COMPARISON OF Ni-Cr AND Co-BASED ALLOYS FOR FUEL INJECTORS

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Introduction

- reduction of fuel consumption and pollutant emission
  - higher efficiency motor development
  - increase of fuel injection pressure in cylinders
  - higher stresses in injection system components

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- inadequacy of steels → use of Co based alloys or Ni-Cr alloys for components mechanically stressed at high temperature

- literature about these alloys mainly concerns wear and corrosion resistance at high temperature, with few data on high temperature fatigue

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A Ni-Cr alloy is compared with previously examined Co-based ones
Materials & specimens

Tensile and fatigue cylindrical (not notched) specimens, 8 mm diameter
- “weloral” Ni-Cr alloy made by powder metallurgy + HIP
- “stellite 6” Co alloys, produced by casting, or by powder metallurgy + HIP

Experimental methods

Mechanical tests
- hardness and micro-hardness tests at R.T.
- tensile tests at R.T., at 250 or 500 °C
- pulsed traction fatigue tests (R ≈ 0) up to $2 \cdot 10^6$ cycles at 500 °C

Crystallographic and micro-structural tests
- both on as received material, and after the 500 °C treatment
- X ray diffraction (Co anode)
- optical and scanning electron metallography and EDS micro-analysis

Fractography
Chemical composition (% wt.)

<table>
<thead>
<tr>
<th>HIP PM Ni-Cr Alloy</th>
<th>Ni</th>
<th>C</th>
<th>Cr</th>
<th>Al</th>
<th>Co</th>
<th>Si</th>
<th>Mn</th>
<th>Fe</th>
<th>V</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>bal.</td>
<td>0.46</td>
<td>48.5</td>
<td>0.055</td>
<td>0.023</td>
<td>0.41</td>
<td>0.11</td>
<td>0.14</td>
<td>0.028</td>
<td>0.028</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cast Co Alloy</th>
<th>Co</th>
<th>C</th>
<th>Cr</th>
<th>W</th>
<th>Ni</th>
<th>Si</th>
<th>Mn</th>
<th>Fe</th>
<th>V</th>
<th>Nb</th>
</tr>
</thead>
<tbody>
<tr>
<td>bal.</td>
<td>1.19</td>
<td>25.5</td>
<td>5.21</td>
<td>1.99</td>
<td>1.56</td>
<td>0.69</td>
<td>0.85</td>
<td>0.028</td>
<td>0.034</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>HIP PM Co Alloy</th>
<th>Co</th>
<th>C</th>
<th>Cr</th>
<th>W</th>
<th>Ni</th>
<th>Si</th>
<th>Mn</th>
<th>Fe</th>
<th>V</th>
<th>Nb</th>
</tr>
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<tbody>
<tr>
<td>bal.</td>
<td>1.48</td>
<td>27.2</td>
<td>4.78</td>
<td>0.30</td>
<td>1.21</td>
<td>0.21</td>
<td>0.44</td>
<td>0.021</td>
<td>0.002</td>
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</table>
XRD Analyses – HIP PM Ni-Cr alloy (Bragg-Brentano geometry, Co anode)

- ≈ 70 % FCC Ni with some Cr in solid solution
- ≈ 30 % BCC Cr
- Possible Cr carbides
Alloy position in the Ni-Cr phase diagram
XRD Analyses - Co alloys (Bragg-Brentano geometry, Co anode)

- **Cast alloy:**
  - Probable prevalence of $\text{Co}_{\text{FCC}}$ in respect to $\text{Co}_{\text{HCP}}$
  - Other phases: Cr carbides and intermetallic compounds
  - Possible phase evolution on heating at 500 °C

- **HIP PM alloy:**
  - Prevalence of $\text{Co}_{\text{FCC}}$, with some $\text{Co}_{\text{HCP}}$
  - Possible presence of intermetallic compounds and carbides
  - No phase evolution on heating at 500 °C
Microstructures - HIP PM Ni-Cr alloy (OM)
Microstructures - HIP PM Ni-Cr alloy
image analysis of SEM – back-scattered (BS) electrons images

Cr-rich BCC phase (black): ≈30%
**Cast Co alloy microstructure**

Main primary dendrites
Inter-dendritic carbides (lamellar)
No differences after 500 °C treatment

**Matrix**

<table>
<thead>
<tr>
<th>Cr</th>
<th>Co</th>
<th>W</th>
<th>Mo</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>71</td>
<td>3.5</td>
<td>0.24</td>
<td>0.65</td>
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</tbody>
</table>

**Cr carbides**

<table>
<thead>
<tr>
<th>Cr</th>
<th>Co</th>
<th>W</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>78</td>
<td>15</td>
<td>6.3</td>
<td>0.43</td>
</tr>
</tbody>
</table>

**Co, W carbides**

<table>
<thead>
<tr>
<th>Cr</th>
<th>Co</th>
<th>W</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>47</td>
<td>29</td>
<td>2.7</td>
</tr>
</tbody>
</table>

OM, 456 x 362 μm

SEM (BS)
HIP PM Co Alloy microstructure

Co rich matrix, dispersed carbides, about 2 μm diameter. Grain size in the range of 5-40 μm with the most part in the range 5-10 μm.
# Hardness and microhardness

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Macroscopic hardness</th>
<th>HV 0.05 Dendritic zones</th>
<th>HV 0.05 Carbides rich zones</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIP NiCr Alloy</td>
<td>370 HV100</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cast Co Alloy</td>
<td>370 HV50</td>
<td>400-430</td>
<td>530-1100</td>
</tr>
<tr>
<td>HIP Co Alloy</td>
<td>460 HV50</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Cast sample: scattered results on precipitated carbide zone (hardness indent large in respect to dimension of carbides)
Mechanical tests

Tensile strength

Stress [MPa]

Deformation (from the crosshead displacement)

- Cast Co alloy, 500°C
- Cast Co alloy, 250°C
- HIP Co alloy, 500°C
- Cast Co alloy, 20°C
- HIP Ni-Cr alloy, 500°C
- HIP Co alloy, 250°C
Fractography – HIP PM NiCr alloy, tensile fracture at 500 °C

The fracture is microscopically ductile (microvoids coalescence) and probably follows the sintered powder boundaries.
Mainly inter-dendritic fracture (a), with some trans-dendritic quasi-cleavage fracture
Fractography – HIP PM Co alloy tensile fracture at 500°C

The fracture is ductile, nucleated by the presence of an inclusion.
Fatigue - HIP PM Ni-Cr alloy
pulsed traction fatigue tests (R ≈ 0), up to $2 \cdot 10^6$ cycles, at 500°C

<table>
<thead>
<tr>
<th>Strength (MPa)</th>
<th>Specimens results</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>660</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>650</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>640</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>630</td>
<td></td>
<td></td>
</tr>
<tr>
<td>620</td>
<td>O</td>
<td></td>
</tr>
<tr>
<td>610</td>
<td></td>
<td></td>
</tr>
<tr>
<td>600</td>
<td>O</td>
<td></td>
</tr>
</tbody>
</table>

Fatigue limit (for $2 \cdot 10^6$ cycles) ≈ 640 MPa

X: specimen broken before $2 \cdot 10^6$ cycles
O: specimen completes $2 \cdot 10^6$ cycles
CAST Co-Alloy
pulsed traction fatigue tests (R ≈ 0), up to $2 \cdot 10^6$ cycles, at 500°C

<table>
<thead>
<tr>
<th>Strength (Mpa)</th>
<th>Specimens results</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>O</td>
</tr>
<tr>
<td>410</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>400</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>390</td>
<td>O</td>
<td>X</td>
</tr>
<tr>
<td>380</td>
<td></td>
<td>O</td>
</tr>
<tr>
<td>370</td>
<td></td>
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</tr>
</tbody>
</table>

Fatigue limit (for $2 \cdot 10^6$ cycles) ≈ 390 MPa

X: specimen broken before $2 \cdot 10^6$ cycles  
O: specimen completes $2 \cdot 10^6$ cycles
HIP PM Co-alloy
pulsed traction fatigue tests (R \approx 0), up to \(2 \cdot 10^6\) cycles, at 500°C

<table>
<thead>
<tr>
<th>Strength (MPa)</th>
<th>Specimens results</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1  2  3  4  5  6  7  8  9  10</td>
<td>X  O</td>
</tr>
<tr>
<td>740</td>
<td>X</td>
<td>1</td>
</tr>
<tr>
<td>720</td>
<td></td>
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</tr>
<tr>
<td>700</td>
<td>X</td>
<td>1</td>
</tr>
<tr>
<td>680</td>
<td>X  O</td>
<td>1  1</td>
</tr>
<tr>
<td>660</td>
<td>O  O</td>
<td>2</td>
</tr>
</tbody>
</table>

Fatigue limit (for \(2 \cdot 10^6\) cycles) \approx 660 MPa

X: specimen broken before \(2 \cdot 10^6\) cycles
O: specimen completes \(2 \cdot 10^6\) cycles
Fractography – HIP PM NiCR alloy, fatigue fracture at 500°C

Nucleation zone (detail)

propagation

640 MPa

660 MPa
Fractography – HIP NiCR alloy, fatigue tests at 500°C

Sample 6 (640 MPa fatigue) initiation inclusion

Sample 3 (640 MPa fatigue) initiation inclusion
Fractography – cast Co alloy, fatigue fracture at 500° C

Nucleation and propagation fatigue fracture zones

detail of stair-step fatigue propagation
Fractography – HIP PM Co alloy, fatigue test at 500°C

Fracture surface observed by means of Stereo Macro-scope.

The fatigue fracture is nucleated by the presence of an inclusion.

Nucleation zone (detail)
Discussion and conclusions (I/II)

★ Hipped PM Ni-Cr are biphasic, with about 70% Ni-rich FCC and 30% Cr BCC phases (confirmed by XRD analyses), with 1-5 µm grain size, with some porosity and inclusions.

★ The cast Co alloy samples are formed by cobalt rich, FCC primary dendrites and lamellar inter-dendritic zones (eutectic mixtures) with high carbides content. EDS micro-analyses evidenced two carbide types: one with high Cr content, the other with high W content.

★ Hipped PM Co alloy samples present a Co rich matrix and dispersed carbides, about 2 µm diameter. Grain size is in the range of 5-40 µm with the most part in the range 5-10 µm.


Discussion and conclusions (II/II)

The best performance both in tensile tests and in fatigue tests was observed for the hipped PM samples. In particular, in monotonic tests, the hipped Cr-Ni alloy was intermediate between the cast Co alloy and the hipped alloy. In fatigue tests the hipped Cr-Ni alloy behaved almost as the hipped Co alloy and much better than the cast Co one.

The tensile fracture of the cast Co alloy is mainly inter-dendritic, completed by a quasi cleavage intra-dendritic fracture. In the HIP treated materials (both the Ni-Cr alloy and the Co one), a ductile fracture is nucleated by inclusions.

In fatigue tests, the crack of cast samples is nucleated by casting defects and propagates on crystallographic planes, in a trans-dendritic way, with a stair morphology. The crack of hipped samples is nucleated by an inclusion and the fracture is mainly ductile.