[Other] Comparison of Ni-Cr and Co-based alloys for fuel injectors

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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.)

HIP PM Ni-Cr Alloy

Ni	C	Cr	Al	Co	Si	Mn	Fe	V	Mg
bal.	0.46	48.5	0.055	0.023	0.41	0.11	0.14	0.028	0.028

Cast Co Alloy

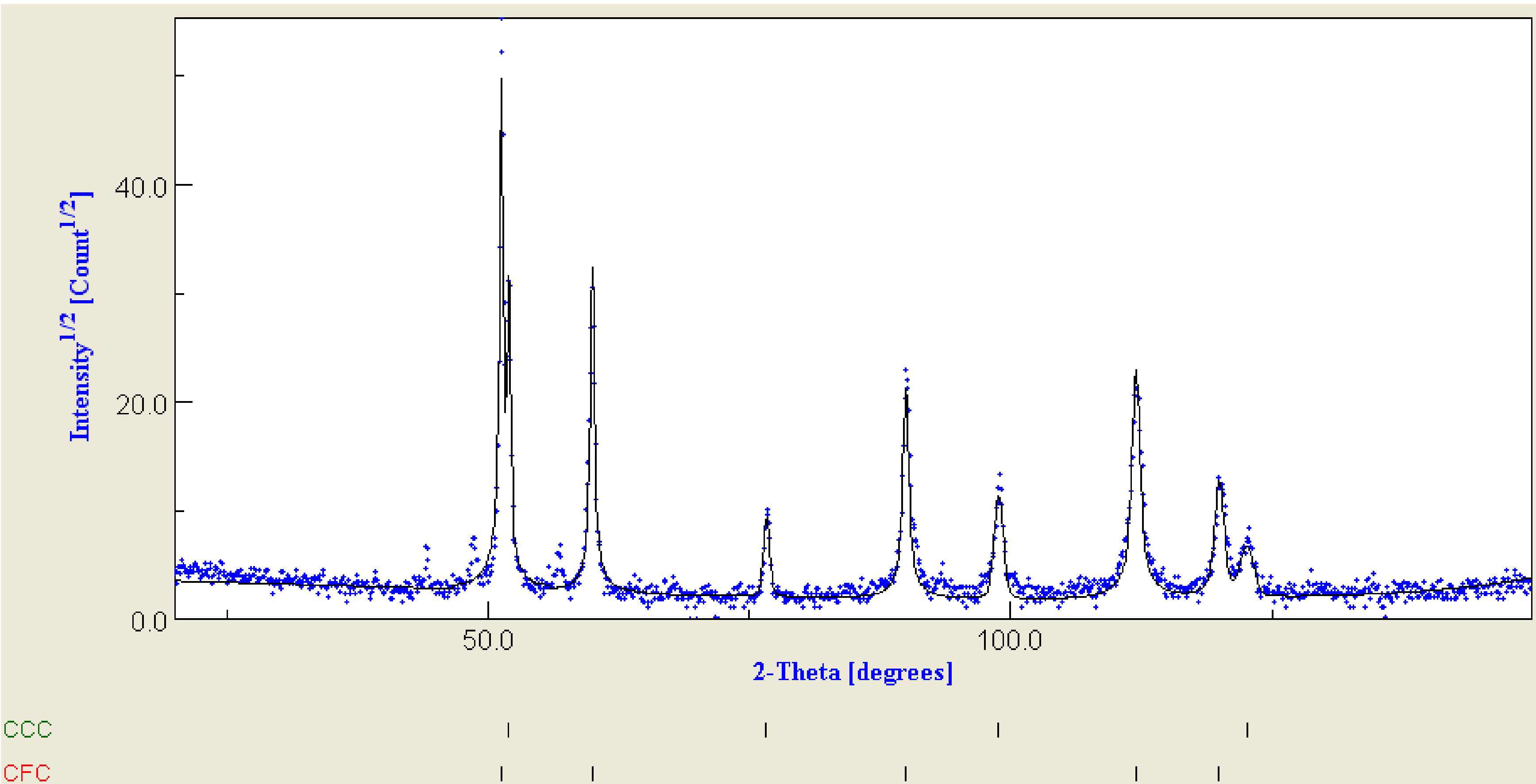
Co	C	Cr	W	Ni	Si	Mn	Fe	V	Nb
bal.	1.19	25.5	5.21	1.99	1.56	0.69	0.85	0.028	0.034

HIP PM Co Alloy

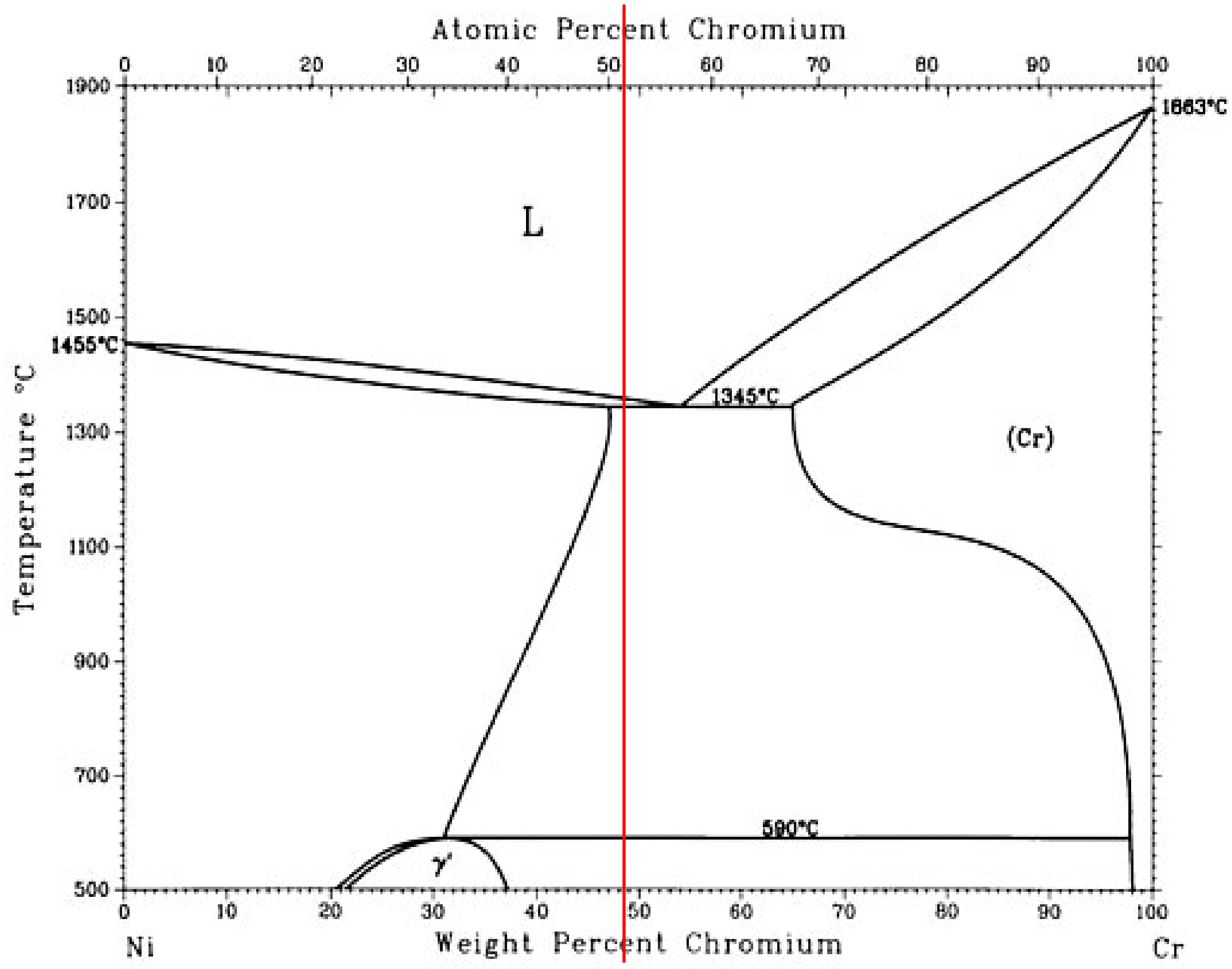
Co	C	Cr	W	Ni	Si	Mn	Fe	V	Nb
bal.	1.48	27.2	4.78	0.30	1.21	0.21	0.44	0.021	0.002

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

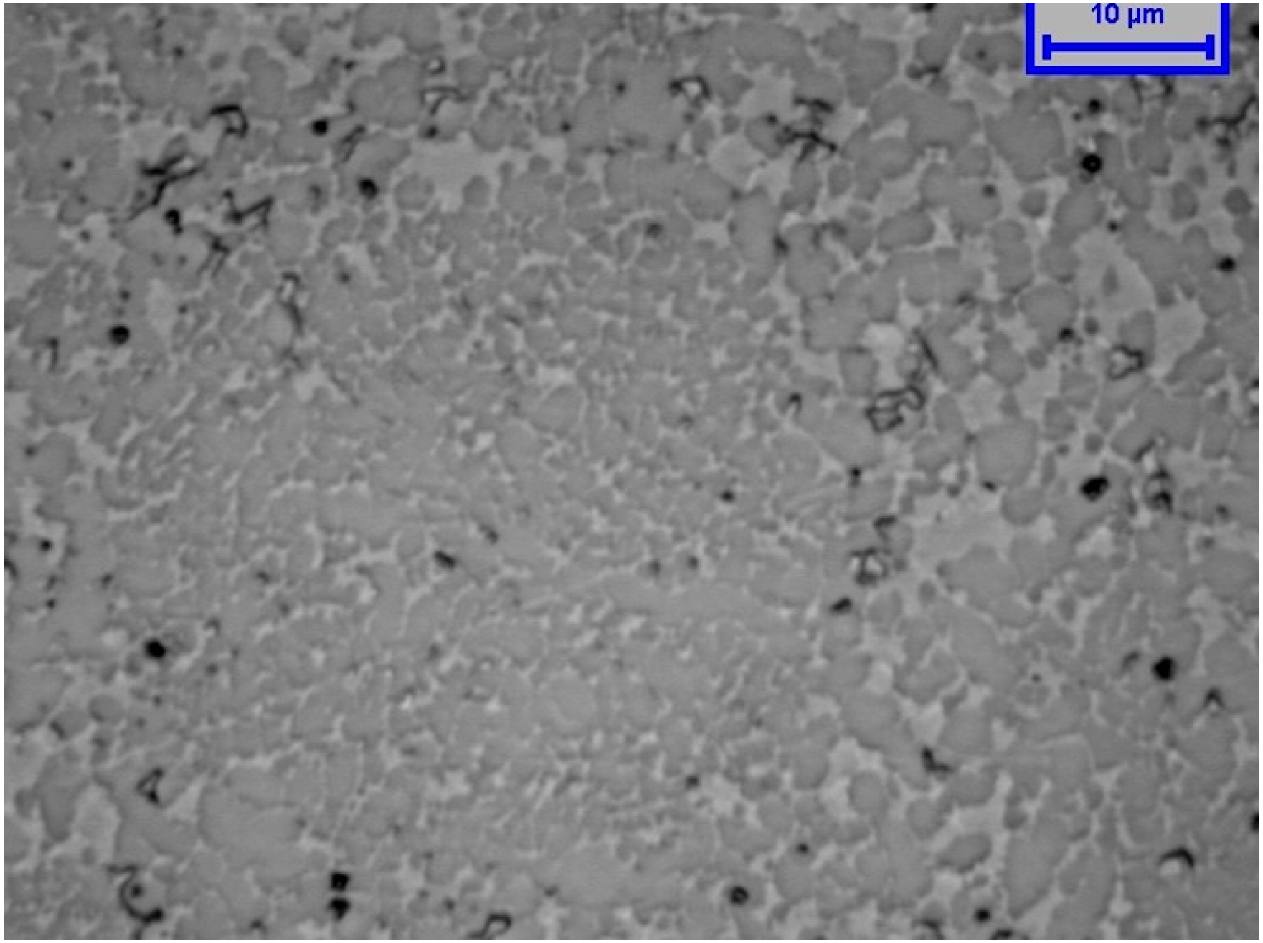


XRD Analyses - Co alloys *(Bragg-Brentano geometry, Co anode)*

- Cast alloy:
  - Probable prevalence of Co_{FCC} in respect to Co_{HCP}
  - Other phases: Cr carbides and intermetallic compounds
  - Possible phase evolution on heating at 500 C

- HIP PM alloy:
  - Prevalence of Co_{FCC}, with some Co_{HCP}
  - Possible presence of intermetallic compounds and carbides
  - No phase evolution on heating at 500 C

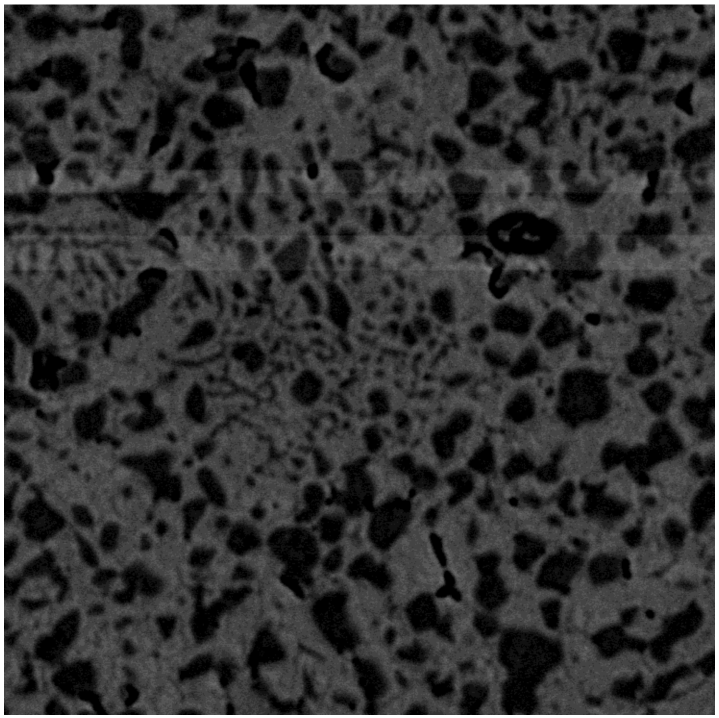
Microstructures - HIP PM Ni-Cr alloy (OM)

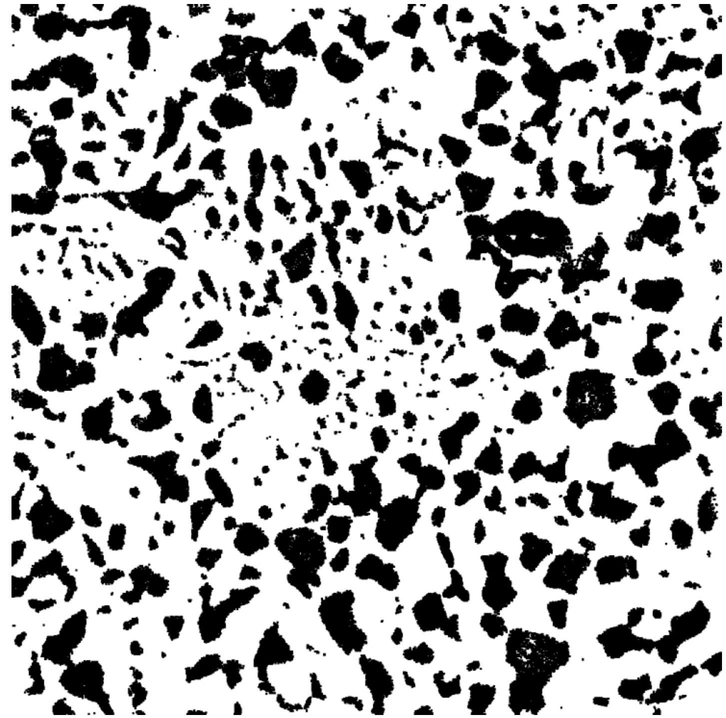


Microstructures - HIP PM Ni-Cr alloy

image analysis of SEM – back-scattered (BS) electrons images

50 x 50 µm





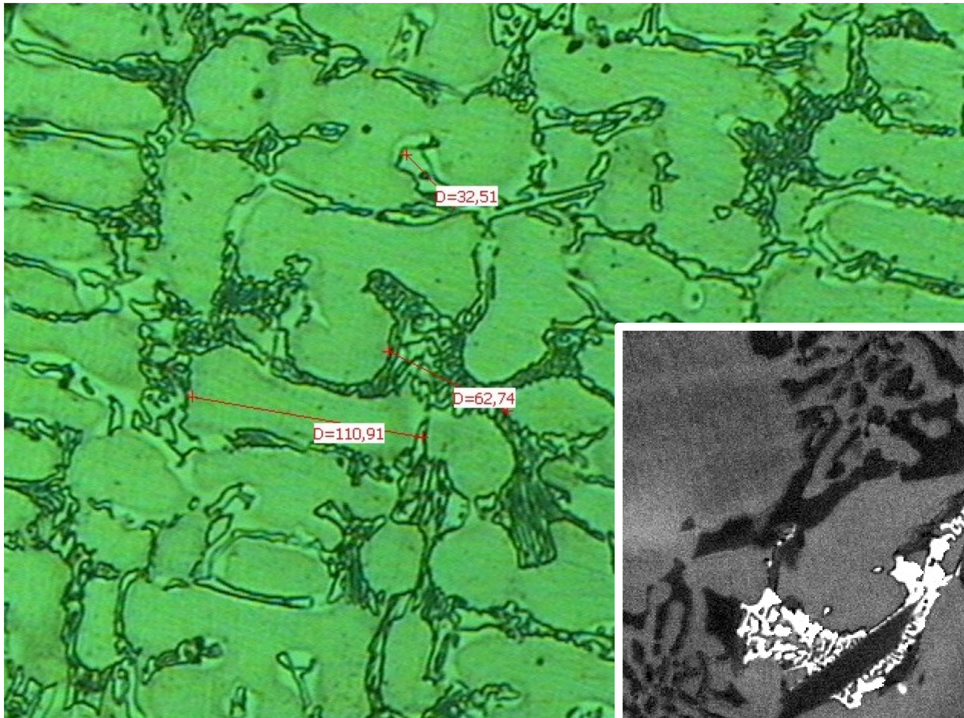
Cr-rich BCC phase (black): ≈30%

Cast Co alloy microstructure

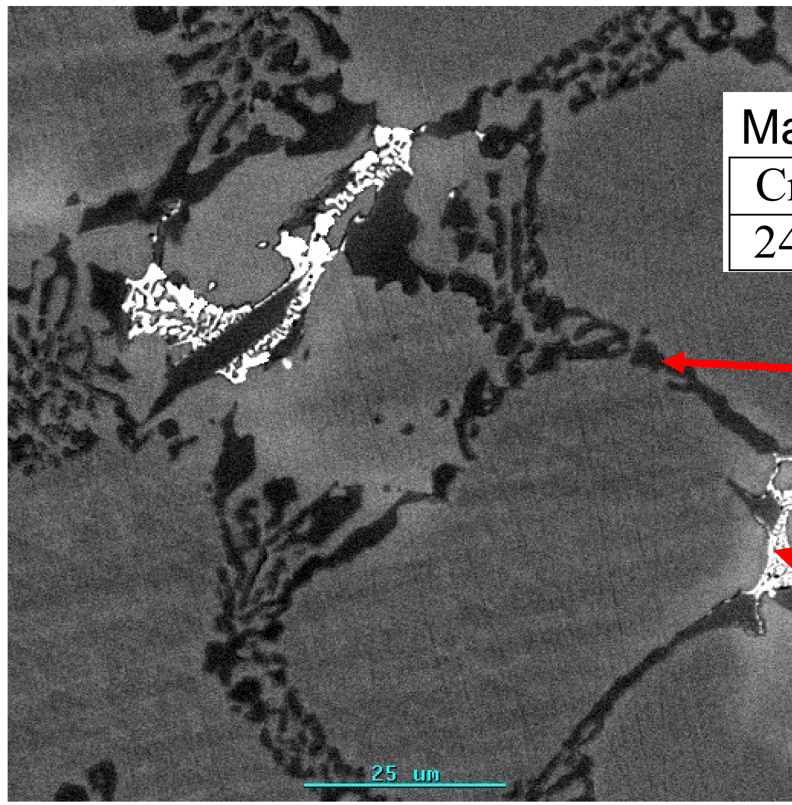
Main primary dendrites

Inter-dendritic carbides (lamellar)

No differences after 500 C treatment



OM, 456 x 362 μm



SEM (BS)

Matrix

Cr	Co	W	Mo	Si
24	71	3.5	0.24	0.65

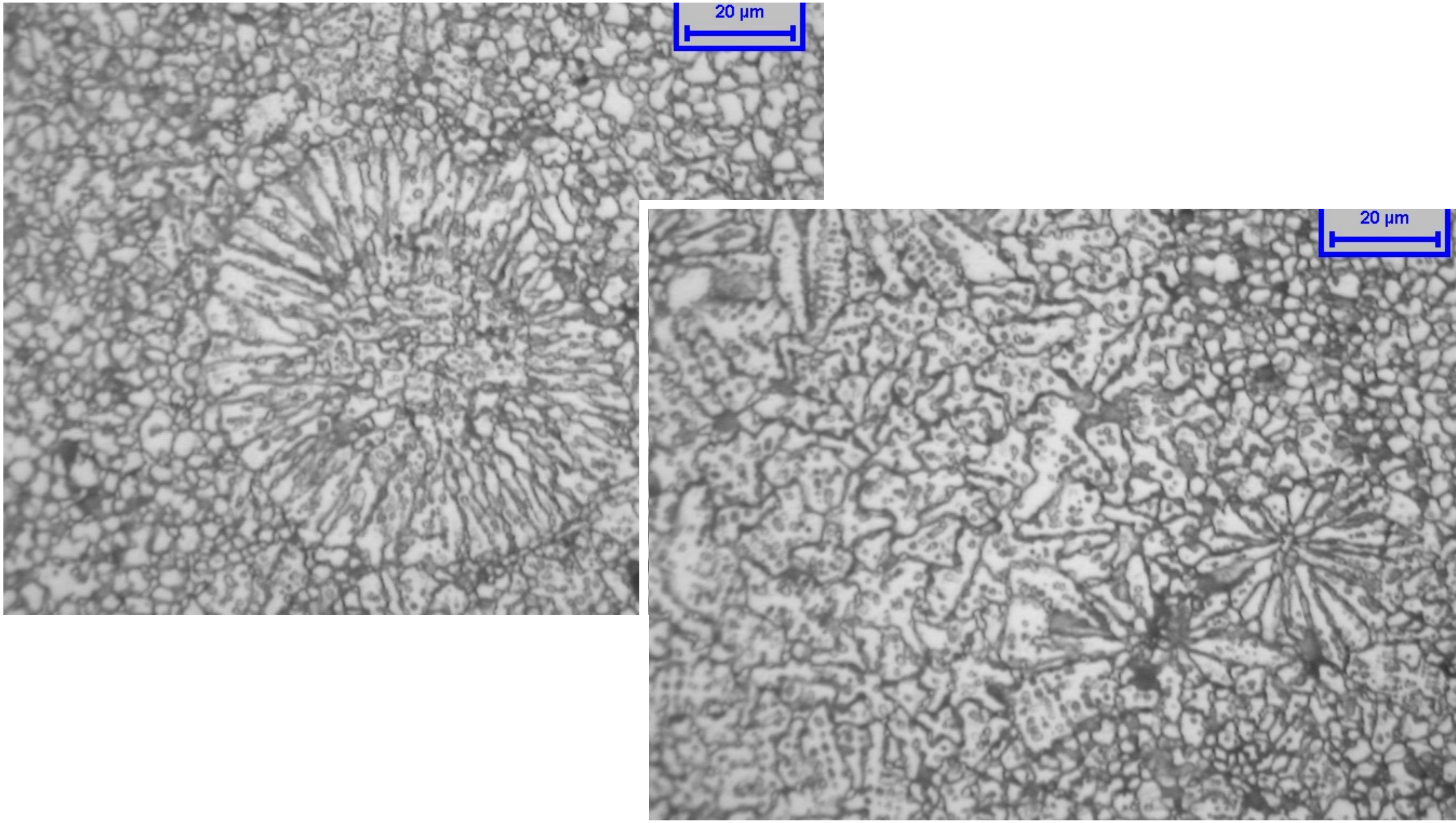
Cr carbides

Cr	Co	W	Mo
78	15	6.3	0.43

Co, W carbides

Cr	Co	W	Mo
21	47	29	2.7

HIP PM Co Alloy microstructure



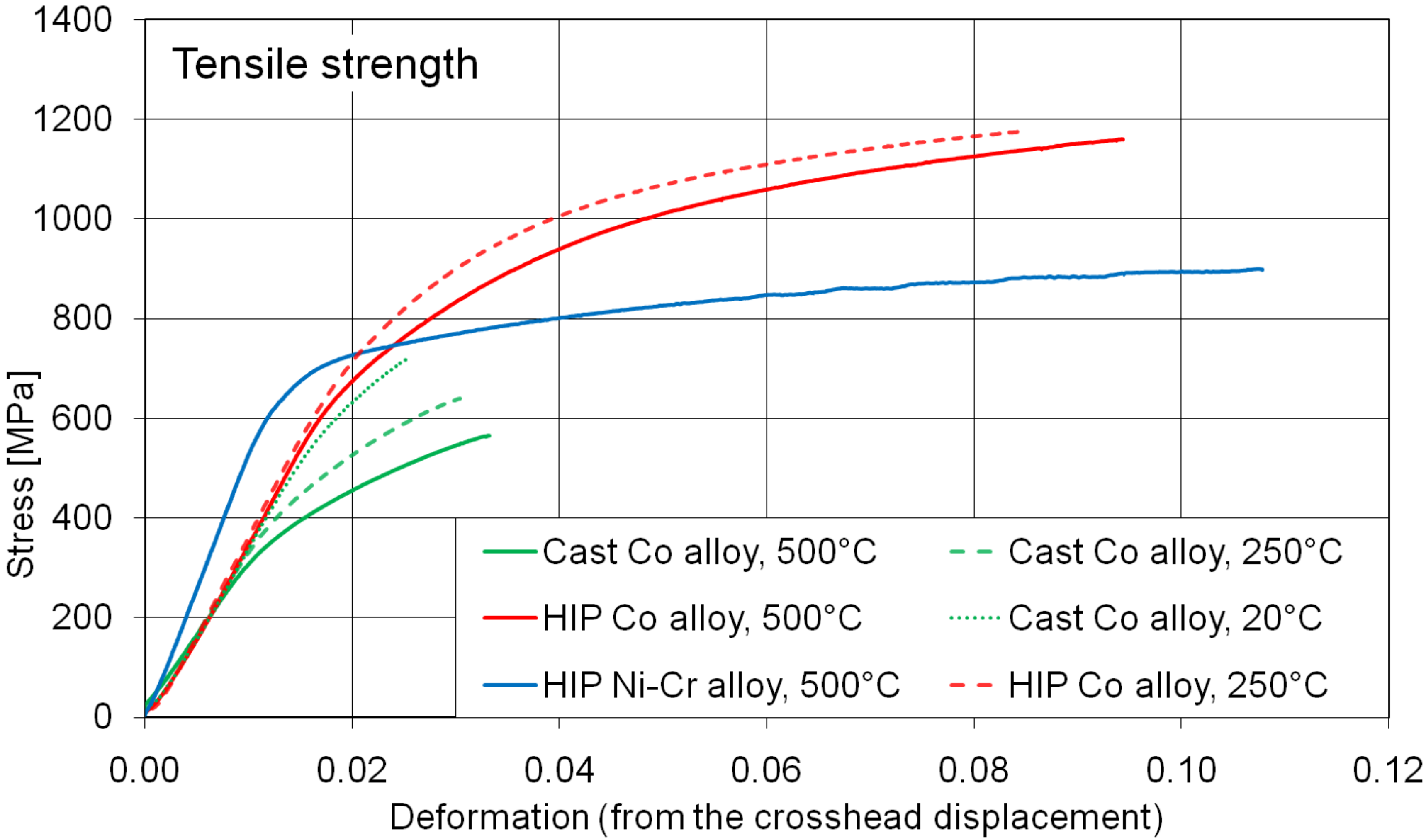
Co rich matrix, dispersed carbides, about 2 µm diameter. Grain size in the range of 5-40 µm with the most part in the range 5-10 µm.

Hardness and microhardness

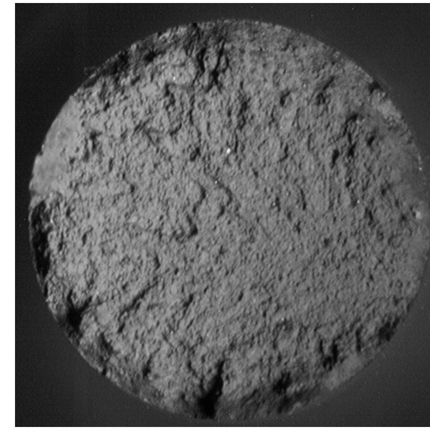
Alloy	**Macroscopic hardness**	HV 0.05 Dendritic zones	HV 0.05 Carbides rich zones
HIP NiCr Alloy	**370 HV100**	-	-
Cast Co Alloy	370 HV50	400-430	530-1100
HIP Co Alloy	460 HV50	-	-

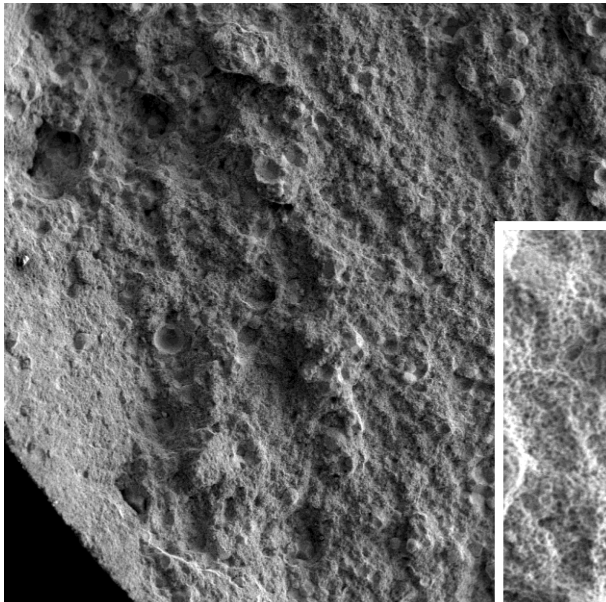
Cast sample: scattered results on precipitated carbide zone (hardness indent large in respect to dimension of carbides)

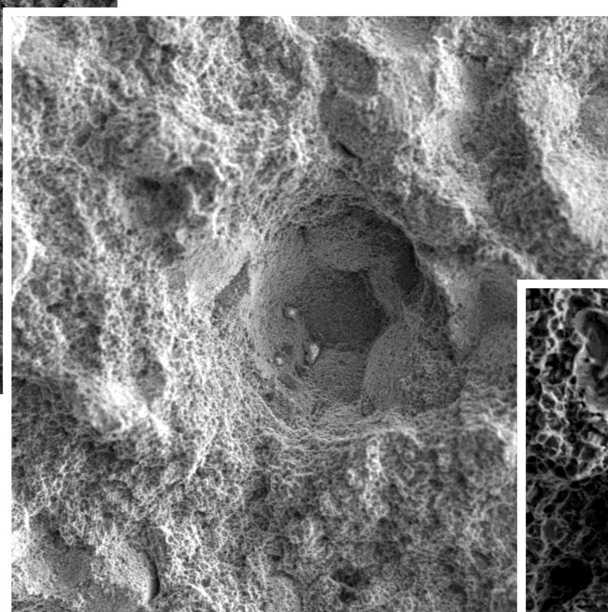
Mechanical tests

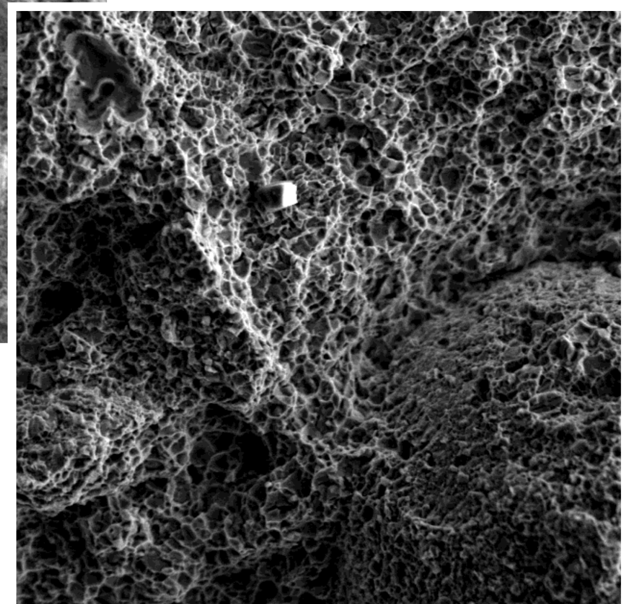


Fractography – HIP PM NiCr alloy, tensile fracture at 500 C



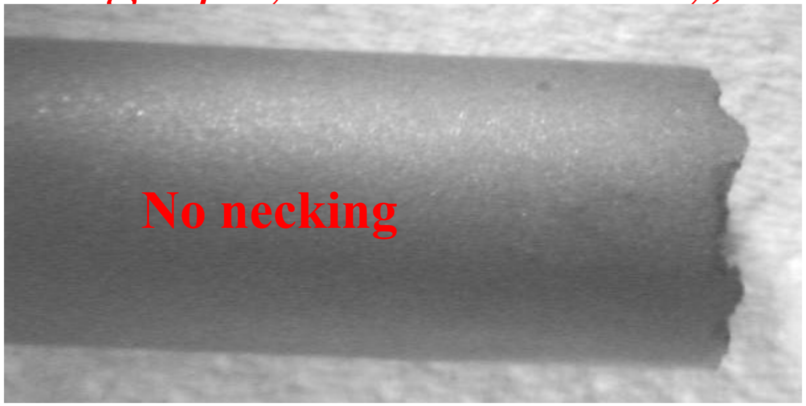


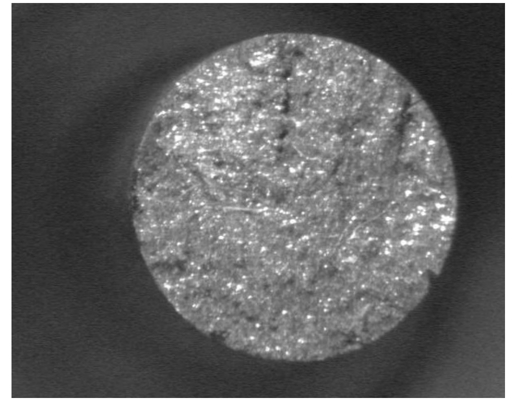


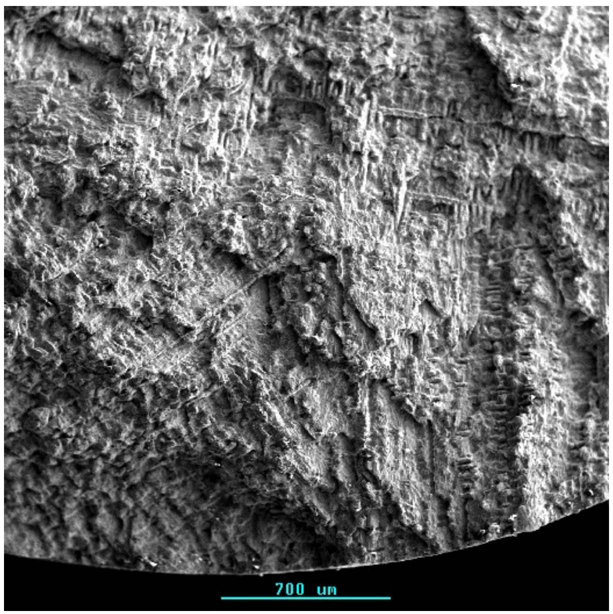


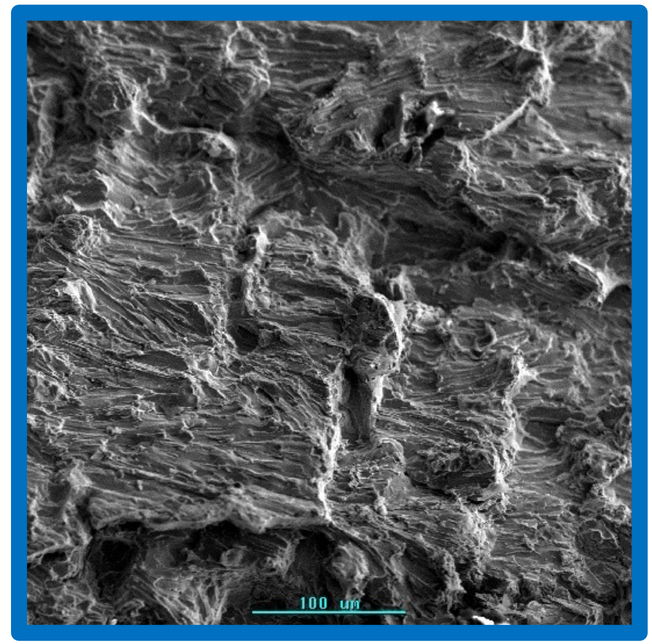
The fracture is microscopically ductile (microvoids coalescence) and probably follows the sintered powder boundaries

Fractography – cast Co alloy, tensile fracture at 500 C





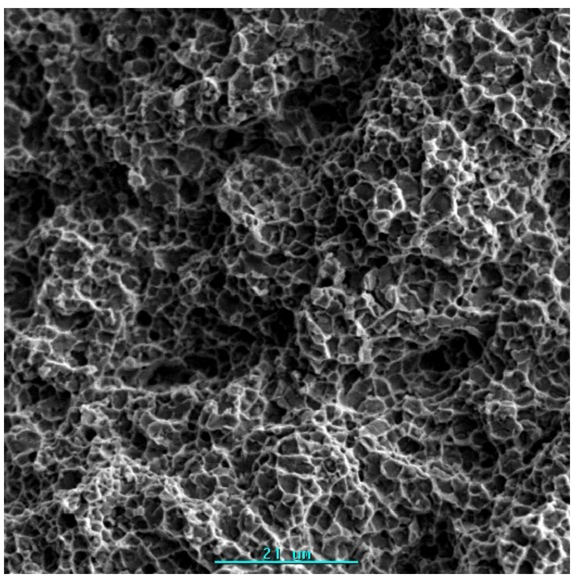


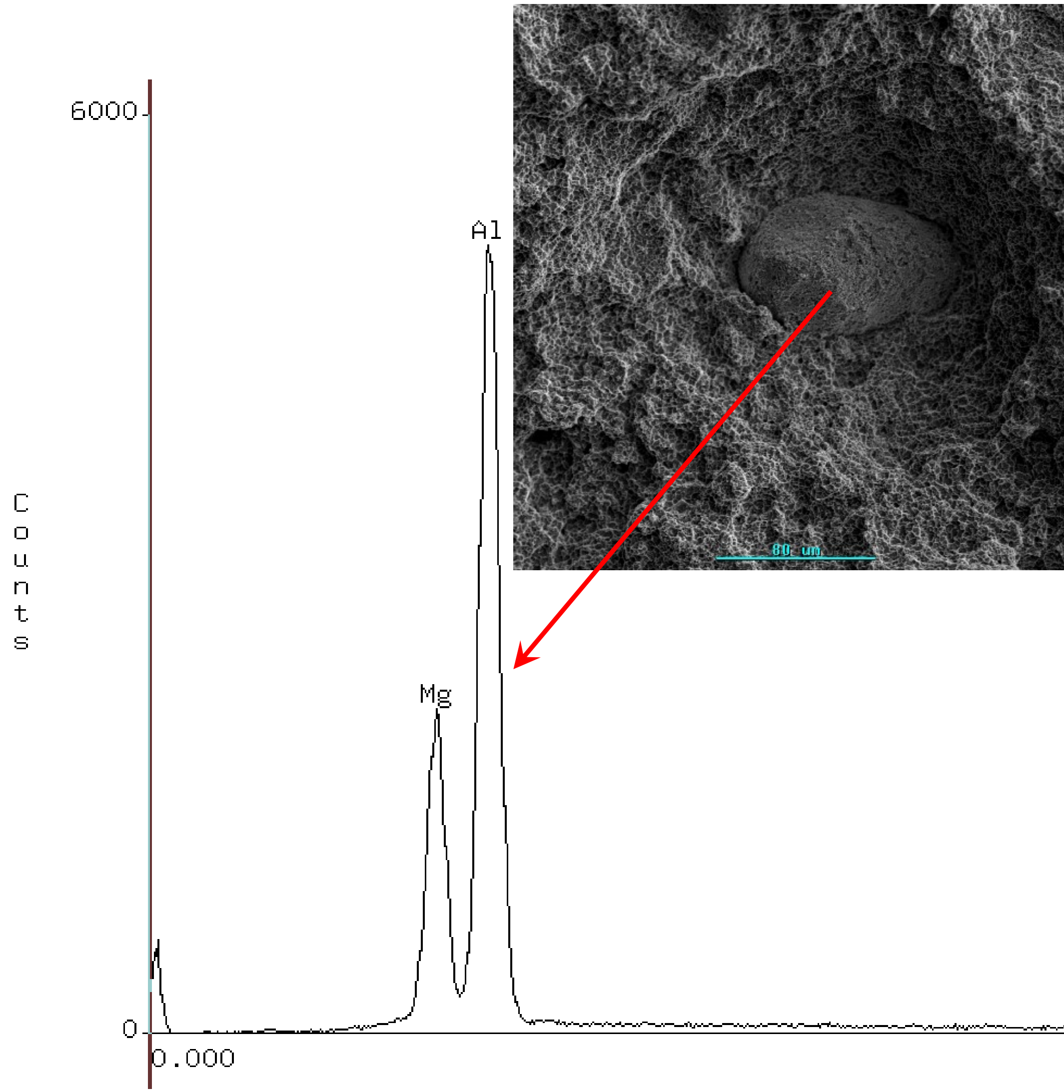


Mainly inter-dendritic fracture (a), with some trans-dendritic quasi-cleavage fracture

Fractography – HIP PM Co alloy tensile fracture at 500 C

Hipped Co Alloy tensile test sample (shear lips presence)





The fracture is ductile, nucleated by the presence of an inclusion

Fatigue - HIP PM Ni-Cr alloy

pulsed traction fatigue tests ($R \approx 0$), up to $2 \cdot 10^6$ cycles, at **500 C**

Strenght	Specimens results										Results	
Mpa	1	2	3	4	5	6	7	8	9	10	X	O
660					X		X				2	
650								X			1	
640		X		O		O			X		2	2
630												
620			O									1
610												
600	O											1

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 ($R \approx 0$), up to $2 \cdot 10^6$ cycles, at **500 C**

Strenght	Specimens results										Results	
Mpa	1	2	3	4	5	6	7	8	9	10	X	O
410	X		X								2	
400							X				1	
390		O		X		O		X		X	3	2
380									O			1
370					O							1

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**

Strenght	Specimens results										Results	
Mpa	1	2	3	4	5	6	7	8	9	10	X	O
740	X										1	
720												
700		X									1	
680				X		O					1	1
660			O		O							2

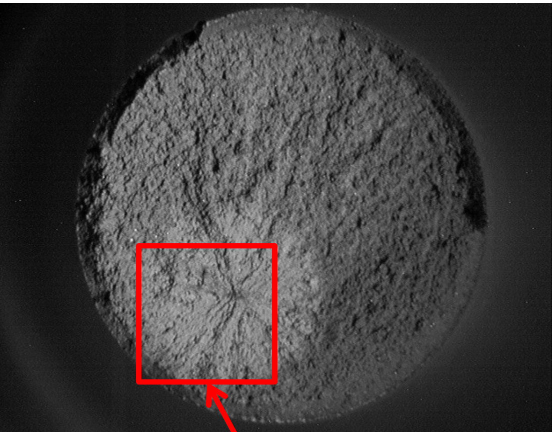
Fatigue limit (for $2 \cdot 10^6$ cycles) ≈ 660 MPa

X: specimen broken before $2 \cdot 10^6$ cycles

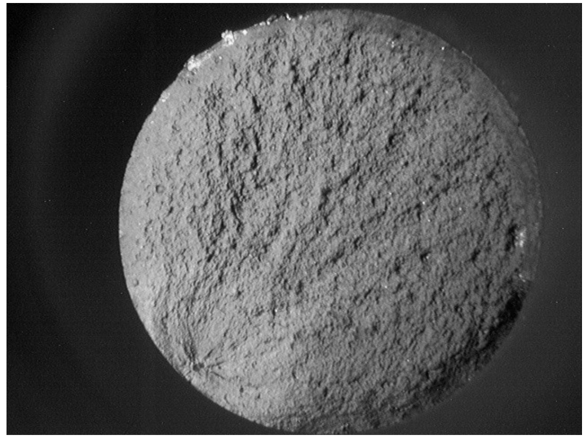
O: specimen completes $2 \cdot 10^6$ cycles

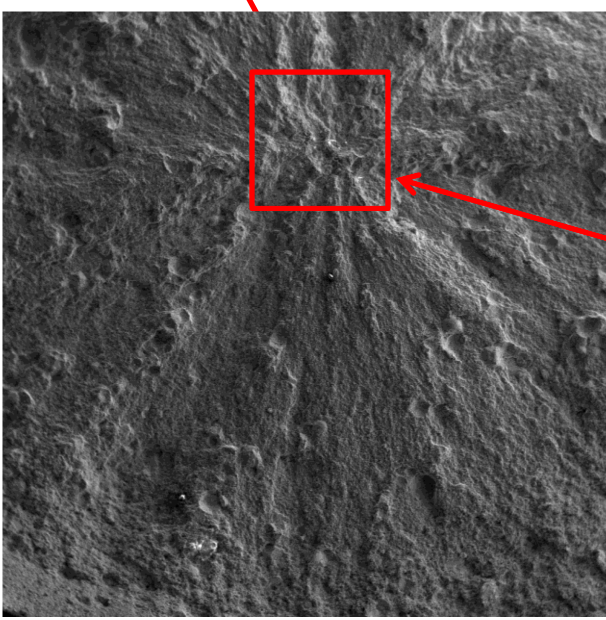
Fractography – HIP PM NiCR alloy, fatigue fracture at 500 C

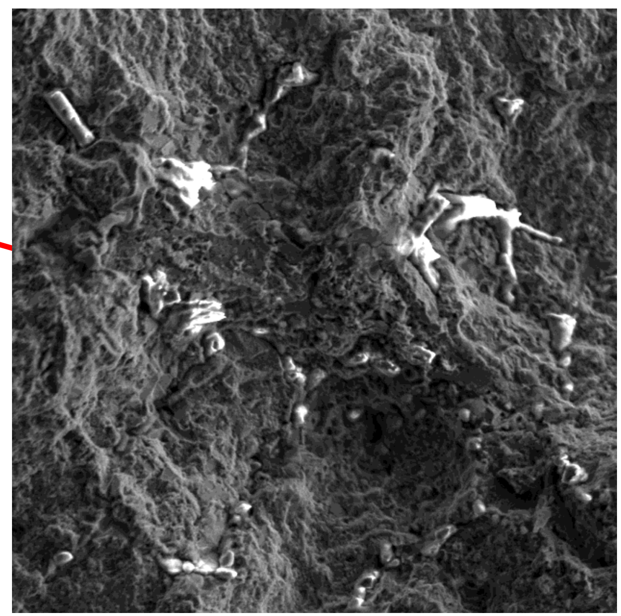
640MPa



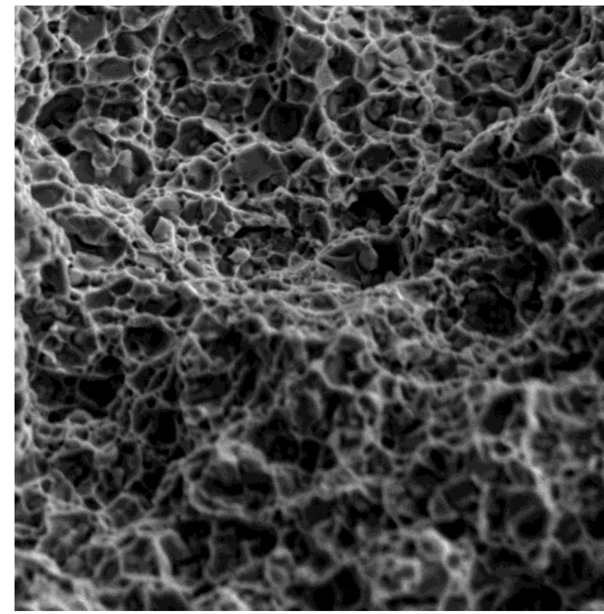
660MPa





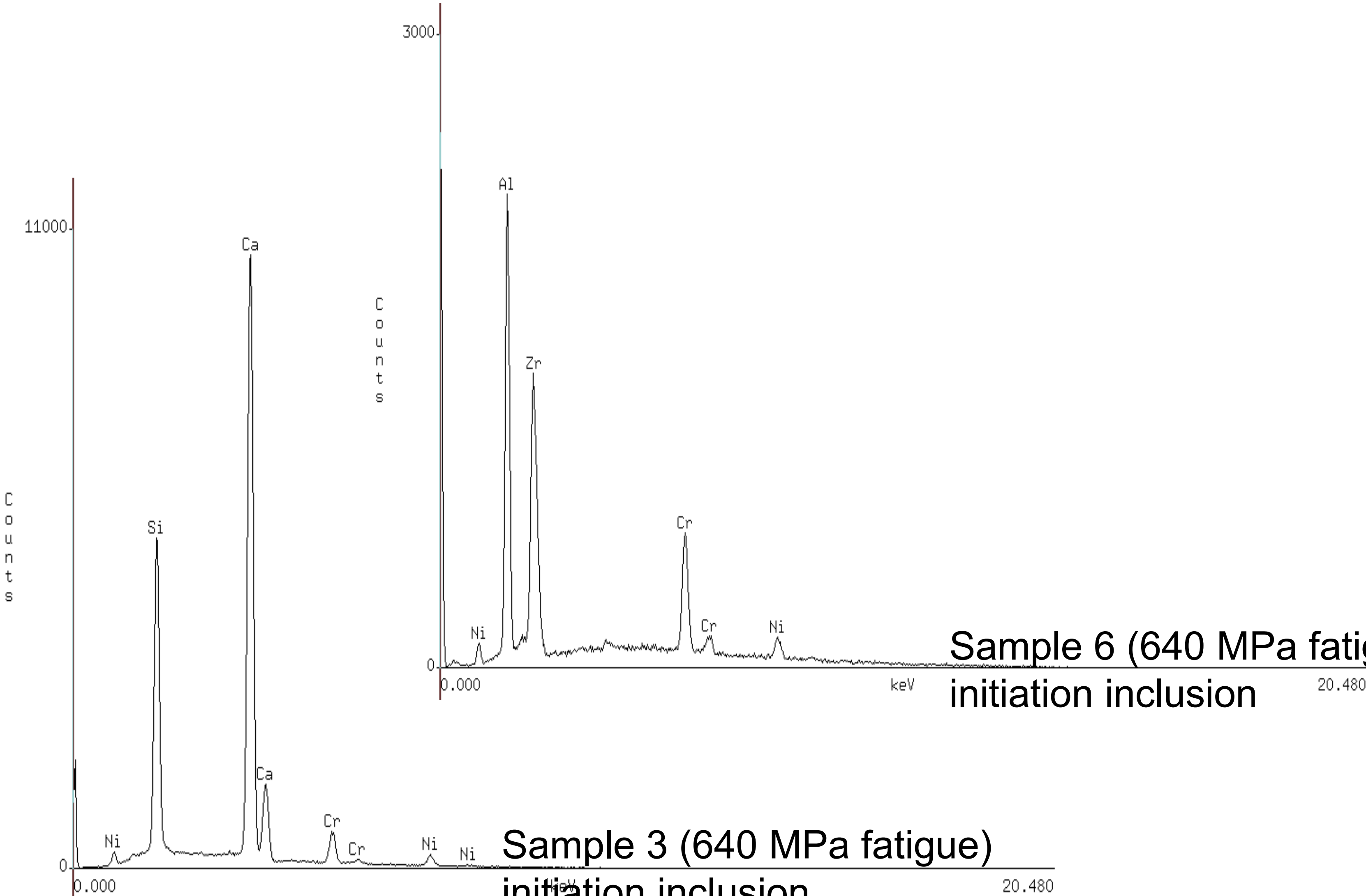


Nucleation zone (detail)



propagation

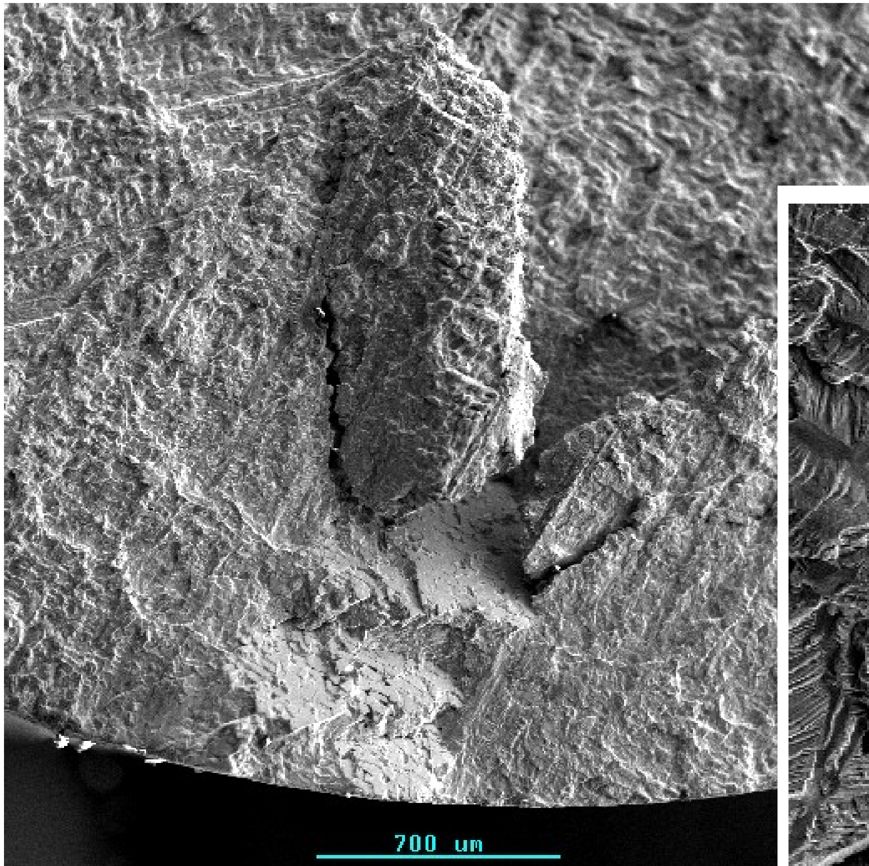
Fractography – HIP NiCR alloy, fatigue tests at 500 C



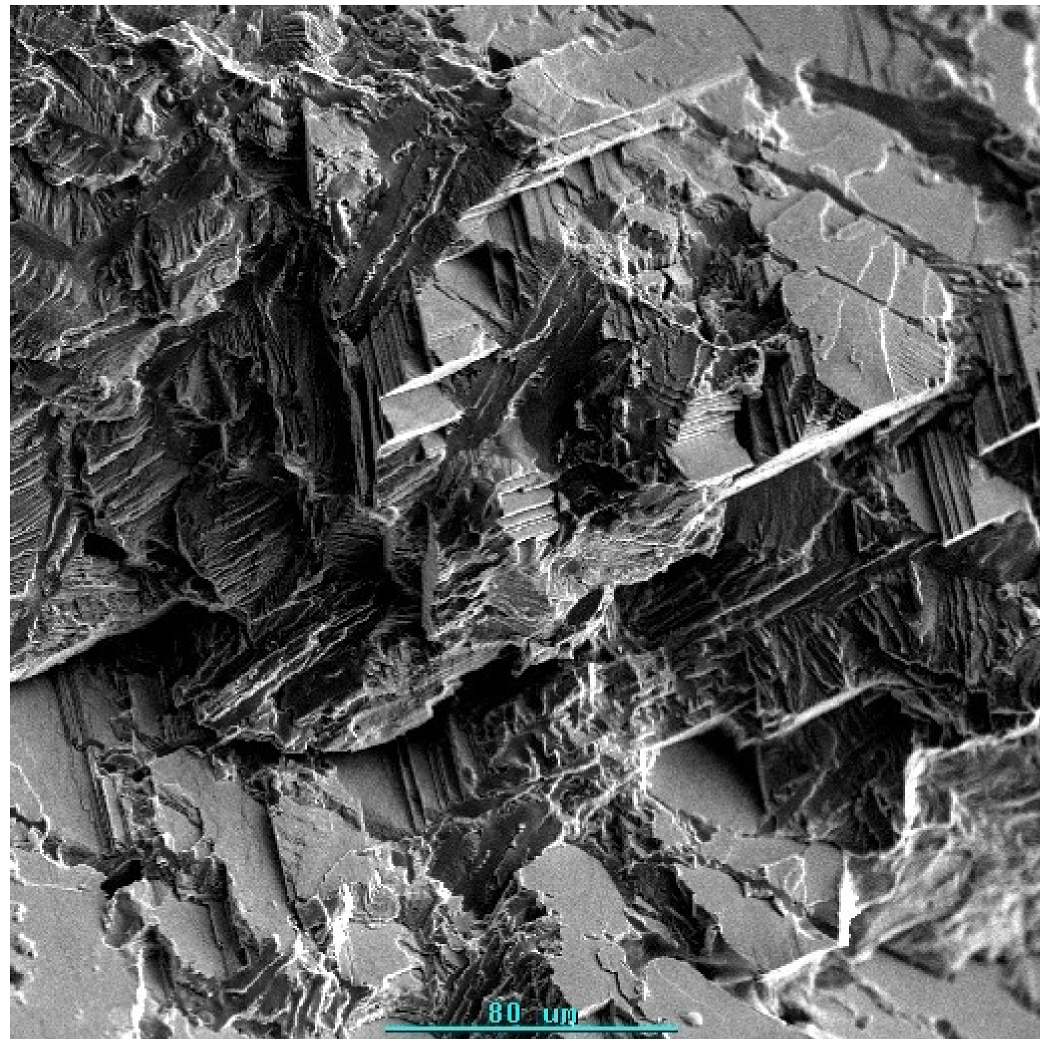
Sample 6 (640 MPa fatigue) initiation inclusion

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

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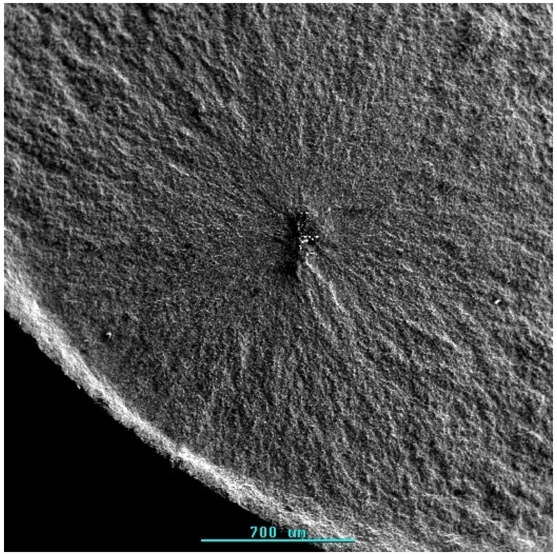
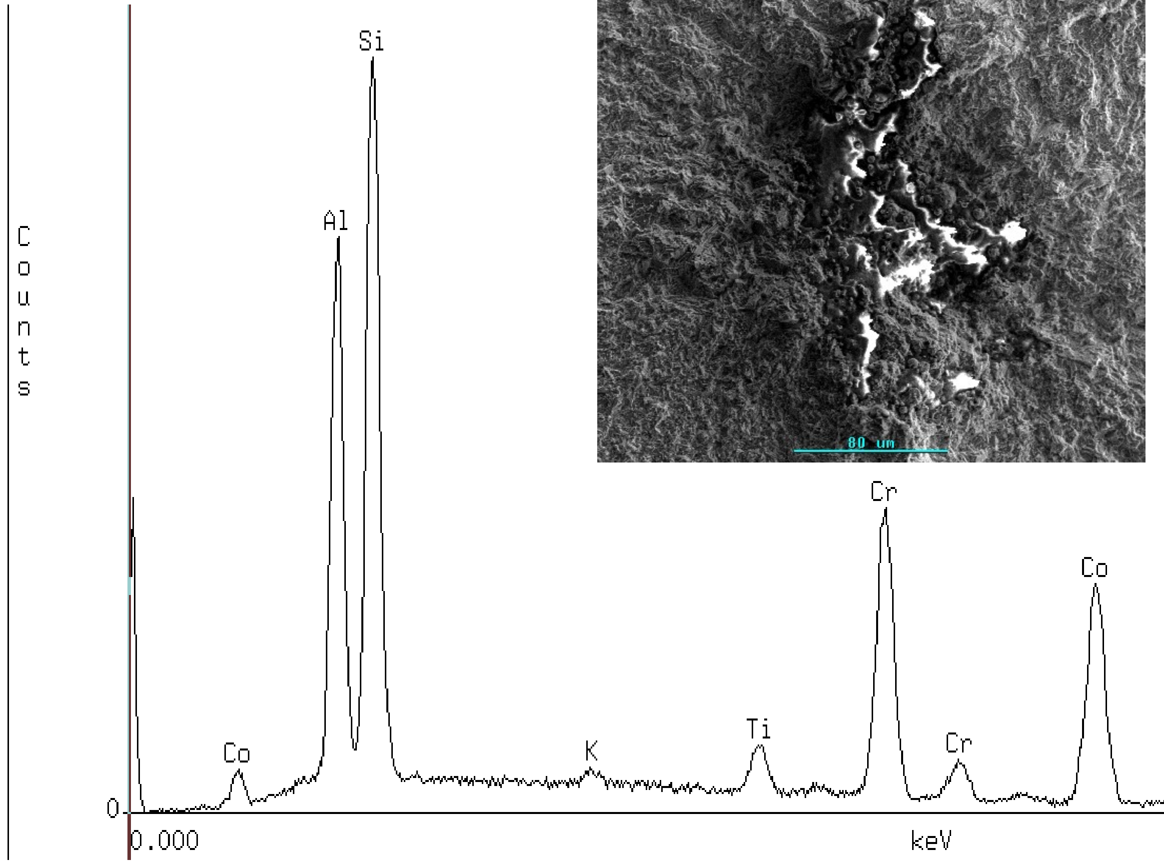
Fractography – HIP PM Co alloy, fatigue test at 500 C

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.