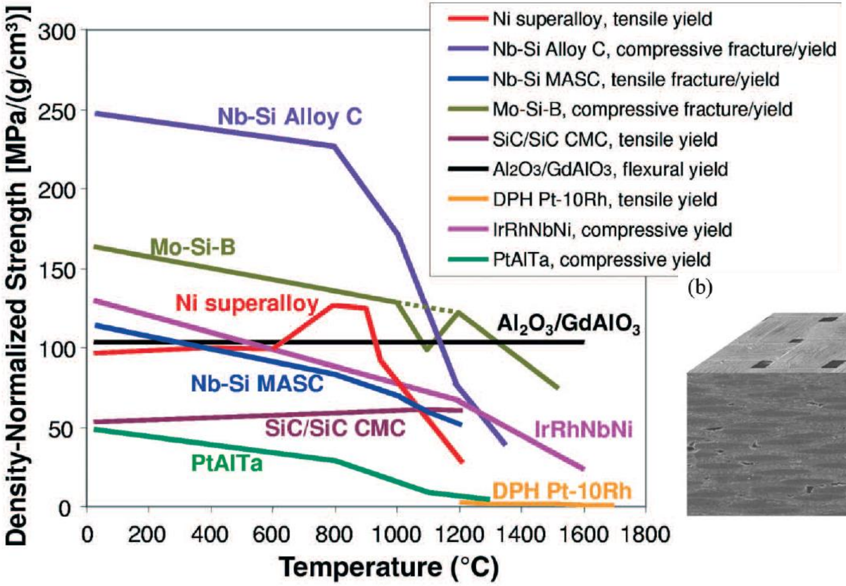

D. B. Miracle, O. N. Senkov. "A critical review of high entropy alloys and related concepts." *Acta Mater.* 122 (2017): 448-511.

# Ceramic Matrix Composites (Woven)

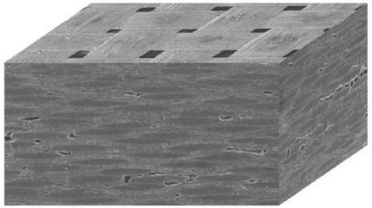
- Good specific strength
- Low tensile strain to failure
- Impact energy absorption?

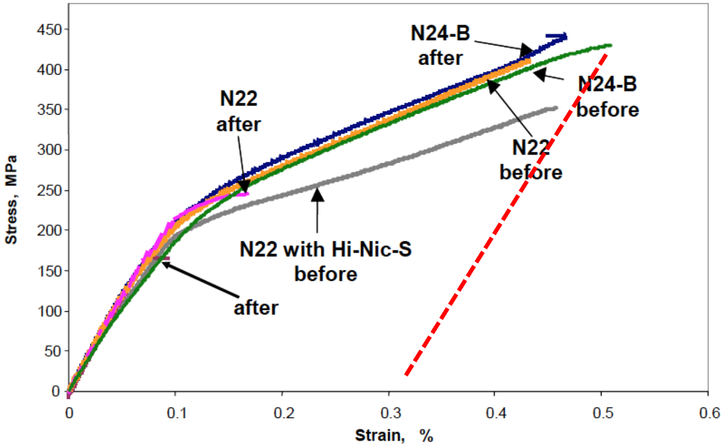



(b)






J-C Zhao and J. H. Westbrook, MRS Bulletin, Sept. 2003

J. A. DiCarlo et al, NASA-TM-2004-213048

# Challenges in Development of New Alloys

## Some Basic Requirements

- **Is there prior work in a given system..?**
- **Start with a qualitative idea & employ quantitative methods (CALPHAD)**
- **Make decent size bulk pieces**
- **Establish property goals**

## Structure-Property-Correlations

- **Bend testing on small samples**
- **Final properties on ASTM size samples**
- **Ductility & Fracture Toughness**
- **Creep Resistance**

## Strength vs. Toughness Check