



REFRACTORY METAL/SILICIDE MULTIPHASE SYSTEMS FOR HIGH-TEMPERATURE STRUCTURAL APPLICATIONS

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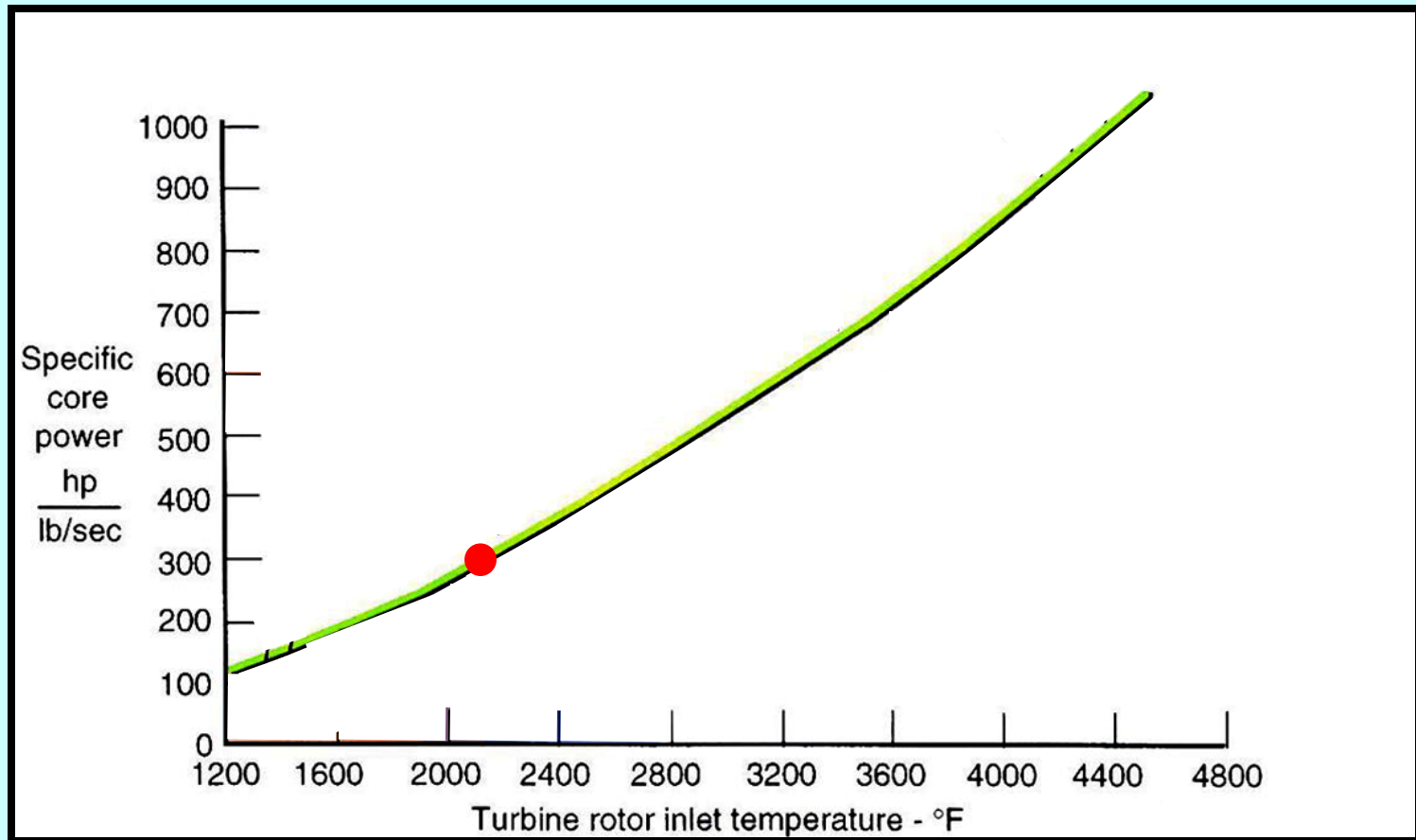
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OPERATING TEMPERATURE VS SPECIFIC CORE POWER



High Operating Temperature $\Rightarrow$ High Thrust

High Specific Strength $\Rightarrow$ High Structural Efficiency

ADVANCED AIRCRAFT ENGINES – HOT SECTION MATERIALS

Temperature

600°C to 1350°C

Properties

Oxidation Resistance

Toughness

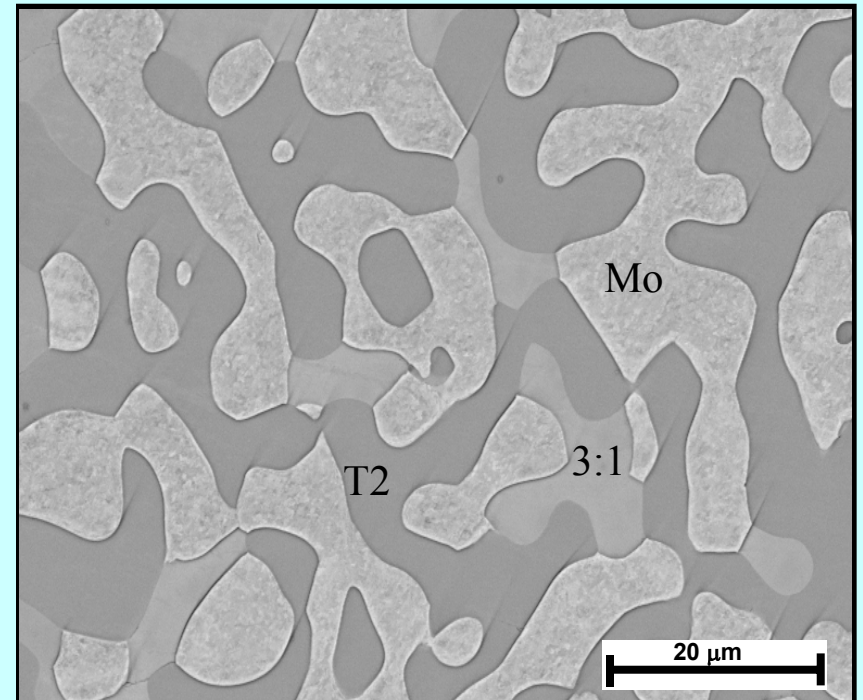
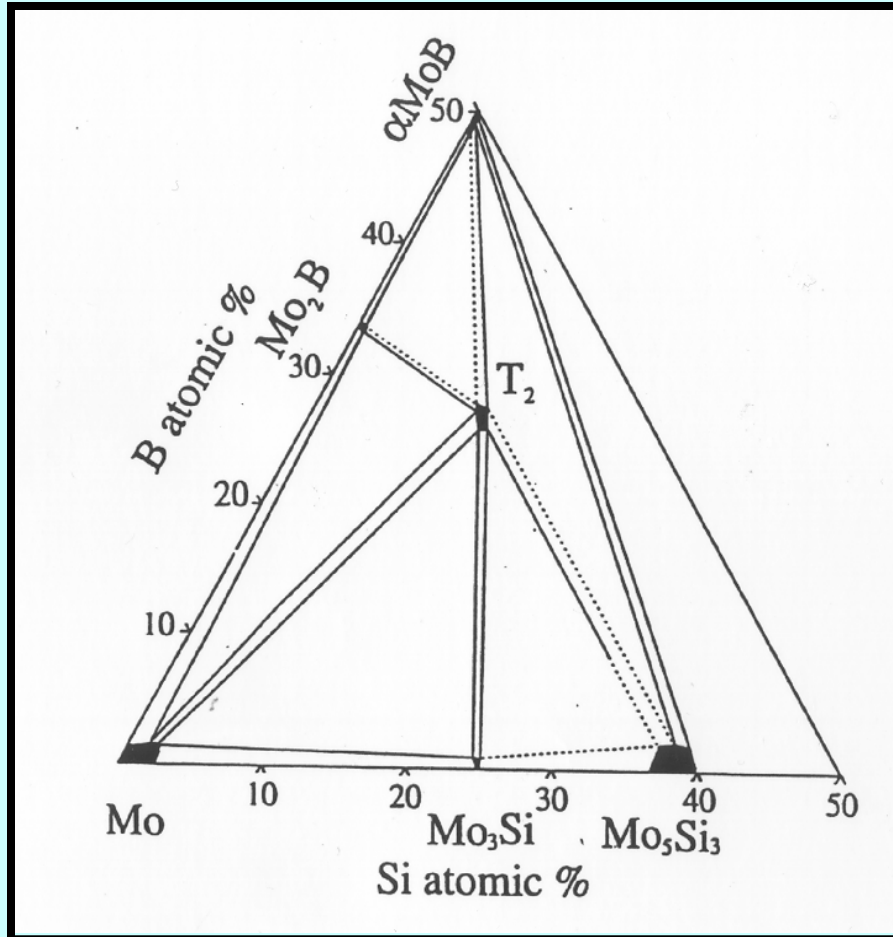
Strength / Creep Resistance

Candidates

Mo- Si - B

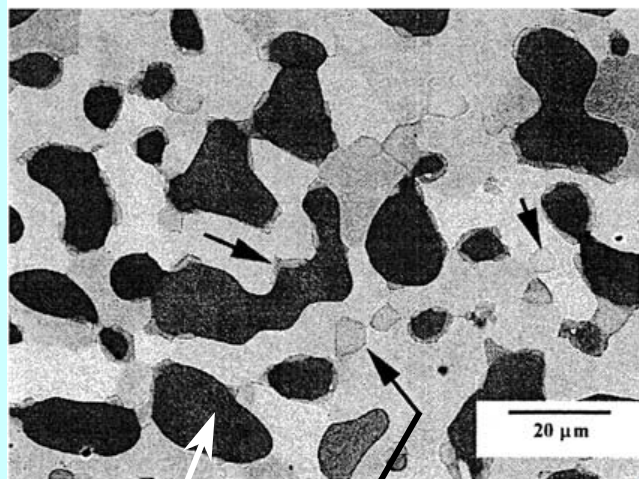
Nb - Ti - Cr - Si - Al -

Mo-Si-B PHASE DIAGRAM (1600°C) & MICROSTRUCTURE



PHASE SPACE OF INTEREST @ 1400°C: Nb/Nb Silicide Alloys

45Nb-26Ti-6.7Cr-12.6Si-1.9Hf-1.9Al-X

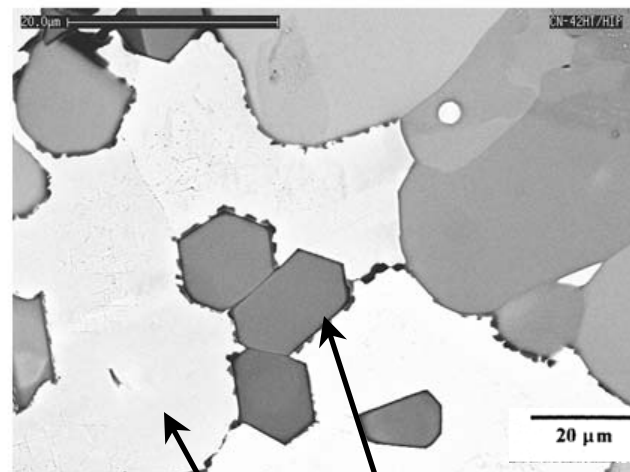


Nb₅Si₃

Ti₅Si₃

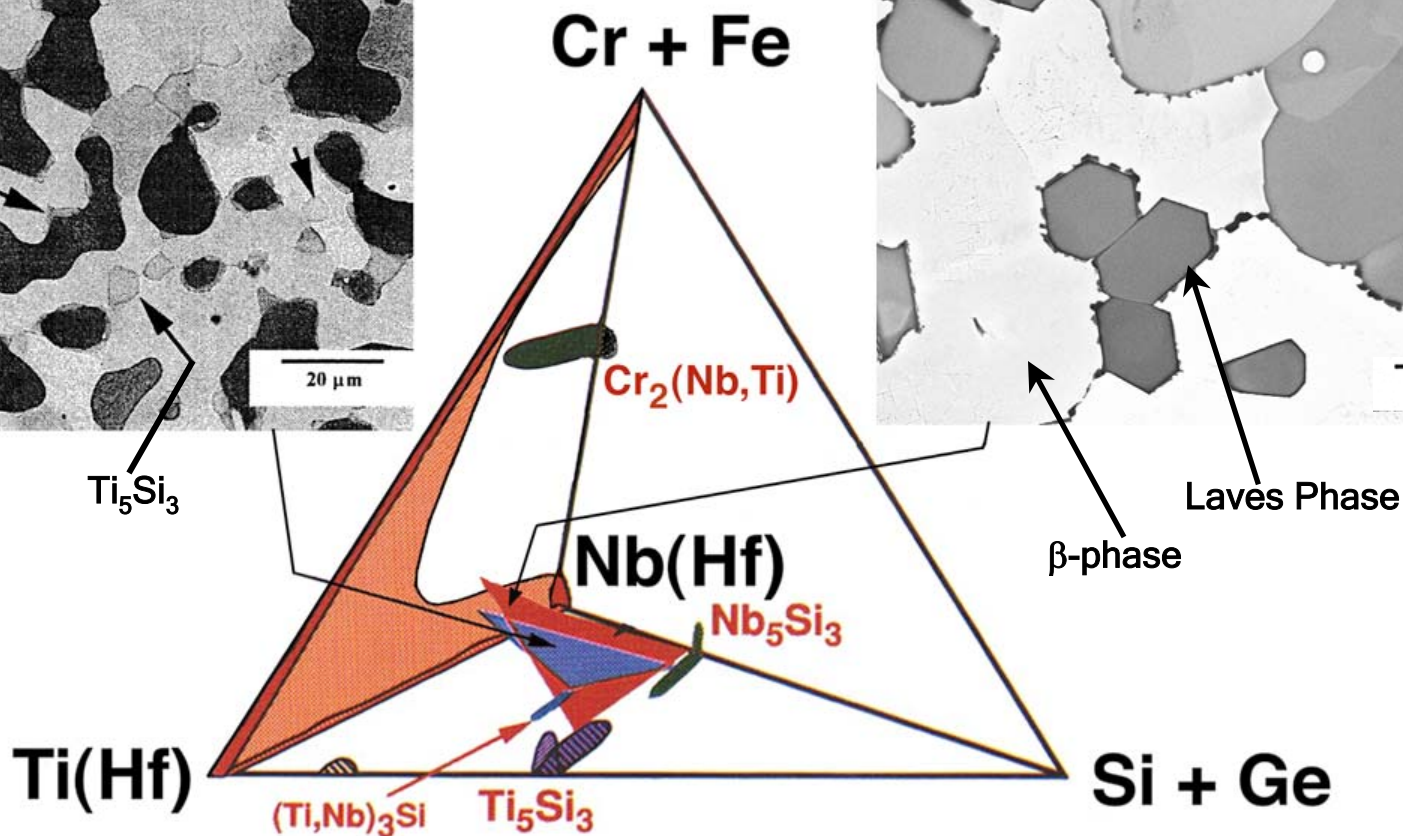
20 μm

47Nb-21.5Ti-9Cr-17.5Si-2Hf-2Al-X



20 μm

20 μm

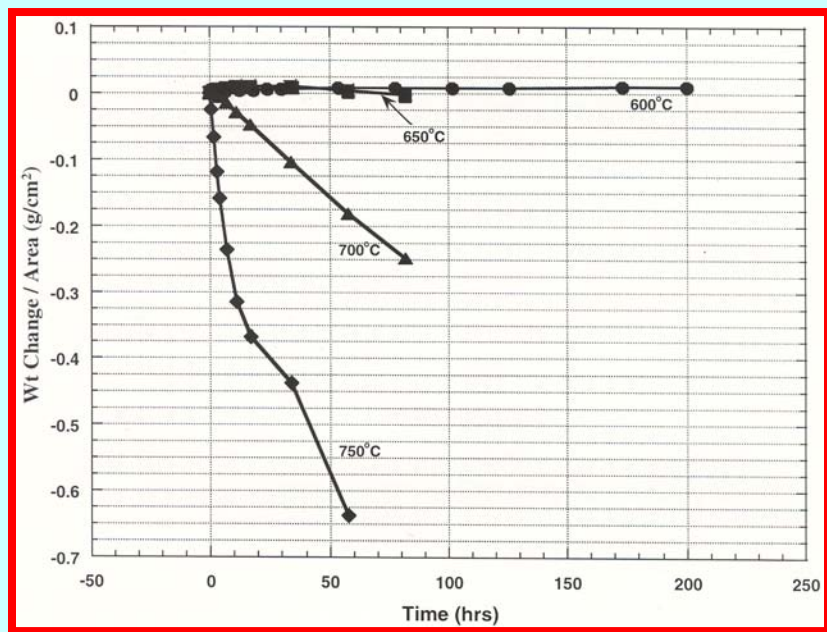


PHYSICAL PROPERTIES*

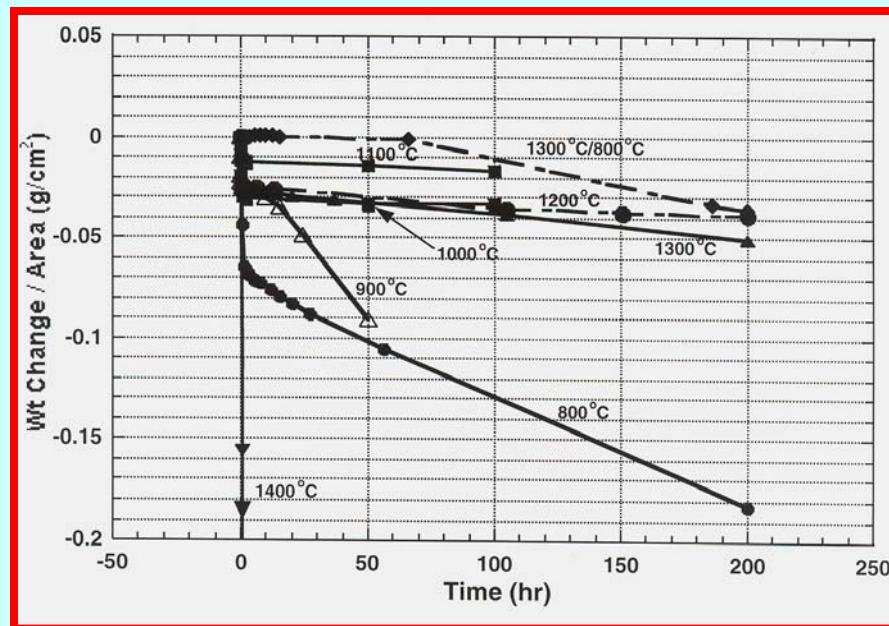
PROPERTY	Mo-Si-B	Nb-Ti-Cr-Hf-Al-Sn
<i>Density</i>	~ 9.5 Mg/m³	~ 7 Mg/m³
<i>Melting Temperature</i>	~ 2100°C	~ 1700 - 1800°C
<i>Thermal Expansion</i>	7 - 11x10⁻⁶ μm/μm	8.1 - 8.6x10⁻⁶ μm/μm
<i>Elastic Modulus</i>	327 - 171 GPa	158-130 GPa
<i>Thermal Conductivity</i>	49.9 - 112 W/m-K	8.6 - 28 W/m-K
<i>Thermal Fatigue Resistance = $k K_{IC} / E\alpha$</i>	~ 15 x 10⁴ (RT)	~ 7 x 10⁴ (RT)
<i>Impact Resistance</i>	~ Very Low	Low (Acceptable)

***Sources: Literature, GE CRD, P&W (Private Communications), NASA**

CYCLIC OXIDATION KINETICS OF Mo-12Si-12B FROM 600-1400°C

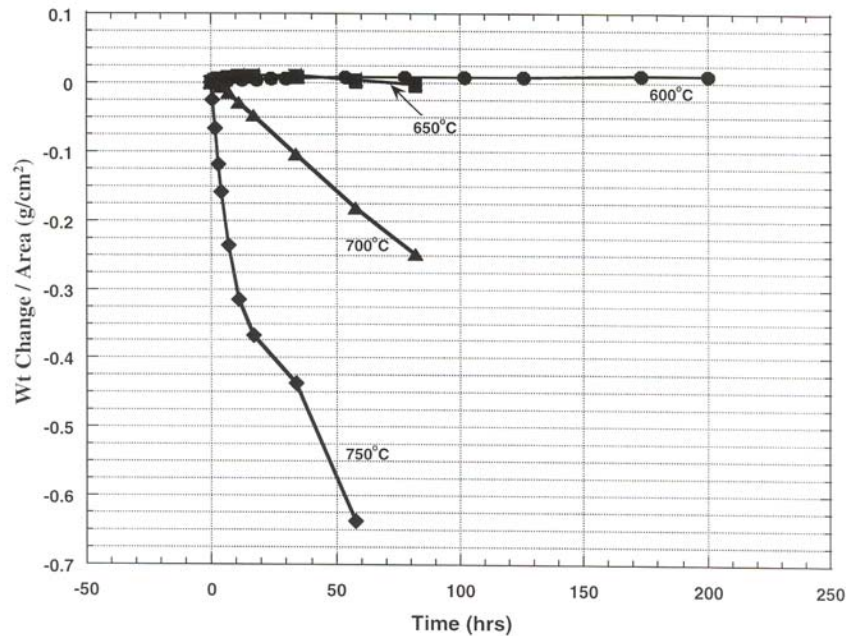


600 - 700°C

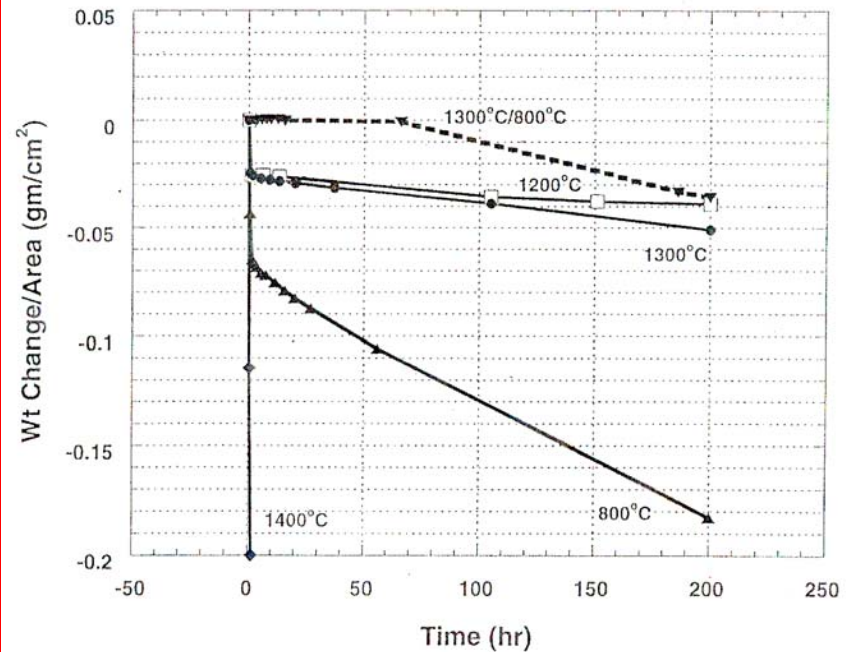


800 - 1400°C

CYCLIC OXIDATION KINETICS OF Mo-12Si-12B FROM 600-1400°C

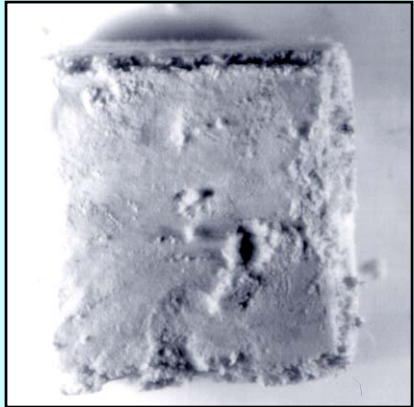


600 - 700°C

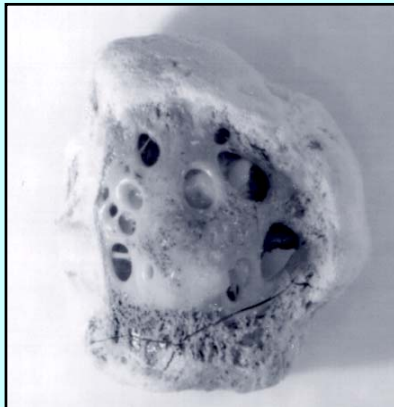


800 - 1400°C

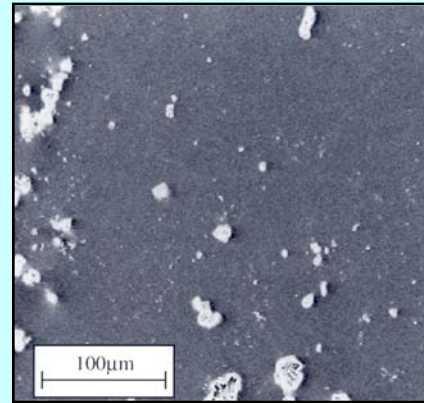
OXIDE SCALE MICROSTRUCTURES: Mo-12Si-12B



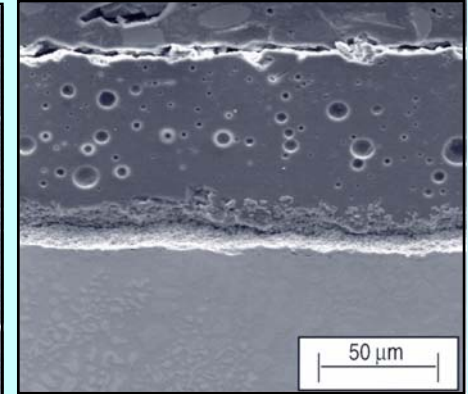
700°C / 82 h



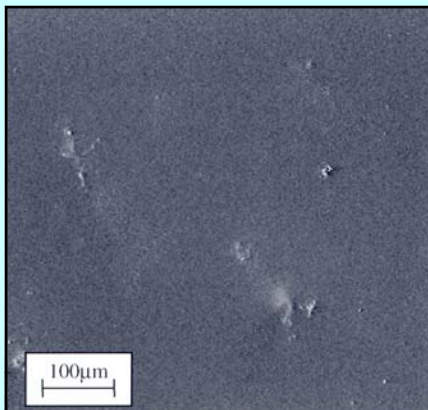
759°C / 58 h



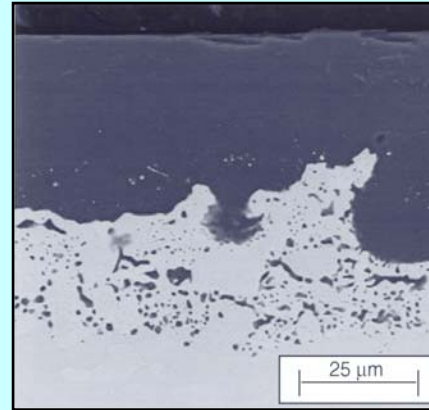
800°C / 200 h



800°C / 200 h

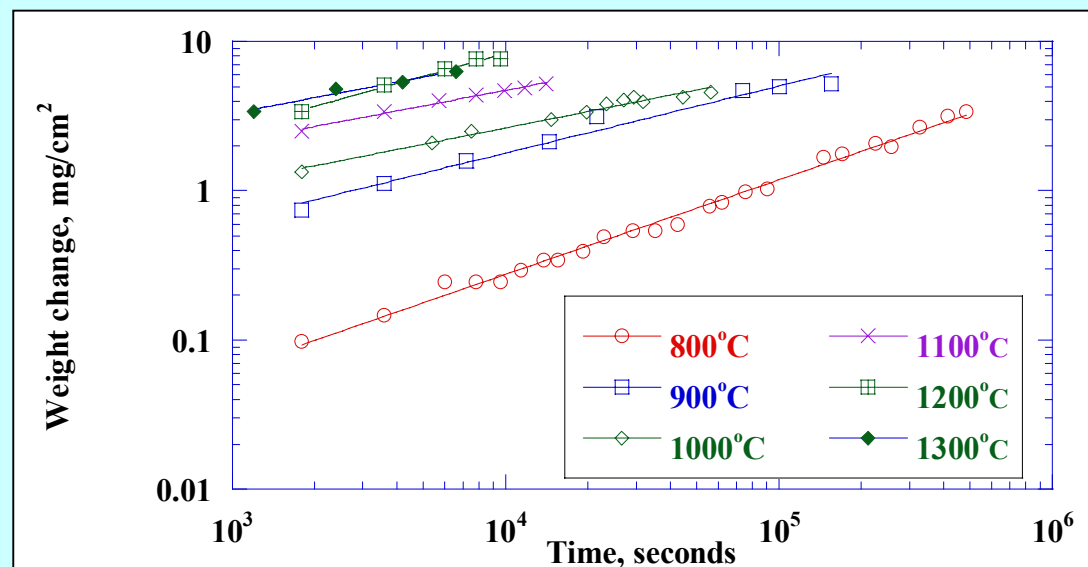
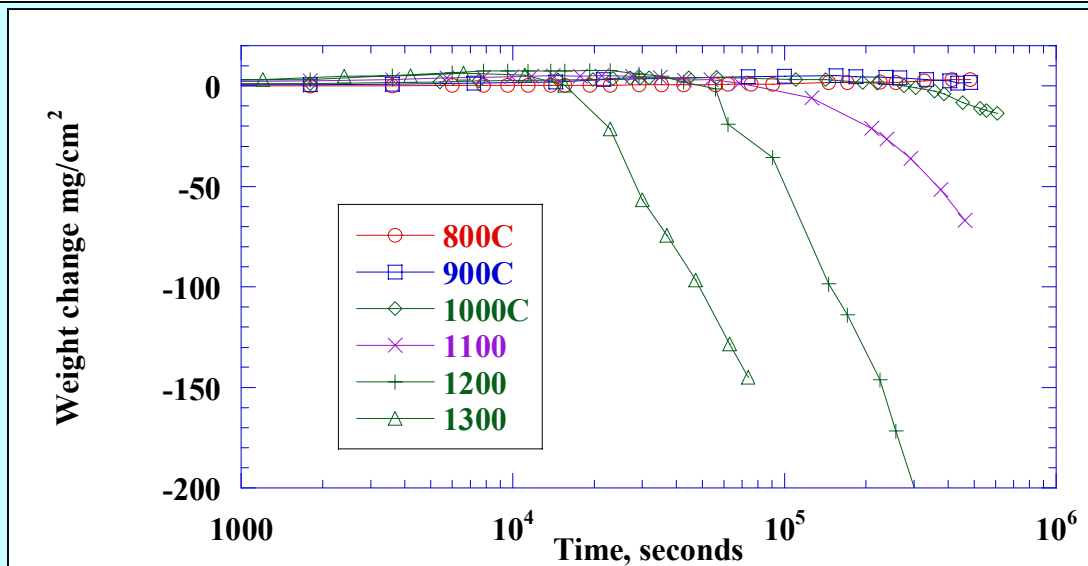


1300°C / 200 h



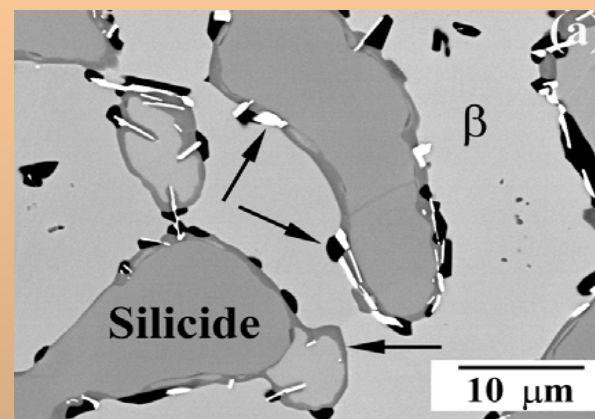
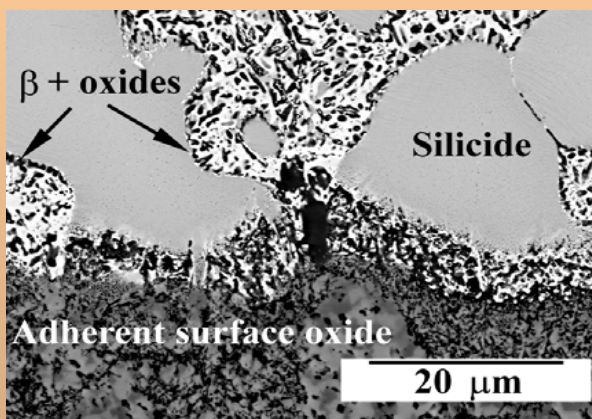
1300°C / 200 h

OXIDATION KINETICS OF Nb / Nb SILCIDE ALLOYS

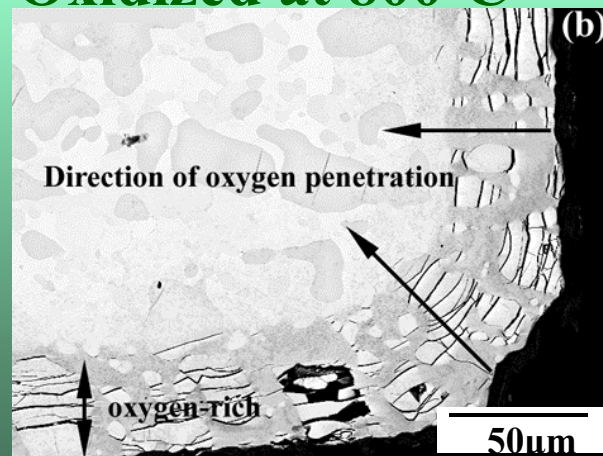
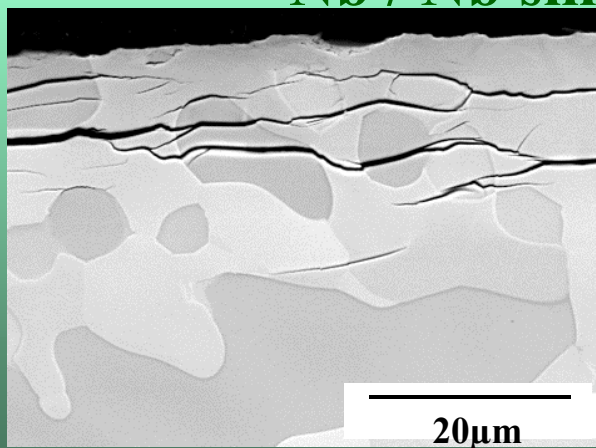


OXIDATION MICROSTRUCTURES

Nb / Nb silicide Oxidized at 1200°C



Nb / Nb silicide Oxidized at 800°C



OXIDATION MECHANISM COMPARISON

Mo-Si-B

- **Competition Between Formation of β -SiO₂ and Volatilization of Mo (MoO₃ Gas).**
 - **Below 800°C, Evaporation of Mo Dominates**
 - **Above 800°C, Protective β -SiO₂ Forms**

Nb-Ti-Cr-Si-Al-Hf-Sn

- **Formation of Complex (Nb Ti) and Si Oxides.**
- **Growth Stresses (Spallation) Limits Duration of Oxidation Protection.**
- **Low Temperature Substrate Silicide Cracking due to Internal Oxidation of Nb_{ss}.**

PROCESSING

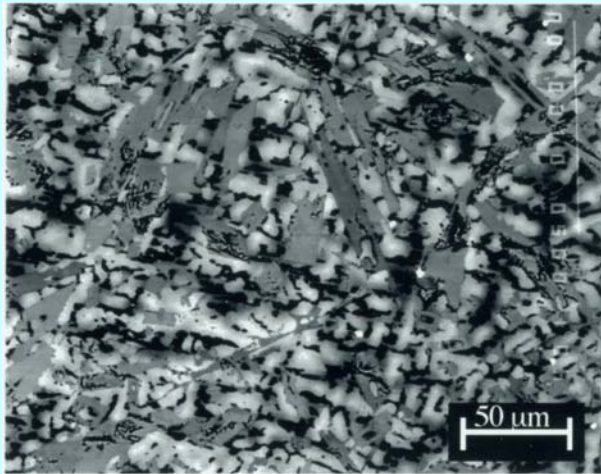
Mo-Si-B

- **Small Button Casting + Heat Treatments**
- **Prealloyed Powder → Sintering + Hipping → Hot-Extrusion**

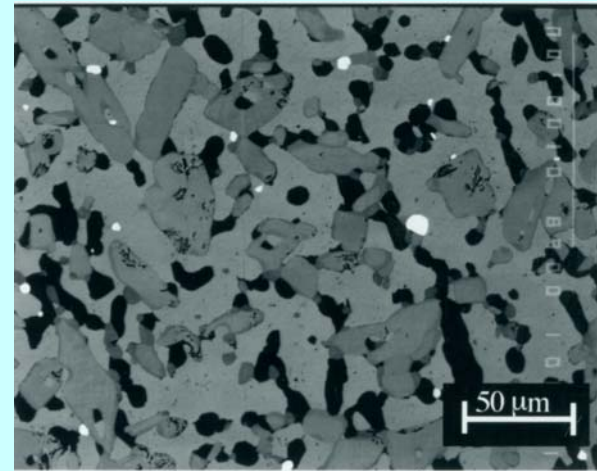
Nb-Ti-Cr-Si-Al-Hf-Sn

- **Induction Skull Melting
(6.25 cm diam. X 60 cm long ingots)
→ Hot Extrusion.**
- **Plasma Rotating Electrode Process
(PREP) Powder → Hot Extrusion.**
- **Gas-Atomization Powder
→ Hot Extrusion.**

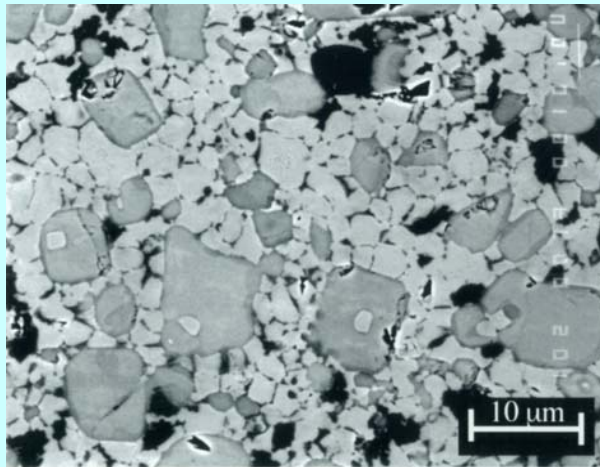
Nb – 21.4Ti – 14.3Cr – 14.4Si – 2.1Hf – 2.4Al – 1.25Sn



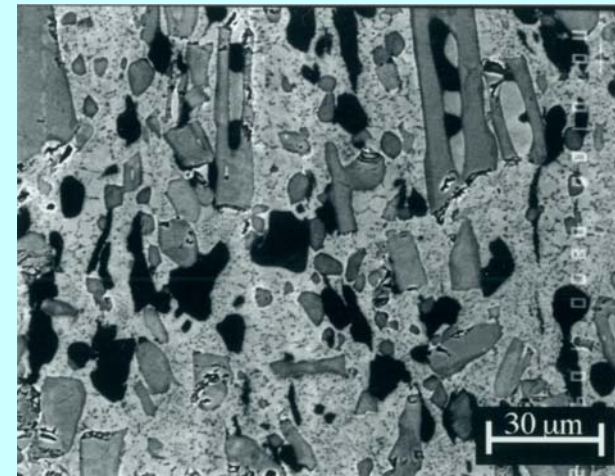
As Cast



1300⁰ C/24h + 1400⁰ C/76h



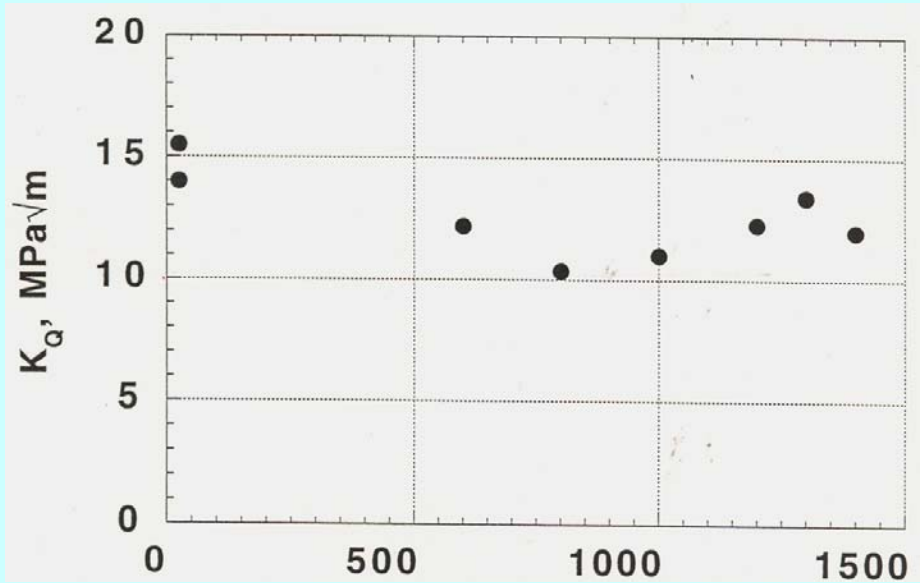
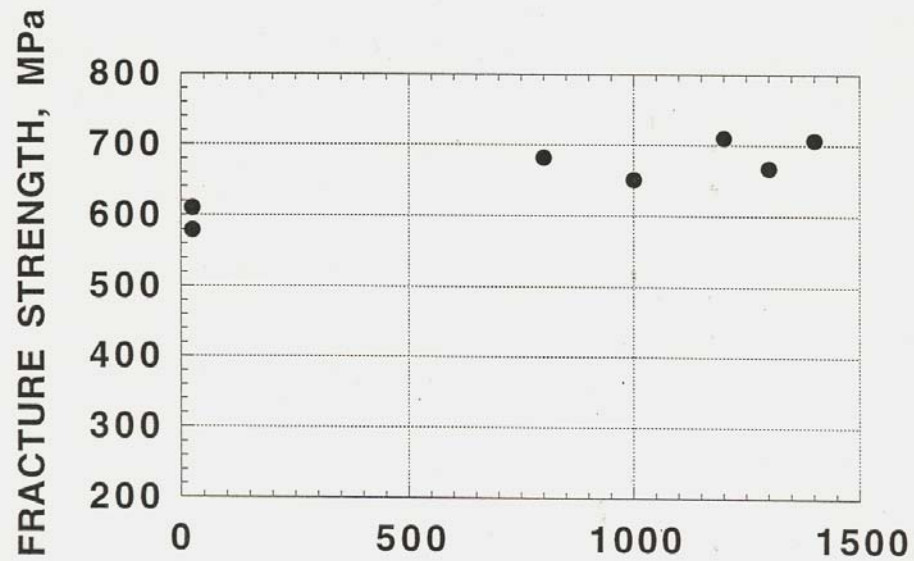
Tran.



Long.

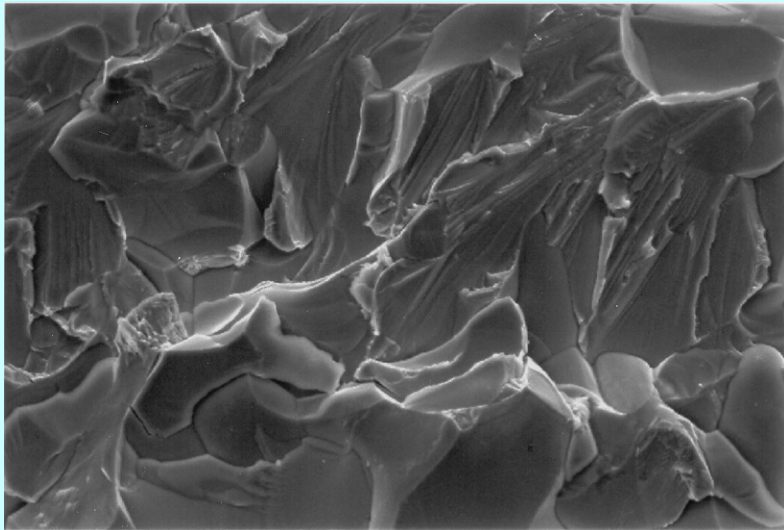
Homo. + Extruded (1350°C/6:1 R)

MECHANICAL PROPERTIES: Mo-12Si-12B

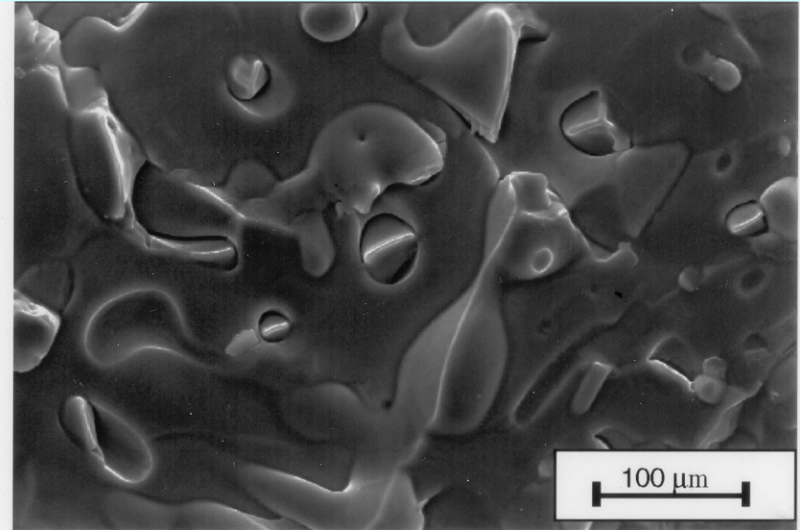


Temperature, °C

FRACTURE SURFACES: Mo – 12Si – 12B

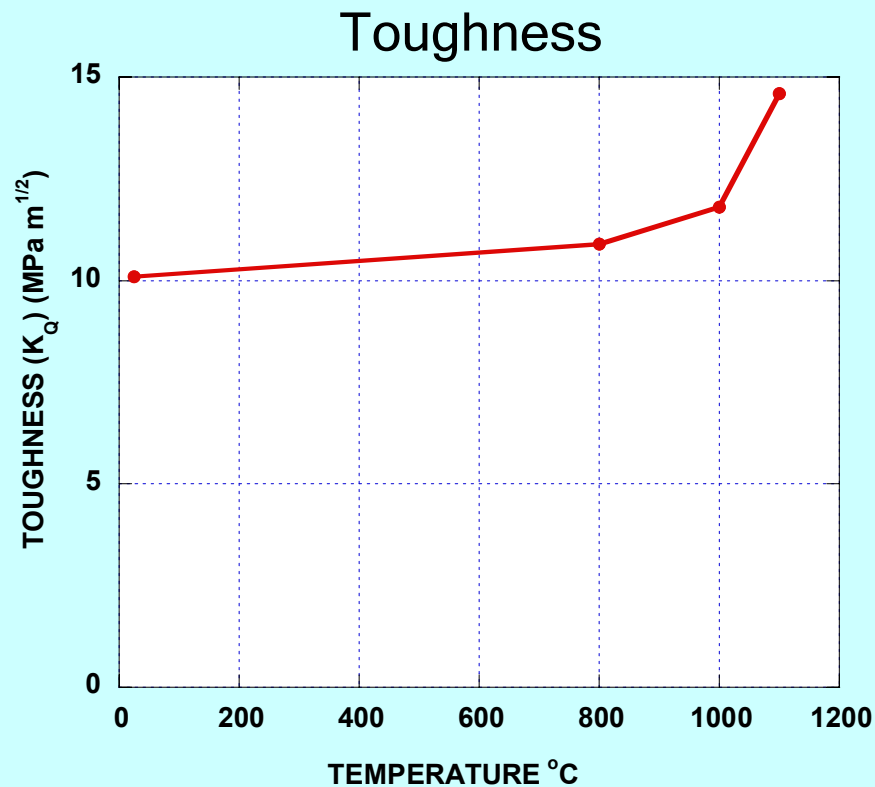
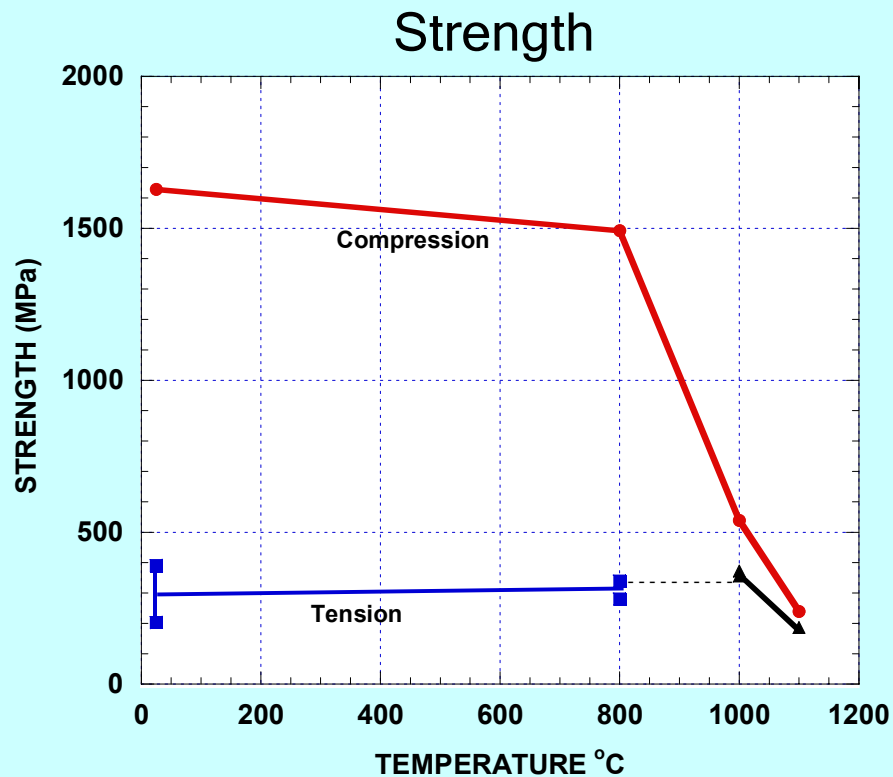


RT

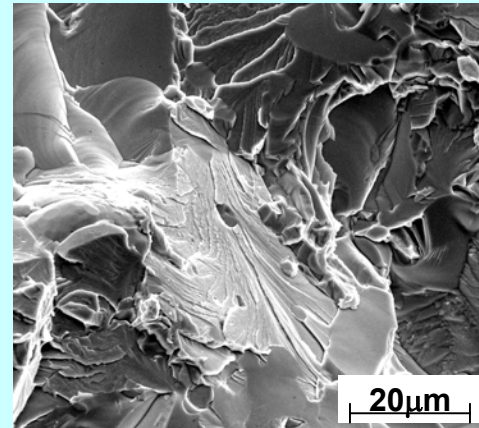
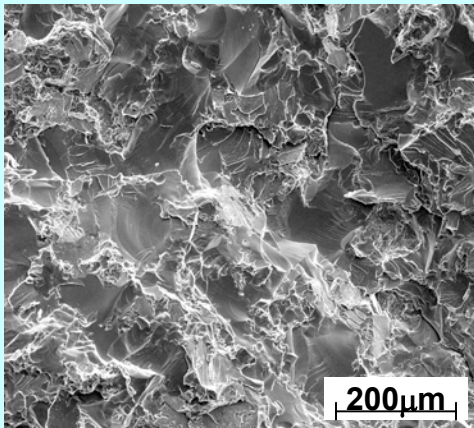


1400°C

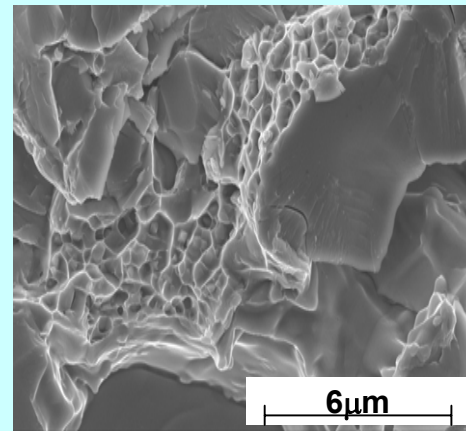
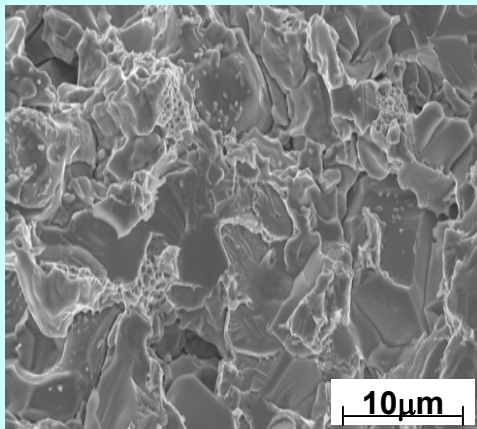
STRENGTH AND TOUGHNESS FOR Nb / Nb SILICIDE



FRACTURE MODES: Nb/Nb Silicides

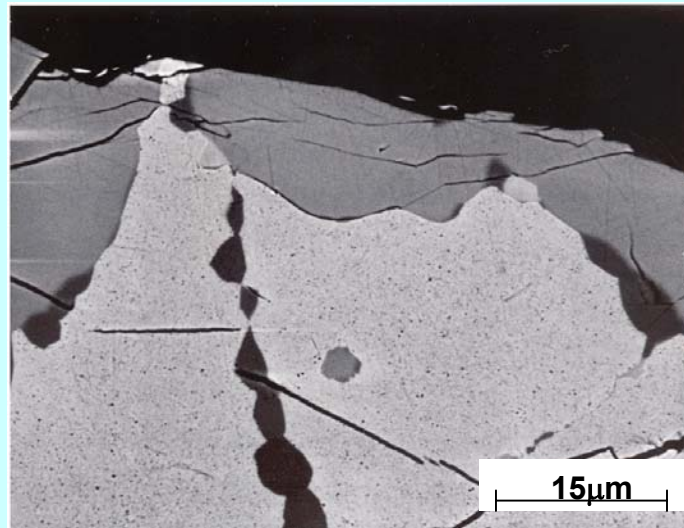
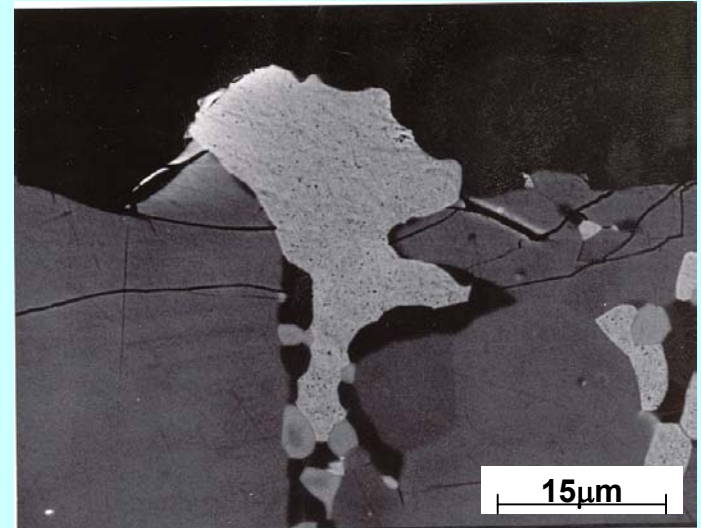
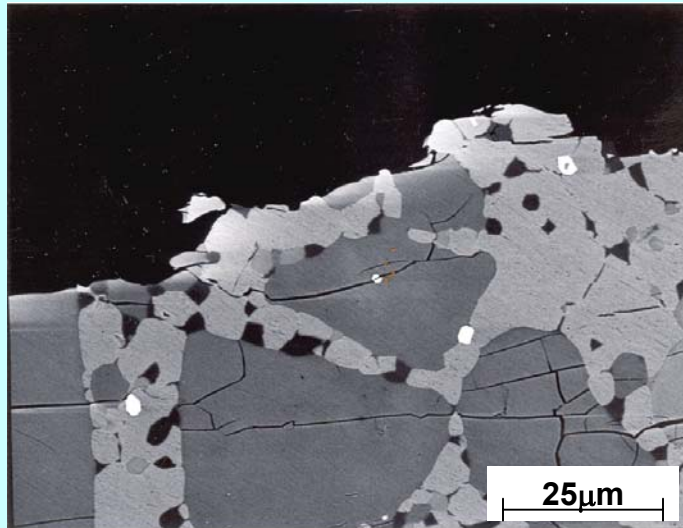


Room Temperature

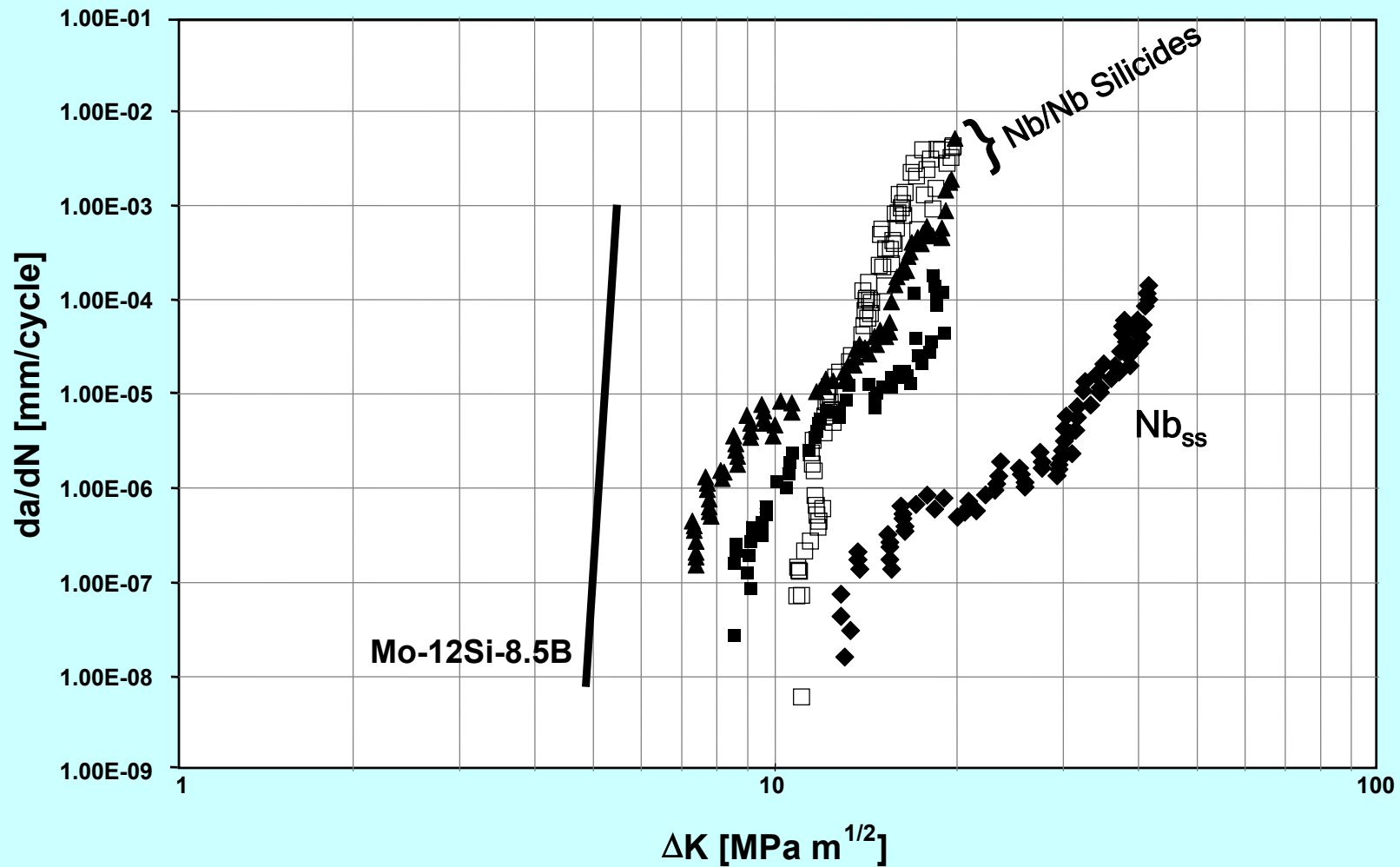


1100°C

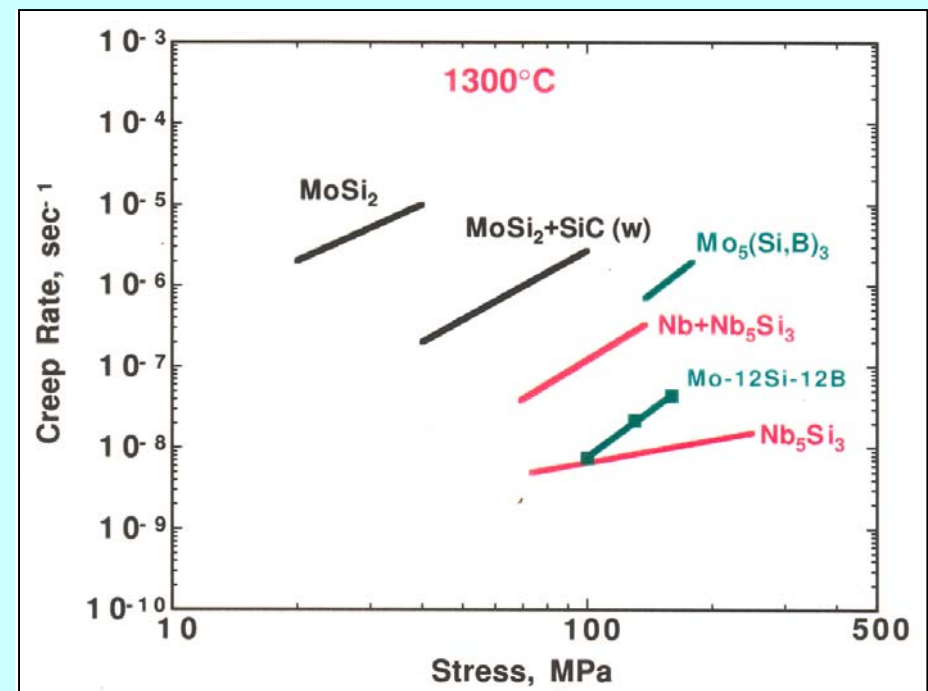
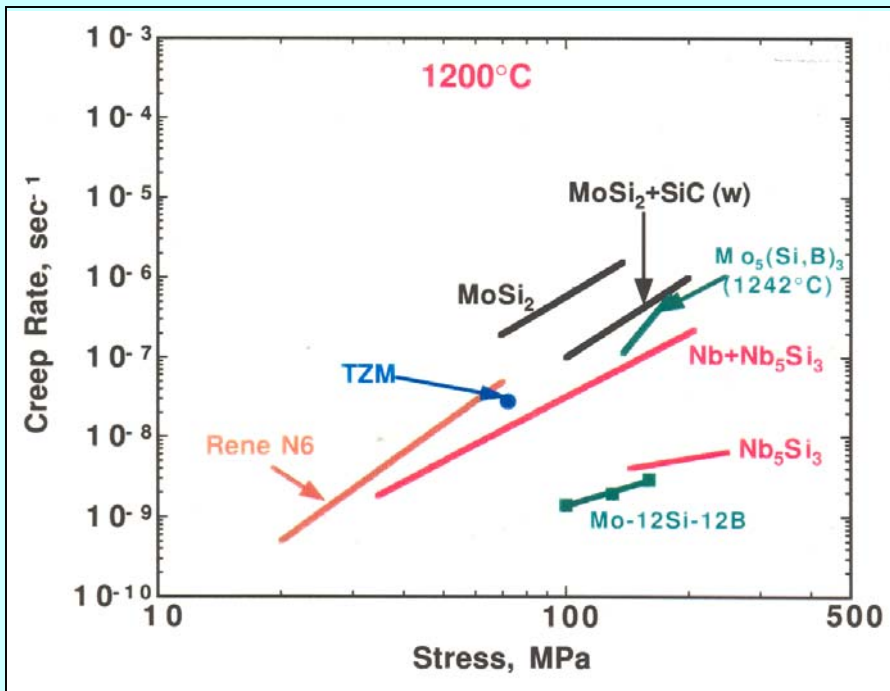
LOW TEMPERATURE DAMAGE MECHANISMS: Nb/Nb Silicides



FATIGUE CRACK GROWTH: Nb and Mo Refractory Metal / Silicides



CREEP BEHAVIOR OF Mo- AND Nb-BASED ALLOYS



SUMMARY / CONCLUSION

- Both Systems Show Promising Microstructural Stability and Reasonable Mechanical Properties i.e., Strength, Creep Resistance and Toughness.
- Both Systems are Brittle at Low Temperatures. Mo-System Exhibits Poor Fatigue and Impact Resistance. Novel Design Methods will be Needed for these Brittle/Ductile Systems
- Oxidation Resistance: Mo System Adequate from 900-1350°C. Nb-System, Limited Protection (~100 h) up to 1200°C. Both Systems will Require Coating.
- Processing and Scale-up are Major Issues for Applications.
- Comprehensive Composition / Processing / Microstructure / Property Data Still Lacking.