Microstructure and creep resistance of Ti-rich Mo + Mo5Si3 + Mo5SiB2 alloys

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Microstructure and Creep Resistance of Ti-rich Mo$_{ss}$ + Mo$_5$Si$_3$ + Mo$_5$SiB$_2$ Alloys

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Background: Mo-Si-B Phase Diagram

Mo$_{ss}$ + A15 + T$_2$

- good creep/oxidation resistance
- acceptable ductility

A15 + T$_1$ + T$_2$

- very good creep/oxidation resistance
- low ductility

Typical alloys:

- Mo-12.5Si-8.5B
- Mo-9Si-8B

50-60% intermetallic phases

T$_m$ $\geq$ 2000°C

Schematic according to Nowotny et al., *Monatshefte für Chemie* (1957)
Nunes et al., *Structural Intermetallics* (1997)

KIT - vertraulich
Background: Mo-Si-B Phase Diagram

**Mo**$_{ss}$ + A15 + T$_2$
- good creep/oxidation resistance
- acceptable ductility

**Optimal Mo**$_{ss}$ + T$_1$ + T$_2$
- very good creep/oxidation resistance
- acceptable ductility

Typical alloys:
- Mo-12.5Si-8.5B
- Mo-9Si-8B

50-60% intermetallic phases
- T$_m$ ≥ 2000°C

Schematic according to Nowotny et al., *Monatshefte für Chemie* (1957)
- Nunes et al., *Structural Intermetallics* (1997)
### Alloyning Concept in Mo-Si-B Alloys

**Stabilizing elements:**
- \( \text{Mo}_{ss} \): Ti, Nb, Ta, W, Zr, Hf, V, Cr
- \( T_2 \): Ti, Nb, Ta, W, Zr, Hf, V, Cr
- \( T_1 \): Ti, Nb, Ta, W
- A15: V, Cr, Al
- D\text{8}_8: Ti, Zr, Hf

<table>
<thead>
<tr>
<th>( \text{Mo}_{ss} + \text{A15} + T_2 )</th>
<th>( \text{Mo}_{ss} + \text{A15} + T_1 )</th>
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<tbody>
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<td>Mo-Si-B</td>
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<tr>
<th>( \text{Mo}_{ss} + T_1 + T_2 )</th>
<th>( \text{Mo}_{ss} + T_2 + \text{D8}_8 )</th>
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</thead>
<tbody>
<tr>
<td>( \text{Mo-Si-B} + \text{V/Cr/Al} )</td>
<td>( \text{Mo-Si-B} + \text{Ti/Nb/Ta/W} )</td>
</tr>
</tbody>
</table>

Some elements can stabilize additional phase equilibria:
- \( \text{Mo}_{ss} + T_1 + T_2 \) by alloying with Ti, Nb, Ta, W

Thermodynamic calculation of Mo-Si-B-xTi alloys

Mo-12.5Si-8.5B-27.5Ti 1600 °C 150 h

- Formation of $T_1$ instead of A15 phase and increase of Mo$_{ss}$ phase fraction at 27 at.% Ti
- Yang et al. [1] found Mo$_{ss} + T_1 + T_2 + A15$ phase equilibria at 1600°C
- Could not be reproduced in this work

How can $T_1$ be stabilized?

Effect of Fe on stability of Mo$_{ss}$ + $T_1$ + $T_2$ phase equilibria

Mo-12.5Si-8.5B-27.5Ti-2Fe 1400 °C 100 h

- Ti-concentration for Mo$_{ss}$ + $T_1$ + $T_2$ phase equilibrium is expanded by 2 at.% Fe
- Heat treatment at lower Temperature increase possible Ti-concentration
- D8$_8$ as a residual phase below 3 vol.%

Validation for Mo-12.5Si-8.5B-xTi-2Fe at 1400°C
Experimental results for Mo-12.5Si-8.5B-xTi-2Fe

Mo-12.5Si-8.5B-27.5Ti-2Fe 1400 °C 100 h

- Results and simulation are in good agreement, slight shift to higher Ti
- $T_1$ stable for wide range of Ti after heat treatment at 1400°C

How is the creep behavior of $Mo_{ss} + T_1 + T_2$ alloys?
Creep behavior of Mo$_{ss}$ + T$_1$ + T$_2$ alloys

- Compression creep behavior was examined in vacuum
- Formation of slight <111> texture during deformation

![Graph showing creep behavior](image)

- T = 1200 °C
- $\sigma = 200$ MPa

Mo-12.5Si-8.5B-27.5Ti-2Fe

50 µm

KIT - vertraulich
Creep behavior of Mo\textsubscript{ss} + T\textsubscript{1} + T\textsubscript{2} alloys

- Compression creep behavior was examined in vacuum
- Formation of slight $<$111$>$ texture during deformation of Mo\textsubscript{ss}

\[ T = 1200 \, ^\circ\text{C} \]
\[ \sigma = 200 \, \text{MPa} \]

\[ \text{Mo-12.5Si-8.5B-27.5Ti-2Fe} \]

\[ \text{HT 1400} \, ^\circ\text{C} \]
\[ \text{HT 1600} \, ^\circ\text{C} \]
Creep behavior of Mo$_{ss} + T_1 + T_2$ alloys

Norton Plot

- Value of $n$ is close to 3
- Suggests dislocation climbed controlled creep in Mo$_{ss}$ as dominate mechanism
Creep behavior of Mo_{ss} + T_1 + T_2 alloys

Arrhenius Plot

- Activation energy only slightly larger than for pure Mo self diffusion (405 kJ/mol)
- suggests dislocation climbed controlled creep in Mo_{ss} as dominate mechanism
- higher value probably by interdiffusion of Ti in Mo
Creep behavior of Mo$_{ss}$ + T$_1$ + T$_2$ alloys

Literature comparison

Mo$_{ss}$ + T$_1$ + T$_2$ alloys have better creep resistance than CMSX-4 at 1200 °C

Mo-12.5Si-8.5B-27.5Ti have lowest minimum strain rates

Summary and Conclusion

- Mo$_{ss}$ + T$_1$ + T$_2$ phase equilibria is stable in Ti-rich Mo-Si-B alloys while Fe is present
- T$_1$ is stabilized for wide range of Ti
- Necessary Ti-concentration depends also on HT temperature
- Simulation and Experiment are in good agreement

- Creep is controlled by dislocation climb in Mo$_{ss}$ at 1200 °C
  - Refinement of microstructure during creep deformation
  - Slight <111> texture in compression direction
  - Stress exponent n is close to 3
  - Activation energy of 470 kJ/mol slightly higher than Mo self diffusion (405 kJ/mol) → Interdiffusion coefficient?
- Creep resistance higher than for CMSX-4
Thank you for your Attention!

Acknowledgement

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