High-temperature strength of $L1_2$-hardened Compositionally Complex Alloys

Sebastian Haas$^1$, Anna Manzoni$^2$, Uwe Glatzel$^1$

$^1$Metals and Alloys, University Bayreuth, Germany
$^2$Helmholtz-Zentrum Berlin für Materialien und Energie
Content

• Introduction:
  ➢ High Entropy Alloys (HEA)
  ➢ Compositionally Complex Alloys (CCA)

• Base alloy Al$_{10}$Co$_{25}$Cr$_8$Fe$_{15}$Ni$_{36}$Ti$_6$ (in at.\%)

• Modification by hafnium and molybdenum

• Mechanical characterization

• Discussion

• Summary
High entropy alloys

- At least 5 components
- Near equiatomic composition

\[ S_{conf} = -R \cdot \sum_{i=1}^{n} (c_i \cdot \ln c_i) \]

- High strength
- High hardness
- Thermal stability
- Sluggish diffusion kinetics
- Oxidation and corrosion resistance

Introduction

High entropy alloys
- Insufficient properties
- No solid-solution stabilization

Compositionally Complex Alloys
Multiphase microstructure as the prominent and promising feature

AlCoCrCuFeNi
- More than 6 phases
- Phases with bcc-structure
- Brittle mechanical behavior

Al_{10}Co_{25}Cr_{8}Fe_{15}Ni_{36}Ti_{6}
- 3 phases left
- Fcc-structured matrix
- Good strength-ductility relation
**Base alloy**

**C1-phase**
- Needle-like precipitates
  - Al-rich (28 at.%) cF12, Fm3m, C1
  - Length up to 50 µm
  - Volume content < 5 %

**γ/γ´-structure**
- Fcc-structure
  - Fe-, Co-, Cr-rich
  - Length up to 50 µm
  - Volume content < 5 %

**Dendritic solidification**
- γ-particles (primary)
  - L1₂-structure
  - Ni-, Al-, Ti-rich
  - Edge length ~ 450 nm
  - Volume content ~ 40 %

**Homogenization:**
- 1220 °C / 20 h
**Annealing:**
- 900 °C / 50 h
Impact of refractory metals hafnium and molybdenum

+ 1 at.% Mo
Solid-solution hardening

- Needle-like C1-phase
- Cubic γ´-particles

+ 0.5 at.% Hf
Stabilization of γ´

Base alloy

Following talk by Dr. Anna Manzoni
Heat treatment variation

Increase of
- $\gamma'$-particle size
- C1-volume fraction

Role of C1-phase in the mechanical behavior?

900°C for 50 hours

950°C for 100 hours

950°C for 100 hours
Material & Methods

Vacuum induction furnace
- Directionally solidified (DS)
- Conventionally cast (CC)
- Argon atmosphere
- Ceramic mould: 1400 °C

Heat treatment:
- Homogenization
- Annealing
  - 900 °C / 50 h
  - 950 °C / 100 h
  - Furnace cooling

Two ways of comparing tensile tests:

Base alloy:
- DS
- CC
- 900 °C – 50 h
- 950 °C – 100 h

Direct. Solid.
- 950°C – 100 h:
  - Base alloy
  - Hf addition
  - Mo addition

Flat specimen
1.0 mm ∙ 1.9 mm ∙ 8.0 mm

room temperature,
600 °C, 700 °C,
800 °C, 900 °C
Tensile tests

1) Base alloy

[Graphs showing stress-strain curves for different temperatures and heat treatments.]

- DS at 900 °C for 50 h
- CC at 900 °C for 50 h
- DS at 950 °C for 100 h

University Bayreuth

Sebastian Haas, Metals and Alloys
Tensile tests
1) Base alloy

Directionally Solidified: 900 °C / 50 h

- High tensile strength
- Good strain to failure
- High reproducibility

- Directional solidified grains in direction of load
- Decrease of needle-like C1-phase
- Decrease of γ´-particle size

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Ultimate tensile strength (in MPa)</th>
<th>Strain to failure (in %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>~23</td>
<td>1197 ± 6</td>
<td>27 ± 1</td>
</tr>
<tr>
<td>600</td>
<td>1006 ± 16</td>
<td>12 ± 2</td>
</tr>
<tr>
<td>700</td>
<td>840 ± 1</td>
<td>17 ± 5</td>
</tr>
<tr>
<td>800</td>
<td>575 ± 7</td>
<td>20 ± 4</td>
</tr>
<tr>
<td>900</td>
<td>319 ± 1</td>
<td>34 ± 1</td>
</tr>
</tbody>
</table>
Tensile tests

2) Addition of Hf and Mo

Base alloy
DS
950 °C
100 h

+ Hf
DS
950 °C
100 h

+ Mo
DS
950 °C
100 h
Tensile tests

2) Addition of Hf

- High tensile strength
- Good strain to failure
- High reproducibility

- Sharp-edged $\gamma'$-particles
- Spherical shape of C1-phase

**Al$_{9.5}$Co$_{25}$Cr$_8$Fe$_{15}$Ni$_{36}$Ti$_6$Hf$_{0.5}$**

<table>
<thead>
<tr>
<th>Temperature ($^\circ$C)</th>
<th>Ultimate tensile strength (in MPa)</th>
<th>Strain to failure (in %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>$1050 \pm 7$</td>
<td>$12 \pm 1$</td>
</tr>
<tr>
<td>700</td>
<td>$904 \pm 12$</td>
<td>$16 \pm 1$</td>
</tr>
<tr>
<td>800</td>
<td>$612 \pm 5$</td>
<td>$24 \pm 1$</td>
</tr>
<tr>
<td>900</td>
<td>$344 \pm 5$</td>
<td>$34 \pm 2$</td>
</tr>
</tbody>
</table>

~23 $^\circ$C

Ultimate tensile strength (in MPa) $1107 \pm 43$

Strain to failure (in %) $20 \pm 1$
Discussion

Detrimental impact of increasing needle-like C1-phase dominates bigger γ’-particles.

Spherical C1-phase improves mechanical properties compared to needle-like geometry.

Is a spherical form of C1-phase beneficial or less detrimental?
Addition of Tungsten: $\text{Al}_9\text{Co}_{25}\text{Cr}_8\text{Fe}_{15}\text{Ni}_{36}\text{Ti}_6\text{W}_1$

1220 °C / 20 h
900 °C / 50 h

2-phase microstructure!
No C1-phase!

Mechanical characterization will provide more information about the role of C1-phase
Summary

Directional solidification increases the ultimate tensile strength:
- 72% at 23 °C
- 80% at 600 °C
- 50% at 700 °C

Less needle-like C1-phase increases the ultimate tensile strength:
- 58% at 23 °C
- 38% at 600 °C
- 19% at 700 °C

Hf-addition (spherical C1) increases the ultimate tensile strength:
- 46% at 23 °C
- 31% at 600 °C
- 29% at 700 °C

Al_{10}Co_{25}Cr_{8}Fe_{15}Ni_{36}Ti_{6}: \( \gamma' \)- and C1-phase change due to …

- Addition of elements in small amounts
- Variation of annealing treatment

C1-phase plays the important role for the mechanical behavior
- Gain more information about thermal & chemical stability
Thank you for your attention!