Thermomechanical Properties of W-Re Alloys & Initial Survey of Molten Tin Corrosion Data

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Motivation for Studying W-Re Alloys

- **Tensile strength of recrystallized W is relatively low compared to other refractory alloys (TZM, Ta-8W-2Hf) for temperatures below 1200-1500˚C**
  - recrystallized tungsten UTS=380 MPa at 20˚C

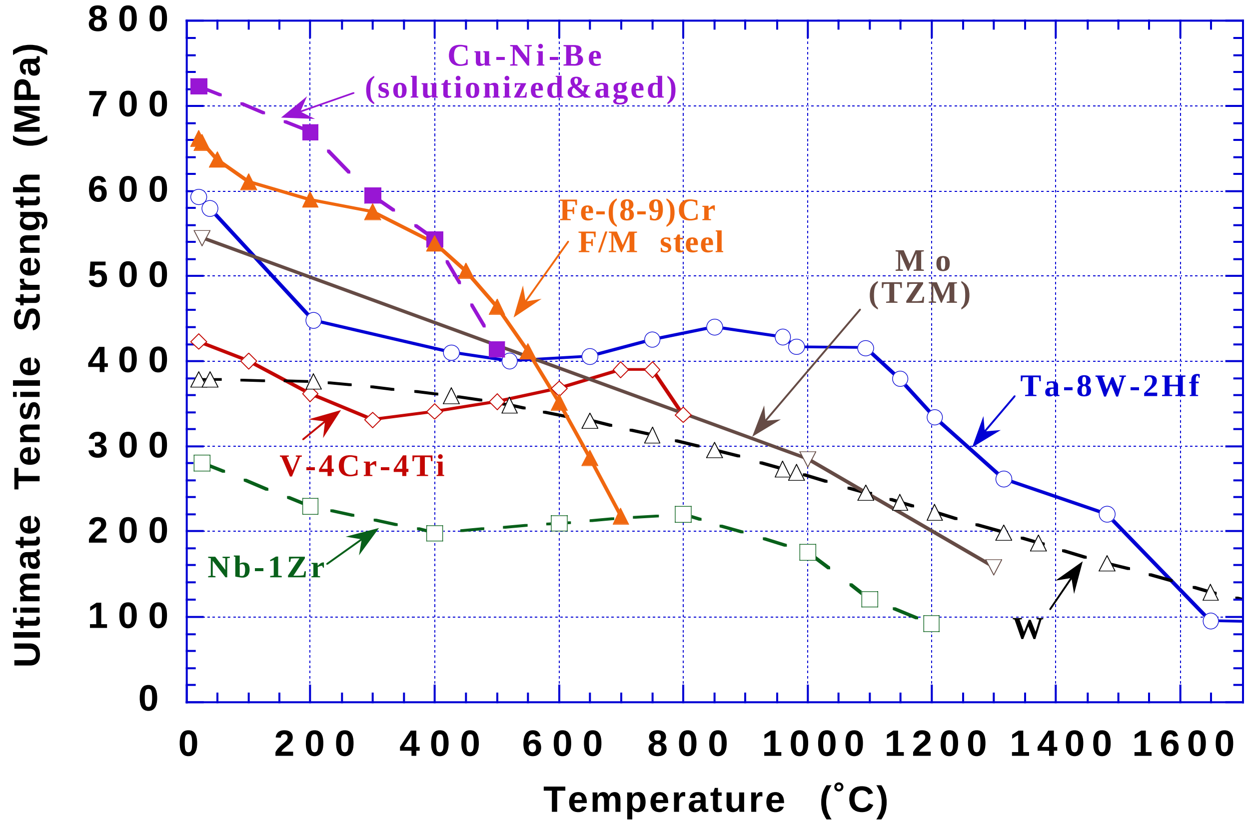
- **Pure tungsten has poor fabricability**

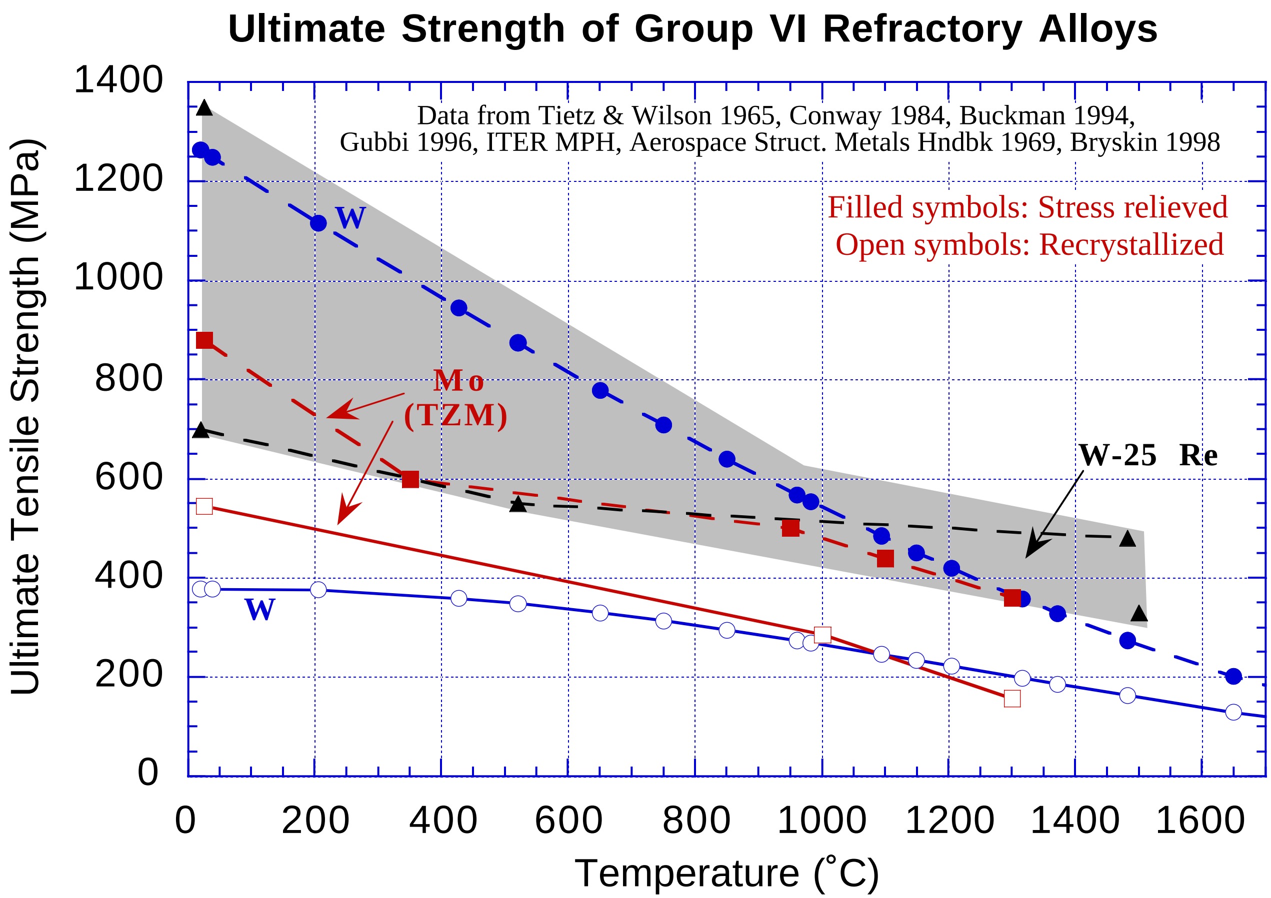
- **W-(5-25%)Re alloys offer potential for improved low temperature fabricability**
  - Low temperature (<1200˚C) strength is not necessarily higher than that of pure W (depends on thermomechanical processing; "solution softening" usually occurs in W-Re alloys, cf. Klopp 1975)

- **Hafnium and carbon are typically added to tungsten alloys (~0.5 at.% Hf, C) in order to improve high temperature creep strength**
  - W-Re (Hf,C) alloys offer possibility of improved creep resistance at high temperatures (>1200˚C) compared to pure W

Data from Tietz & Wilson (1965), Conway (1984), Buckman (1994),
Zinkle et al (1998), ITER MPH, and Aerospace Structural Metals Handbook (1969)

Comparison of the Ultimate Strength of Recrystallized Refractory Alloys and High-Conductivity Structural Alloys





Ultimate Strength of Group VI Refractory Alloys
Data from Tietz & Wilson 1965, Conway 1984, Buckman 1994,
Gubbi 1996, ITER MPH, Aerospace Struct. Metals Hndbk 1969, Bryskin 1998
Filled symbols: Stress relieved
Open symbols: Recrystallized
W
Mo
(TZM)
W-25 Re
W
Ultimate Tensile Strength (MPa)
Temperature (˚C)
0
200
400
600
800
1000
1200
1400
1600

Summary of Recrystallized Tungsten Properties (from IMPH)

Ultimate Tensile Strength (unirradiated)

σ_{UTS}(MPa)=377.9 + 0.03207*T - 1.955x10^{-4}*T^{2} + 5.129x10^{-8}*T^{3} (T in ˚C)

Yield Strength (Unirradiated)

σ_{Y}(MPa)= 94.2 - 0.0214*T -2.12x10^{-4}*T^{2} -7.48x10^{-10}*T^{3} (T in ˚C)

Elongation

e_{tot}(%)=20.8 + 0.053*T-2.18x10^{-5}*T^{2} (T>500˚C)

Elastic constants

E_{Y} (GPa) =398 - 0.00231*T - 2.72x10^{-5} T^{2} (T in ˚C)

ν=0.279 + 1.09x10^{-5} T (T in ˚C)

Thermophysical properties

α_{m} (10^{-6}/˚C)= 3.922 + 5.835x10^{-5}*T + 5.705x10^{-11}*T^{2} - 2.046x10^{-14}*T^{3} (T in ˚C)

C_{P} (J/kg-K) = 128.3 + 0.0328*T - 3.41x10^{-6}*T^{2} (T in ˚C)

K_{th} (W/m-K)=174.9 - 0.107 T + 5.01x10^{-5} T^{2} - 7.835x10^{-9}*T^{3} (T in ˚C)

Recommended operating temperature limits (structural applications)

Tmin = 800˚C (due to rad.-induced increase in DBTT at low T_{irr})

Tmax = 1400˚C (Li, Pb-Li corrosion/chemical compatibility and thermal creep)

Summary of Recrystallized W-(5-10%) Re Properties

Ultimate Tensile Strength (unirradiated)

σ_{UTS}(MPa)=377.9 + 0.03207*T - 1.955x10^{-4}*T^{2} + 5.129x10^{-8}*T^{3} (T in ˚C) –use pure W values

Yield Strength (Unirradiated)

σ_{Y}(MPa)= 94.2 - 0.0214*T -2.12x10^{-4}*T^{2} -7.48x10^{-10}*T^{3} (T in ˚C) –use pure W values

Elongation

e_{tot}(%)=20.8 + 0.053*T-2.18x10^{-5}*T^{2} (T>500˚C) --use pure W values

Elastic constants

E_{Y} (GPa) =398 - 0.00231*T - 2.72x10^{-5} T^{2} (T in ˚C) --pure W values; W-25Re E(20˚C)=410 GPa

ν=0.279 + 1.09x10^{-5} T (T in ˚C) W-25Re ν(20˚C)=0.30, G(20˚C)=159 GPa

Thermophysical properties

α_{m} (10^{-6}/˚C)= 3.9 + 5.8x10^{-5}*T + 5.7x10^{-11}*T^{2} - 2.0x10^{-14}*T^{3} (T in ˚C) --use pure W values

C_{P} (J/kg-K) = 128+ 0.033*T - 3.4x10^{-6}*T^{2} ??? (T in ˚C) --use pure W values

K_{th} (W/m-K)~85 W/m-K (1000-2400˚C) --conductivity decreases with increasing Re content

Recommended operating temperature limits (structural applications)

Tmin = 800˚C (due to rad.-induced increase in DBTT at low T_{irr})

Tmax = 1400˚C (Li, Pb-Li corrosion/chemical compatibility and thermal creep)

Maximum temperatures of structural alloys (bare walls) in contact with high-purity liquid coolants, based on a 5 μm/yr corrosion limit

	Li	Pb-17 Li	Flibe
F/M steel	550-600°C [1,2,3]	450°C [1,2,9]	700°C ? 304/316 st. steel [13]
V alloy	600-700°C [1,4,5]	~650°C [1,10]	?
Nb alloy	>1300°C [6,7]	>600°C [10] (>1000°C in Pb) [11]	>800°C [14]
Ta alloy	>1370°C [6,7]	>600°C [10] (>1000°C in Pb) [11]	?
Mo	>1370°C [6,7]	>600°C [10]	>1100°C? [15,16]
W	>1370°C [6,7]	>600°C [10]	>900°C? [15]
SiC	~550°C ? [8]	>800°C ? [12]	?

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Chemical Compatibility of Structural Materials with Molten Tin (static tests)

Nb: no corrosion observed at ~600˚C
chemical attack occurred at 800˚C [1] and 1000˚C [2,3]

Ta: chemical attack observed at both 600-630 [1,4] and 800˚C [1]
intergranular penetration observed at 1000˚C [2,3,5]

Mo: minimal corrosion observed below ~600˚C [4]
chemical attack observed at both 630 and 800˚C [1]
significant corrosion (predominantly intergranular) observed at 1000˚C [2,3-5,6]
-1.7% weight loss after 340 h at 1000˚C [4,6]

W: good chemical resistance at 630˚C; moderate attack at 800˚C [1]
Very little corrosion (10 ppm weight loss) observed after 40 h at 1000˚C [6]
moderate corrosion (<5 μm) observed after 100 h at 1000˚C [3]

Austenitic, Ferritic stainless steels: rapid attack at temperatures above 400-500˚C [7]

References

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Summary of maximum temperatures of structural alloys (bare walls) in contact with high-purity liquid or gaseous coolants, based on a 5 μm/yr corrosion limit

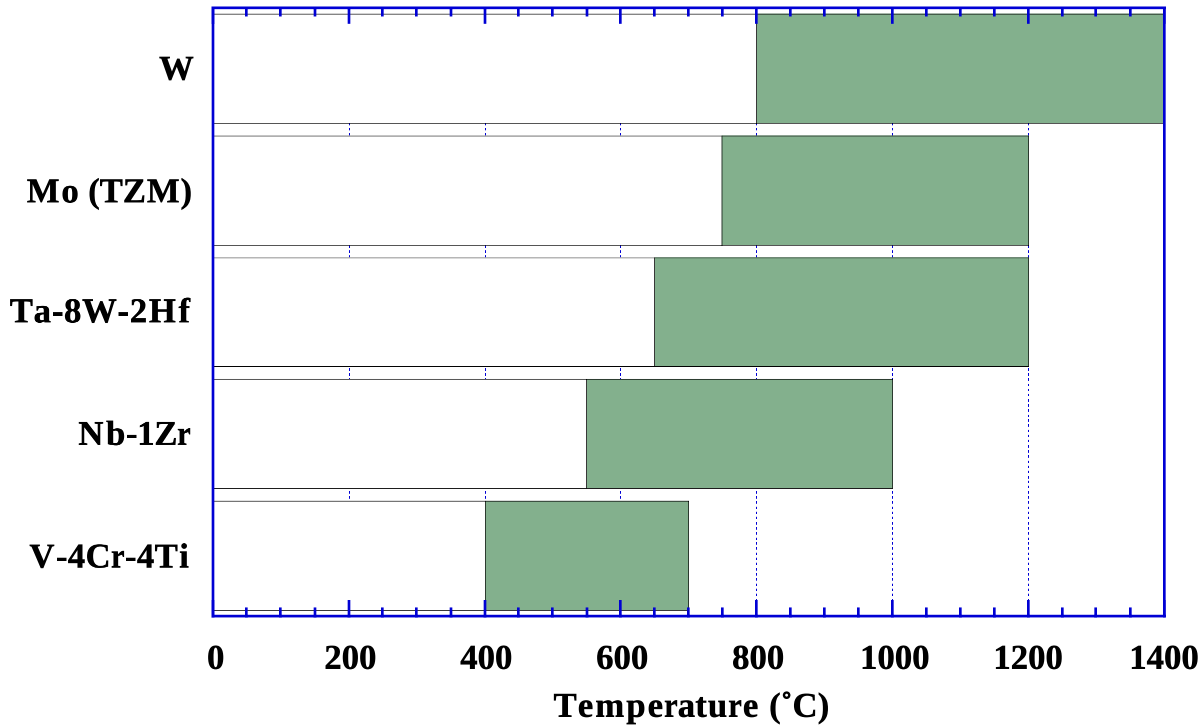
	Li	Pb-17 Li	Sn-20 Li (pure Sn)	Flibe	He*
F/M steel	550-600°C	450°C	~400°C	700°C ? 304/316 st. steel	--
V alloy	600-700°C	~650°C	?	?	~600˚C?§
Nb alloy	>1300°C	>600°C (>1000°C in Pb)	800-850°C	>800°C	?
Ta alloy	>1370°C	>600°C (>1000°C in Pb)	>600°C (>900°C/Sze)	?	?
Mo	>1370°C	>600°C	>700°C (1000°C/Sze)	>1100°C?	~1100°C **
W	>1370°C	>600°C	~1000°C	>900°C?	~1100°C **
SiC	~550°C ?	>800°C ?	?	?	--

* assumes 1 appm O in 50 MPa He gas
** see accompanying APEX presentation by N.M. Ghoniem

§ the temperature limit for vanadium and other Group V metals in helium will be determined by oxide dissolution and oxygen absorption kinetics; recent work (e.g., B.A. Pint et al. 1998) suggests that the temperature limit for V-4Cr-4Ti may be ~600˚C due to interstitial oxygen hardening/embrittlement effects

dashed line (--) indicates that the corrosion-based temperature limit is higher than the structural temperature limit

Estimated Operating Temperature Limits for Refractory Alloys in Fusion Reactors



- Lower temperature limit based on radiation hardening/ fracture toughness embrittlement (K_{1C}<30 MPa-$m^{1/2}$)
- Upper temperature limit based on 100 MPa creep rupture strength; chemical compatibility considerations may cause further decreases in the max operating temp.