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

The graph shows the ultimate tensile strength (MPa) of Group VI refractory alloys as a function of temperature (°C). The data is from various sources: Tietz & Wilson (1965), Conway (1984), Buckman (1994), Gubbi (1996), ITER MPH, and Aerospace Structural Metals Handbook (1969). The filled symbols represent stress-relieved conditions, while the open symbols indicate recrystallized conditions. Specific alloys include W-Mo (TZM) and W-25 Re.
Summary of Recrystallized Tungsten Properties (from IMPH)

Ultimate Tensile Strength (unirradiated)
\[ \sigma_{UTS}(\text{MPa}) = 377.9 + 0.03207 \times T - 1.955 \times 10^{-4} \times T^2 + 5.129 \times 10^{-8} \times T^3 \quad (T \text{ in } ^\circ\text{C}) \]

Yield Strength (Unirradiated)
\[ \sigma_Y(\text{MPa}) = 94.2 - 0.0214 \times T - 2.12 \times 10^{-4} \times T^2 - 7.48 \times 10^{-10} \times T^3 \quad (T \text{ in } ^\circ\text{C}) \]

Elongation
\[ \varepsilon_{\text{tot}}(\%) = 20.8 + 0.053 \times T - 2.18 \times 10^{-5} \times T^2 \quad (T > 500{^\circ}\text{C}) \]

Elastic constants
\[ E_Y (\text{GPa}) = 398 - 0.00231 \times T - 2.72 \times 10^{-5} T^2 \quad (T \text{ in } ^\circ\text{C}) \]
\[ v = 0.279 + 1.09 \times 10^{-5} T \quad (T \text{ in } ^\circ\text{C}) \]

Thermophysical properties
\[ \alpha_m (10^{-6}/^\circ\text{C}) = 3.922 + 5.835 \times 10^{-5} \times T + 5.705 \times 10^{-11} \times T^2 - 2.046 \times 10^{-14} \times T^3 \quad (T \text{ in } ^\circ\text{C}) \]
\[ C_p (\text{J/kg-K}) = 128.3 + 0.0328 \times T - 3.41 \times 10^{-6} \times T^2 \quad (T \text{ in } ^\circ\text{C}) \]
\[ K_{\text{th}} (\text{W/m-K}) = 174.9 - 0.107 T + 5.01 \times 10^{-5} T^2 - 7.835 \times 10^{-9} T^3 \quad (T \text{ in } ^\circ\text{C}) \]

Recommended operating temperature limits (structural applications)
- \( T_{\text{min}} = 800{^\circ}\text{C} \) (due to rad.-induced increase in DBTT at low \( T_{\text{irr}} \))
- \( T_{\text{max}} = 1400{^\circ}\text{C} \) (Li, Pb-Li corrosion/chemical compatibility and thermal creep)
Summary of Recrystallized W-(5-10%) Re Properties

Ultimate Tensile Strength (unirradiated)
\[ \sigma_{\text{UTS}}(\text{MPa}) = 377.9 + 0.03207 \times T - 1.955 \times 10^{-4} \times T^2 + 5.129 \times 10^{-8} \times T^3 \]  
(T in °C) – use pure W values

Yield Strength (Unirradiated)
\[ \sigma_y(\text{MPa}) = 94.2 - 0.0214 \times T - 2.12 \times 10^{-4} \times T^2 - 7.48 \times 10^{-10} \times T^3 \]  
(T in °C) – use pure W values

Elongation
\[ e_{\text{tot}}(\%) = 20.8 + 0.053 \times T - 2.18 \times 10^{-5} \times T^2 \]  
(T > 500°C) -- use pure W values

Elastic constants
\[ E_Y(\text{GPa}) = 398 - 0.00231 \times T - 2.72 \times 10^{-5} \times T^2 \]  
(T in °C) -- pure W values; W-25Re \( E(20°C) = 410 \) GPa
\[ v = 0.279 + 1.09 \times 10^{-5} \times T \]  
(T in °C)  
W-25Re \( v(20°C) = 0.30, G(20°C) = 159 \) GPa

Thermophysical properties
\[ \alpha_m(10^{-6}/\text{°C}) = 3.9 + 5.8 \times 10^{-5} \times T + 5.7 \times 10^{-11} \times T^2 - 2.0 \times 10^{-14} \times T^3 \]  
(T in °C) -- use pure W values
\[ C_p(\text{J/kg-K}) = 128 + 0.033 \times T - 3.4 \times 10^{-6} \times T^2 \]  
(T in °C) -- use pure W values
\[ K_{\text{th}}(\text{W/m-K}) \approx 85 \) W/m-K (1000-2400°C) -- conductivity decreases with increasing Re content

Recommended operating temperature limits (structural applications)
\( T_{\text{min}} = 800°C \) (due to rad.-induced increase in DBTT at low \( T_{\text{irr}} \))
\( T_{\text{max}} = 1400°C \) (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

<table>
<thead>
<tr>
<th></th>
<th>Li</th>
<th>Pb-17 Li</th>
<th>Flibe</th>
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<tr>
<td>F/M steel</td>
<td>550-600°C</td>
<td>450°C</td>
<td>700°C ?</td>
</tr>
<tr>
<td></td>
<td>[1,2,3]</td>
<td>[1,2,9]</td>
<td>304/316 st. steel [13]</td>
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<tr>
<td>V alloy</td>
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<td>[1,4,5]</td>
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<tr>
<td></td>
<td>[6,7]</td>
<td>[10]</td>
<td>[14]</td>
</tr>
<tr>
<td></td>
<td>(&gt;1000°C in Pb) [11]</td>
<td></td>
<td></td>
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<tr>
<td>Ta alloy</td>
<td>&gt;1370°C</td>
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<td>?</td>
</tr>
<tr>
<td></td>
<td>[6,7]</td>
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<tr>
<td>Mo</td>
<td>&gt;1370°C</td>
<td>&gt;600°C</td>
<td>&gt;1100°C ?</td>
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<tr>
<td></td>
<td>[6,7]</td>
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<td>[15,16]</td>
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<tr>
<td>SiC</td>
<td>~550°C ?</td>
<td>&gt;800°C ?</td>
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<td>[8]</td>
<td>[12]</td>
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</table>

References:
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
2. H. Shimotake and J.C. Hesson, Trans. ANS 8 (1965) 413-415
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

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<tr>
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<th>Sn-20 Li (pure Sn)</th>
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<th>He*</th>
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<td>- -</td>
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<td>~650°C</td>
<td>?</td>
<td>?</td>
<td>~600°C?§</td>
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<tr>
<td>Nb alloy</td>
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<td>&gt;600°C</td>
<td>800-850°C</td>
<td>&gt;800°C</td>
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<tr>
<td>Ta alloy</td>
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<td>&gt;600°C</td>
<td>&gt;600°C</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Mo</td>
<td>&gt;1370°C</td>
<td>&gt;600°C</td>
<td>&gt;700°C</td>
<td>&gt;1100°C?</td>
<td>~1100°C **</td>
</tr>
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<td>&gt;800°C ?</td>
<td>~1000°C</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

* 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

- W
- Mo (TZM)
- Ta-8W-2Hf
- Nb-1Zr
- V-4Cr-4Ti

§ Lower temperature limit based on radiation hardening/ fracture toughness embrittlement ($K_{IC}<30$ 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.