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Microstructural, Mechanical and Fatigue Properties of Cobalt Alloys

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Introduction - General goals

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



- inadequacy of steels → use of **cobalt based alloys** (Stellites) for components mechanically stressed at high temperature



- **literature about Co alloys** mainly concerned on wear and corrosion resistance at high temperature
- **few data about high temperature fatigue** available

Materials & specimens

Tensile and fatigue cylindrical (not notched) specimens, 8 mm diameter

- “stellite 6” type alloy produced by casting
- “stellite 6” type alloy produced by powder metallurgy + hipping

Experimental methods

Mechanical tests

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

Crystallographic and micro-structural tests

- both on as received material, and after 250 or 500 °C treatments
- X ray diffraction (Co anode)
- optical and electronic metallography and EDS micro-analysis

Fractography

*Chemical composition of cast or HIP
stellite grade 6. (% wt.)*

CAST

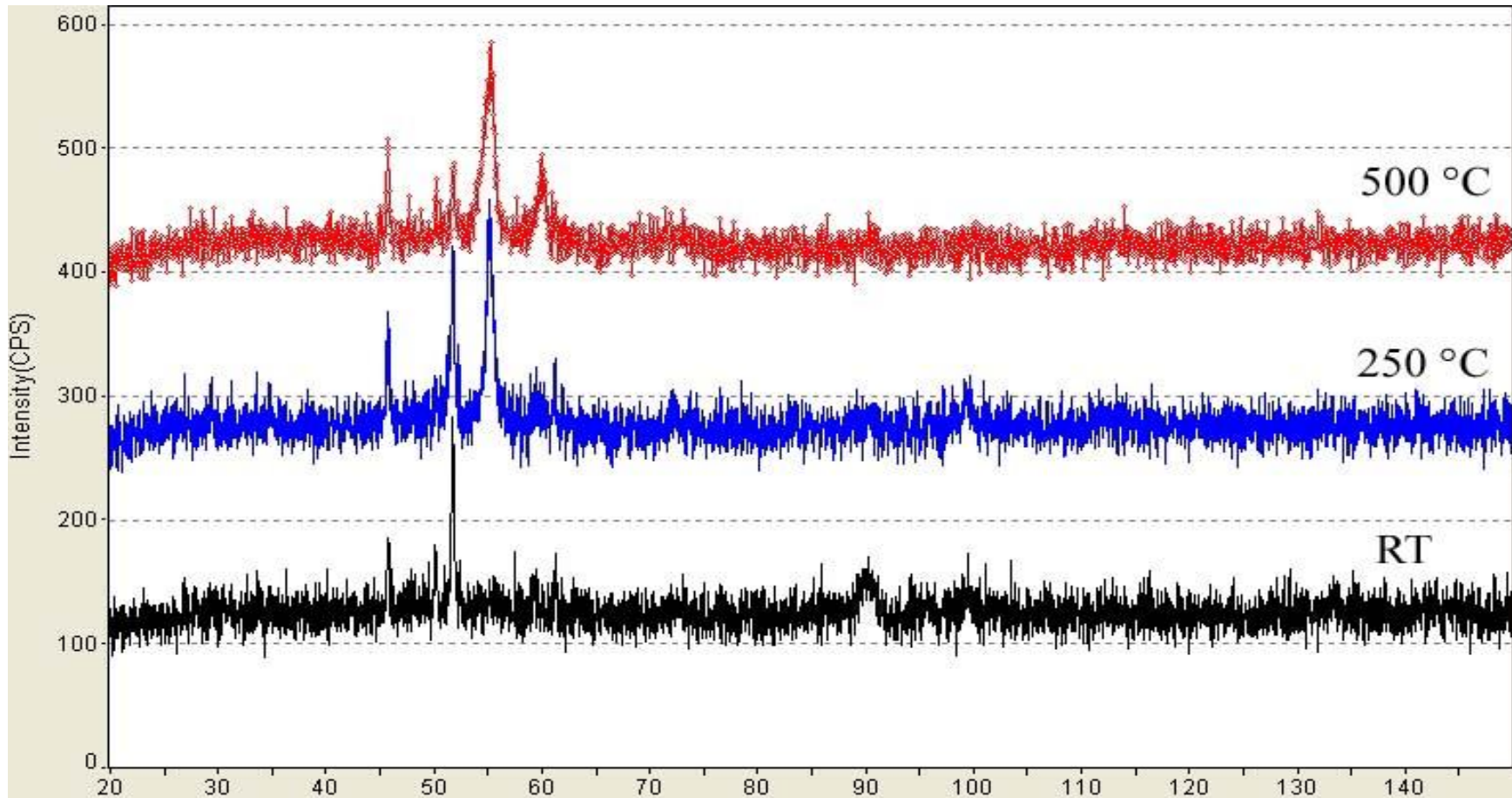
Co	C	Cr	W	Ni	Si	Mn	Fe	V	Nb
bal.	1.19	25.54	5.21	1.99	1.56	0.69	0.85	0.028	0.034

HIP

Co	C	Cr	W	Ni	Si	Mn	Fe	V	Nb
bal.	1.48	27.21	4.78	0.30	1.21	0.21	0.44	0.021	0.002

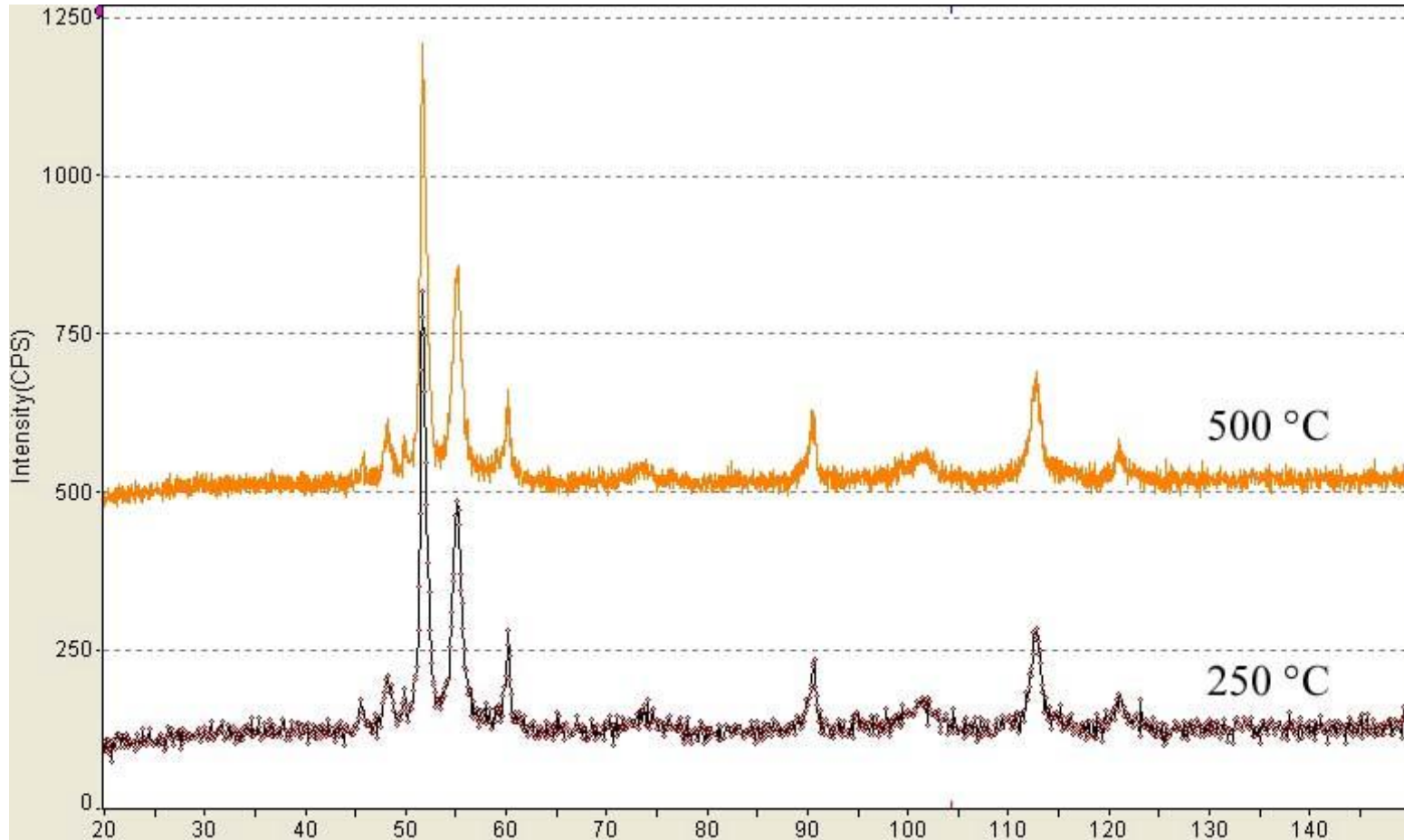
Cast sample XRD Analyses (Brag-Brentano geometry, Co anode)

- Shallow and partially overlapped peaks (e.g. 40-65 ° range)
- Possible phases: Co_{CFC} , Co_{HCP} , $\text{Co}_{25}\text{Cr}_{25}\text{W}_8\text{C}_2$, Cr_7C_3 , Cr_{23}C_6 , Cr_3C_2 , $\text{Co}_3\text{W}_3\text{C}$, $\text{Co}_4\text{W}_2\text{C}$, $\text{Co}_6\text{W}_6\text{C}$, W_2C , Co_3W , Co_7W_6
- Probable prevalence of Co_{CFC} in respect to Co_{HCP}
- Possible phase evolution on heating at 250 or 500 °C

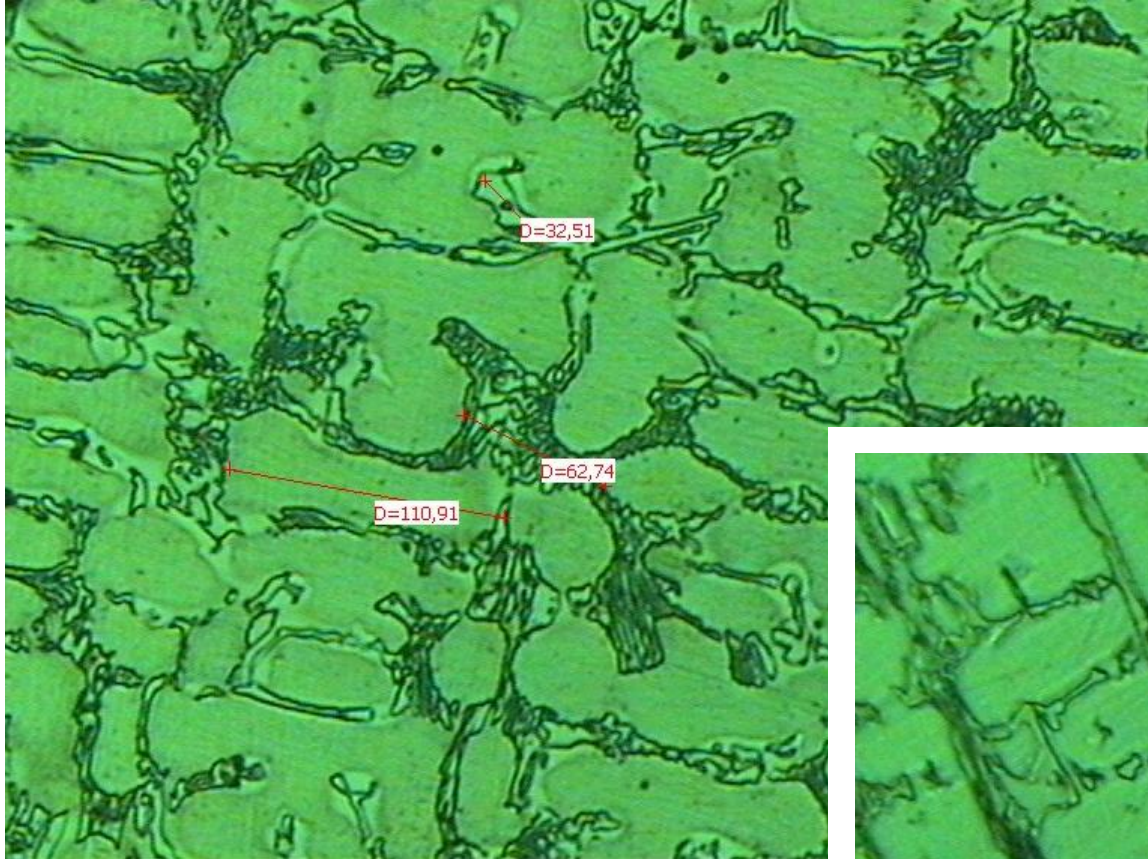


Hipped sample XRD Analyses (Brag-Brentano geometry, Co anode)

- Shallow and partially overlapped peaks (e.g. 40-65 ° range)
- Possible phases: Co_{CFC} , Co_{HCP} , $\text{Co}_{25}\text{Cr}_{25}\text{W}_8\text{C}_2$, Cr_7C_3 , Cr_{23}C_6 , Cr_3C_2 , $\text{Co}_3\text{W}_3\text{C}$, $\text{Co}_4\text{W}_2\text{C}$, $\text{Co}_6\text{W}_6\text{C}$, W_2C , Co_3W , Co_7W_6
- Probable prevalence of Co_{CFC} in respect to Co_{HCP}
- No phase evolution on heating at 250 or 500 °C



Cast samples micro-structure

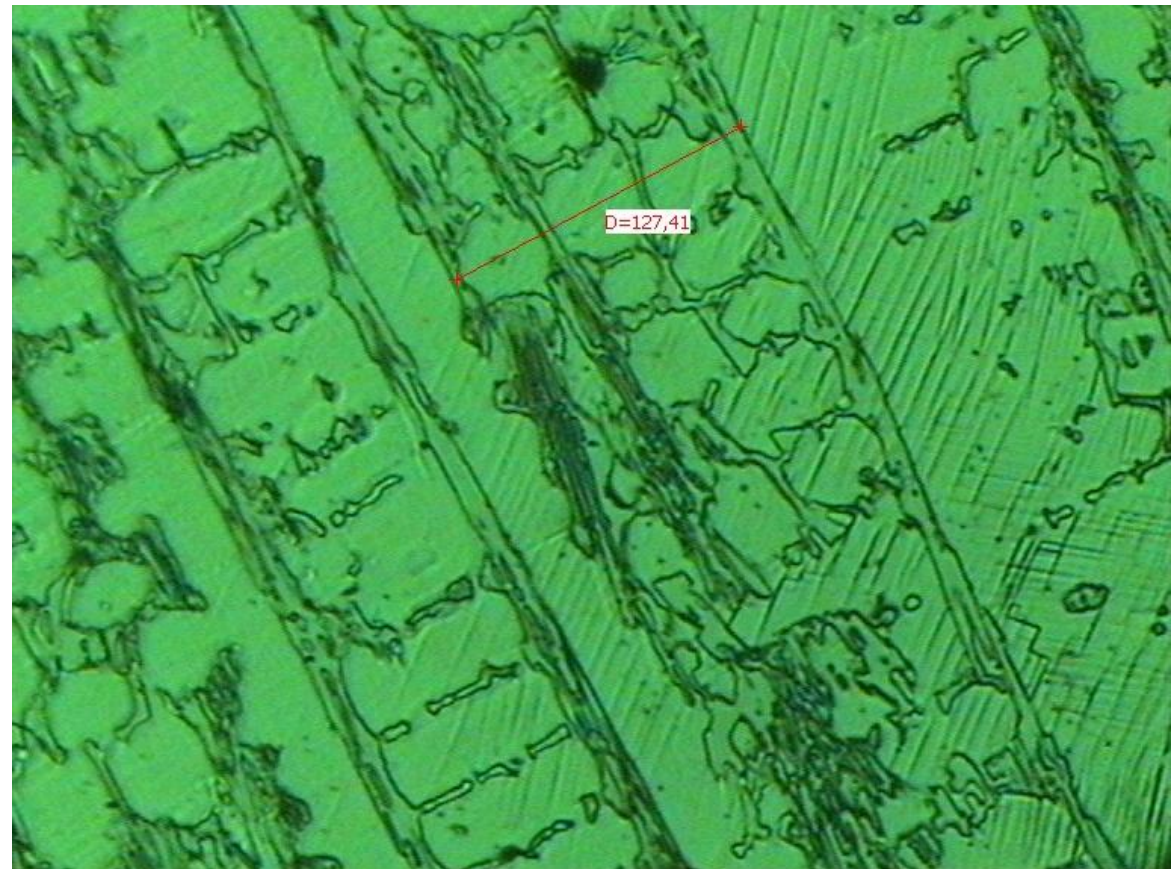


As received, 456 x 362 μm

No microstructural differences due to treatment at 250 and 500 C are noticeable

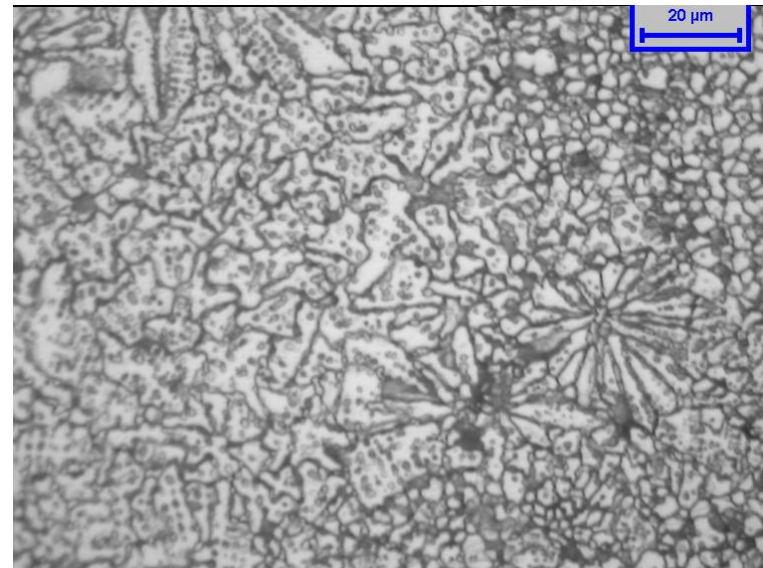
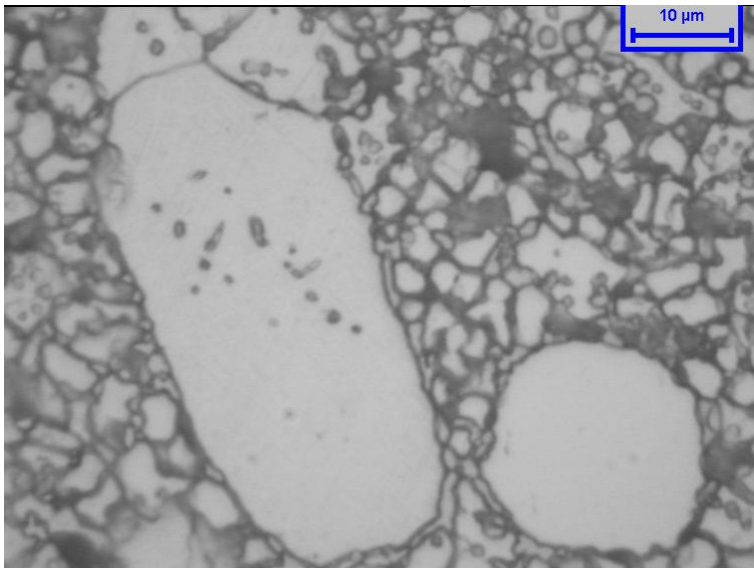
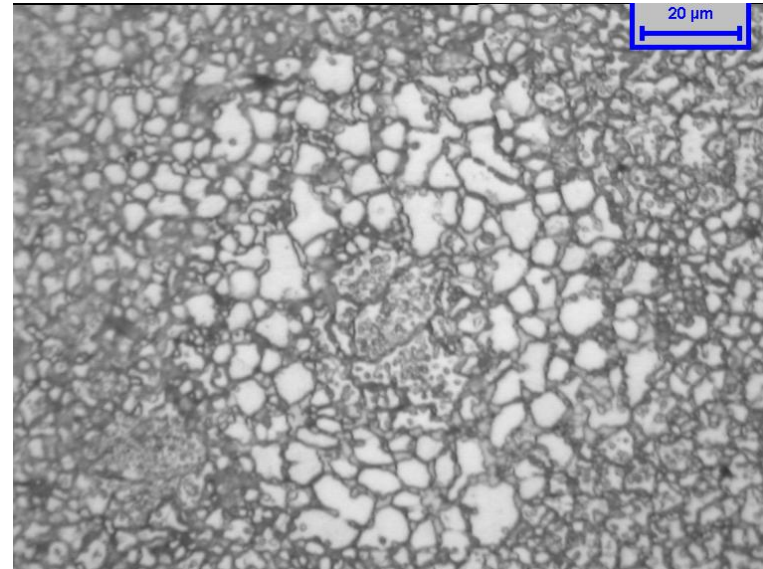
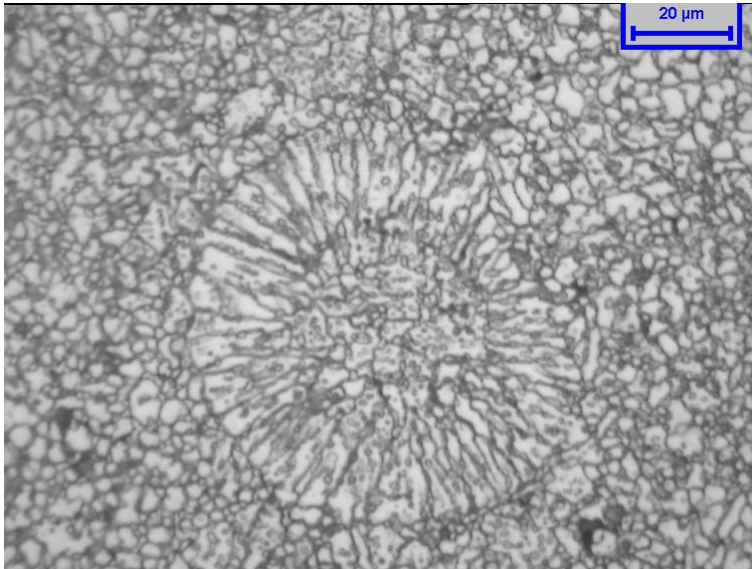
Main primary dendrites

Inter-dendritic carbides (mainly lamellar form)



After treatment at 500 C, 456 x 362 μm

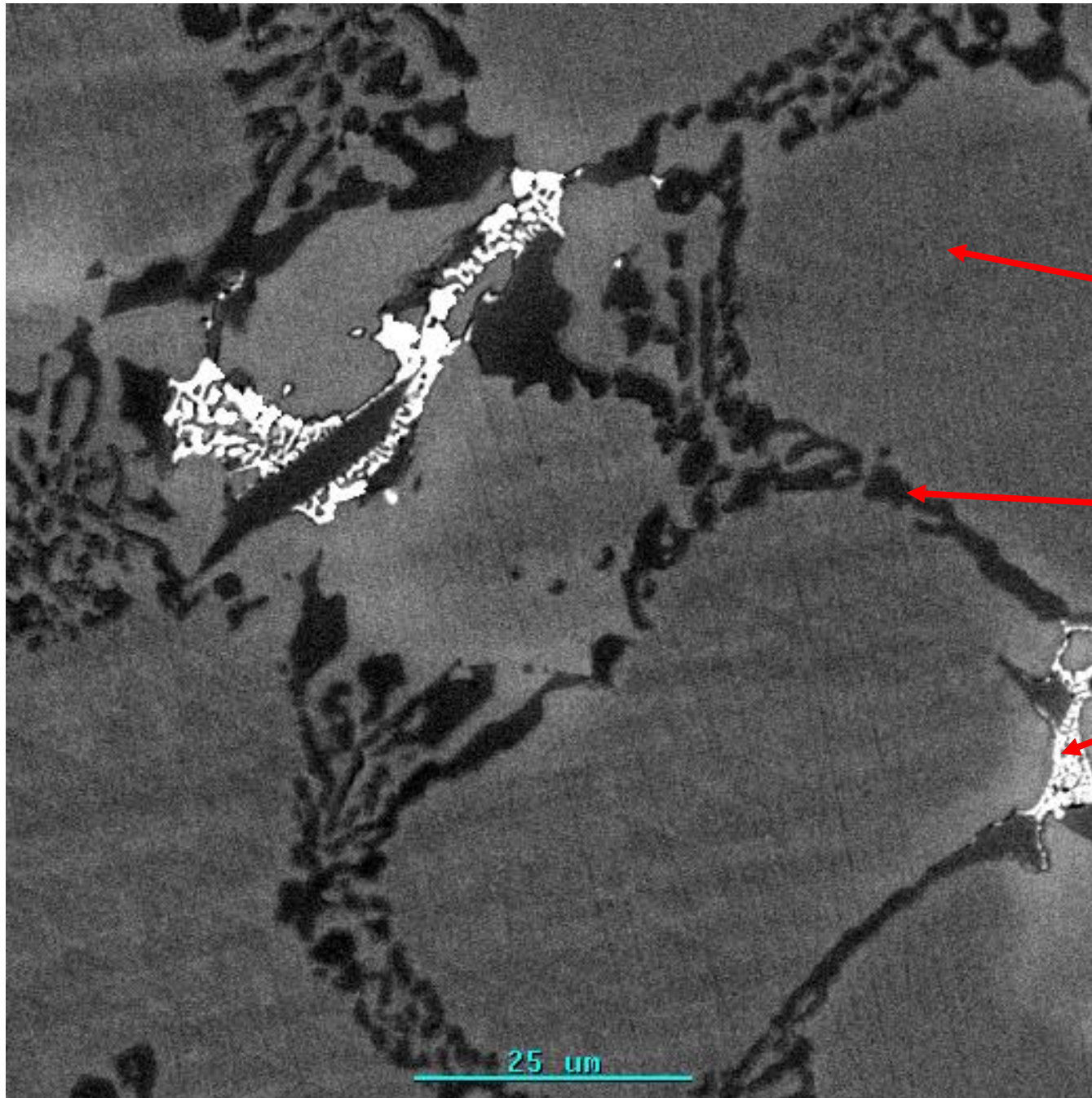
Hipped sample microstructure



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 .

Larger grains are richer in Co (EDS analysis).

Cast sample micro-analysis (EDS)



Metallic matrix

Cr	Co	W	Mo	Si
24	71	3.5	0.24	0.65

Cr rich carbides

Cr	Co	W	Mo
78	15	6.3	0.43

Co, W rich carbides

Cr	Co	W	Mo
21	47	29	2.7

**Back-scattered
electrons image**

Hardness and micro-hardness

Samples	HV 50	HV 0.05 Dendritic zones	HV 0.05 Carbides rich zones
Room temperature	370	400-430	530-1100
Heating at	395	390-410	550- 1000
Heating at	385	380-400	800-1100

low heat treatment effect on
hardness of matrix

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

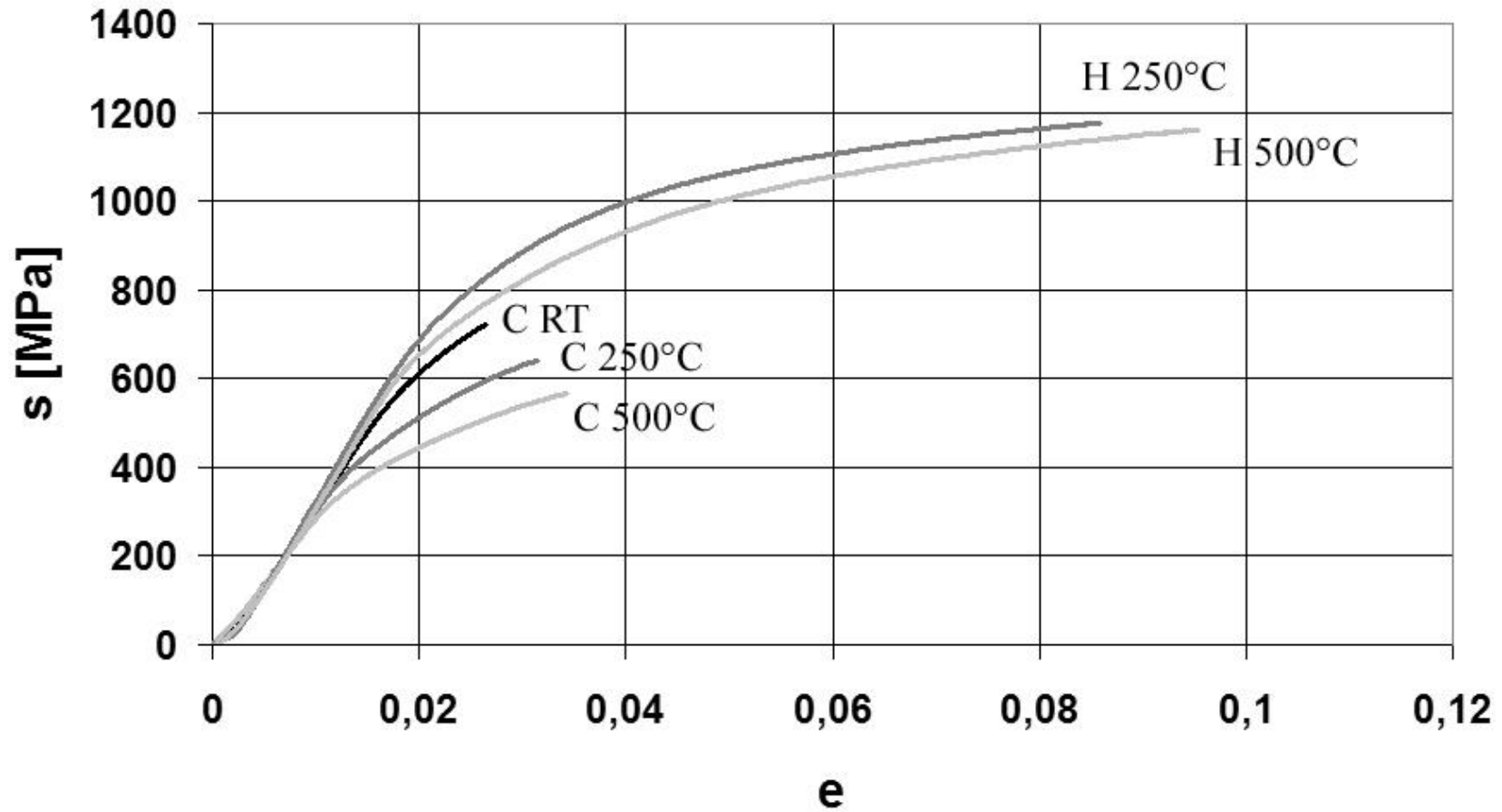
The hardness tests effected on the
transverse section of the **HIP**
samples reveal 660 HV for the 50 g
tests and 460 HV for the 50 kg
tests.



As received cast sample, 92 x 69 μm

Mechanical tests

Tensile test



Mechanical tests

Fatigue

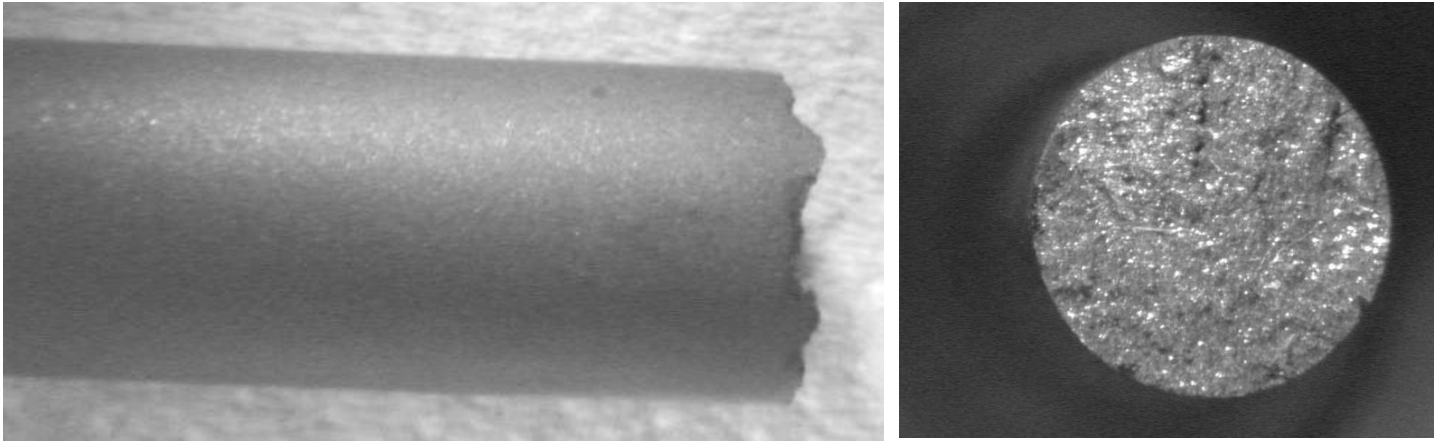
Fatigue tests:

- pulsed traction fatigue $R \approx 0$
- staircase method up to $2 \cdot 10^6$ cycles, 30 Hz, temperature 250 or 500 °C

Results:

- the highest fatigue resistance was observed for HIP samples
- there is a great difference in the behaviour of cast and hiped samples
- results obtained through 250 or 500 °C tests are similar but the best behaviour has been observed at the lower temperature
- under the maximum stress the fracture occurred after a greater cycle number for the samples tested at the lower temperature

Mechanical tests

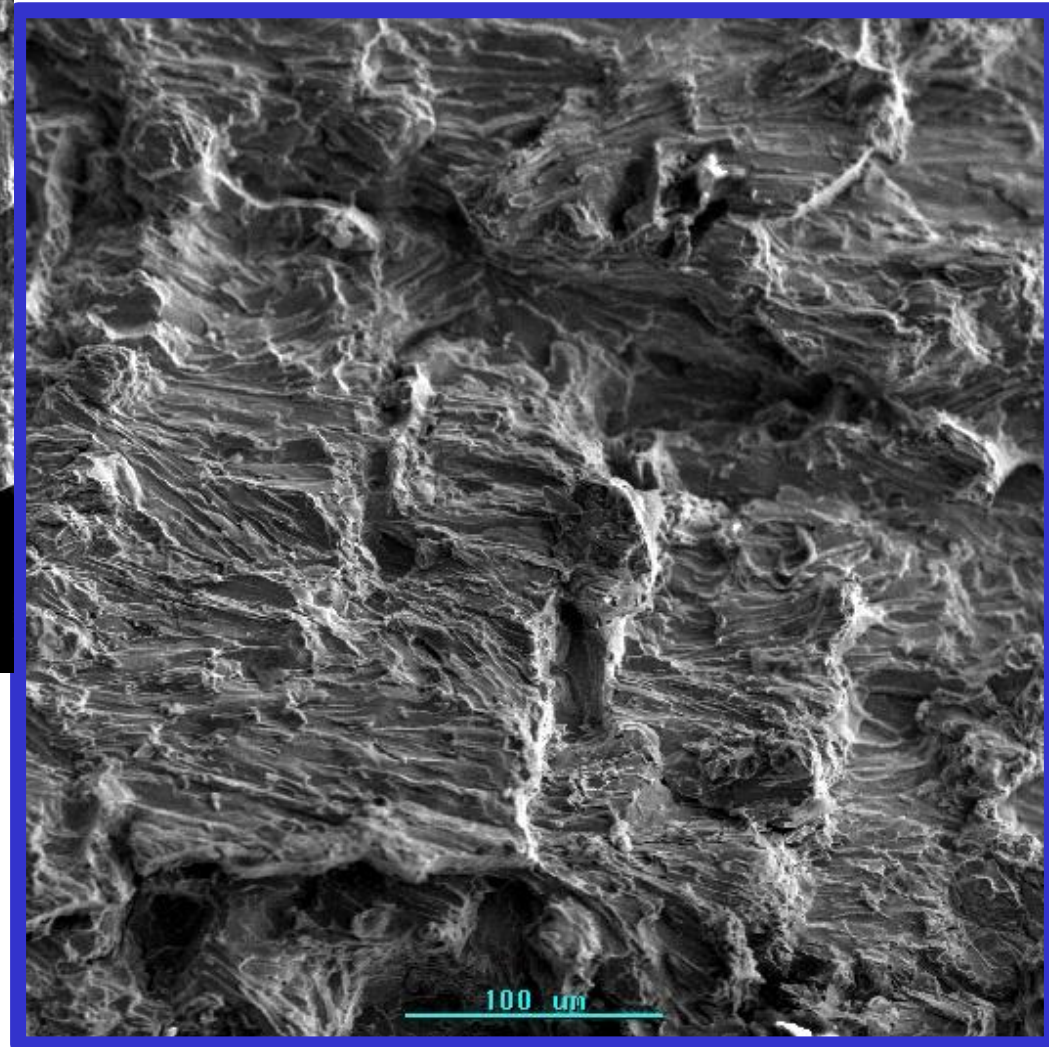
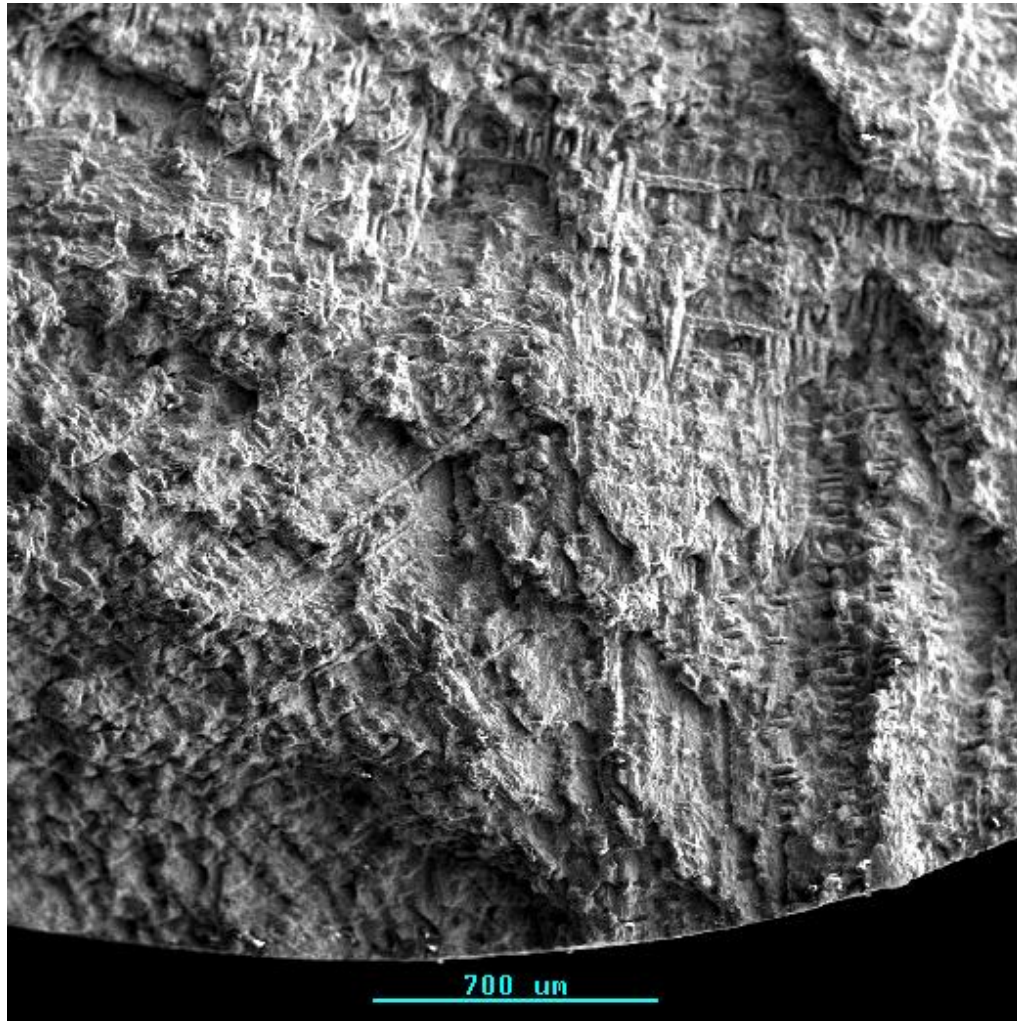


Cast tensile test sample (no necking).



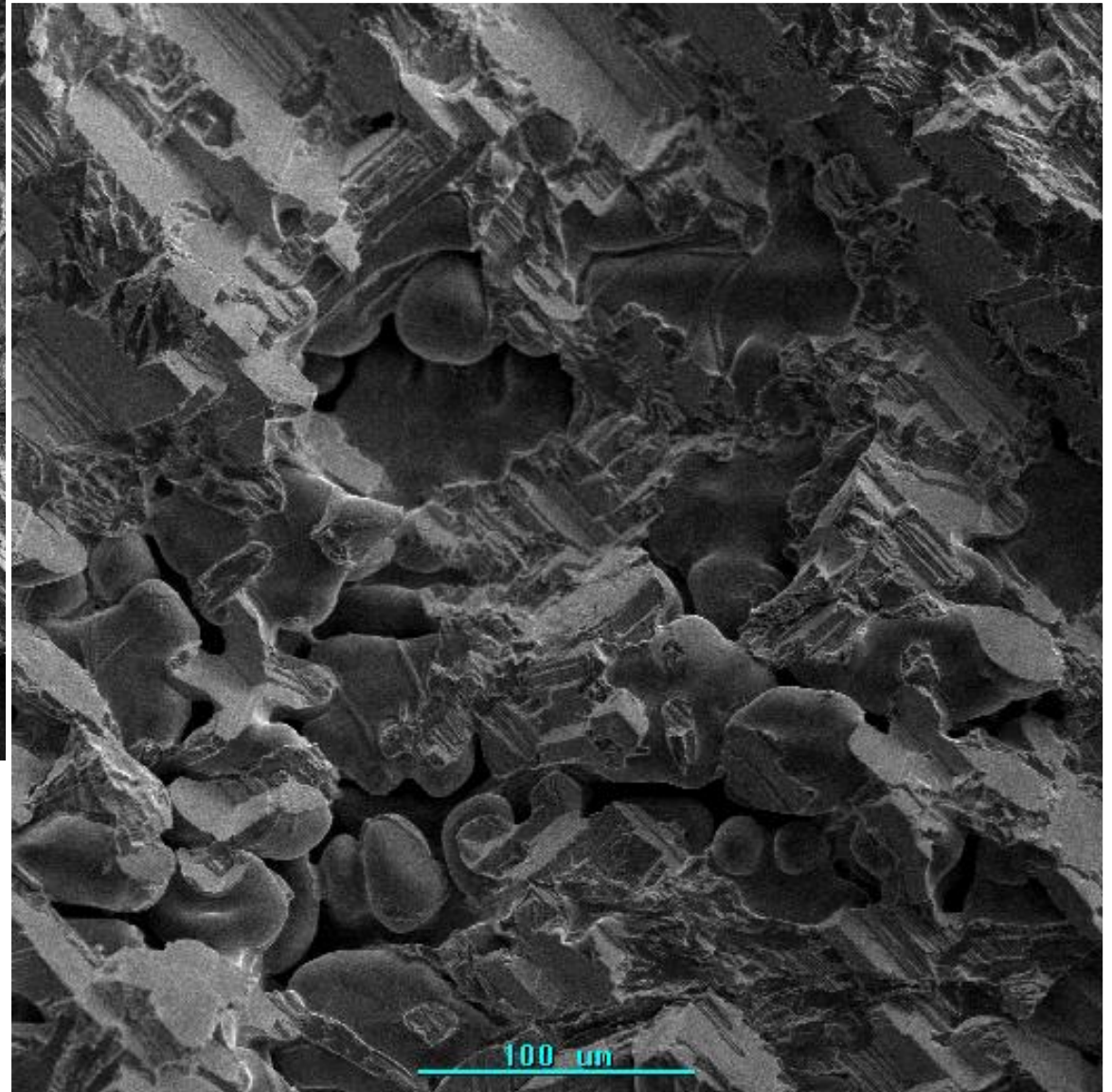
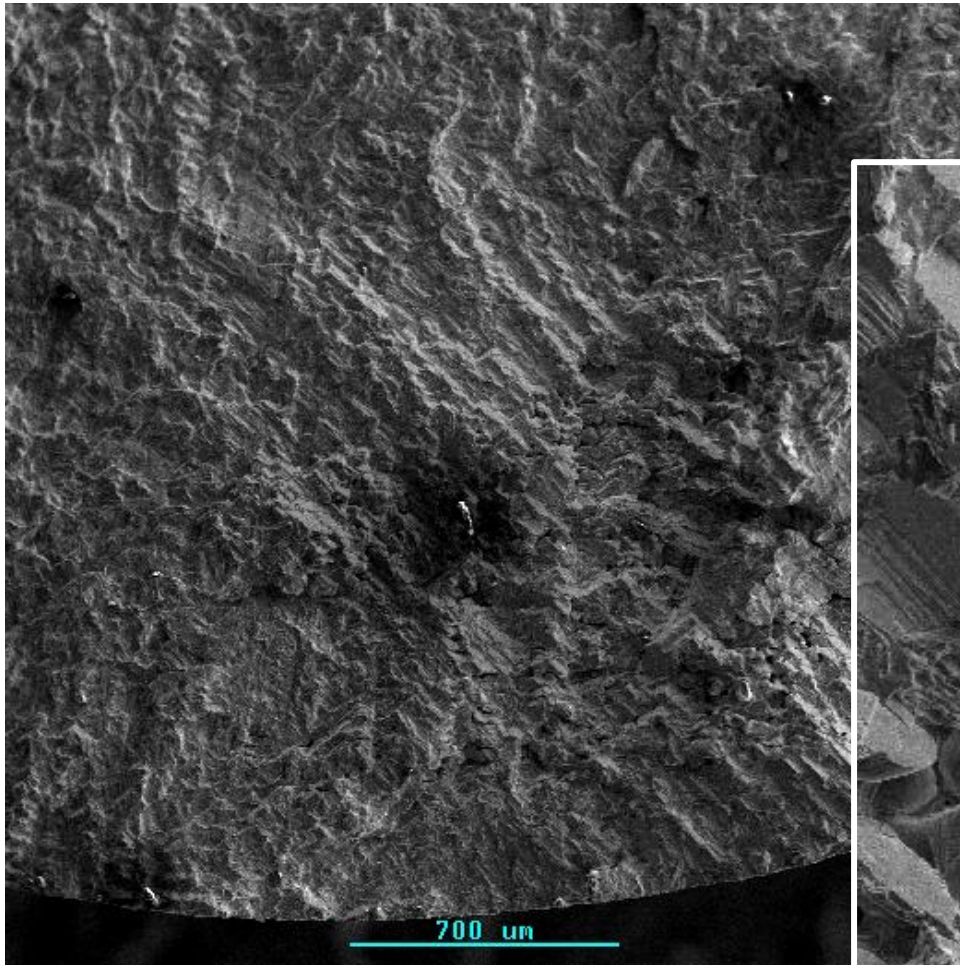
Hipped tensile test sample (shear lips presence)

Fractography – cast sample tensile test fracture at 500 °C



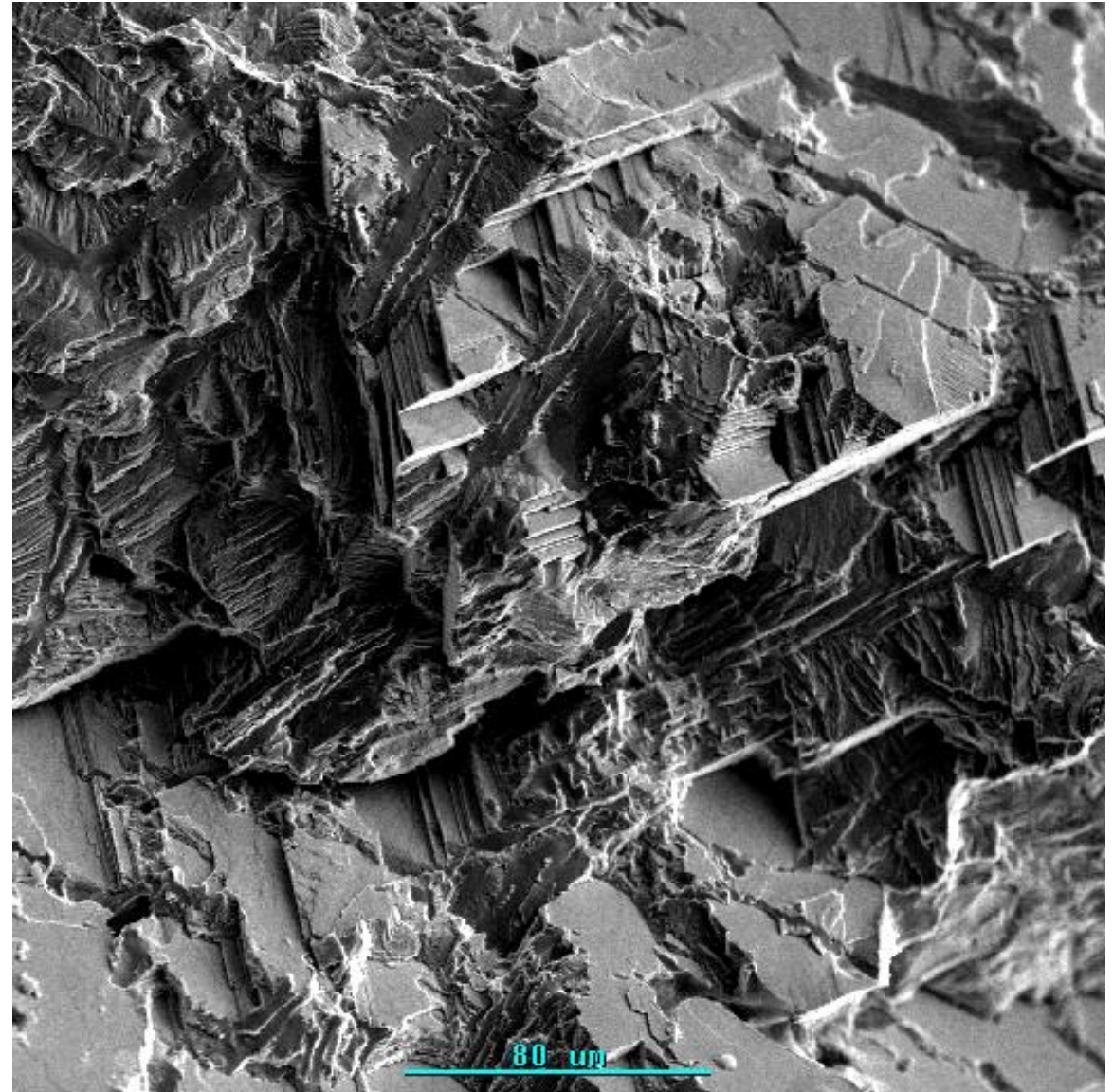
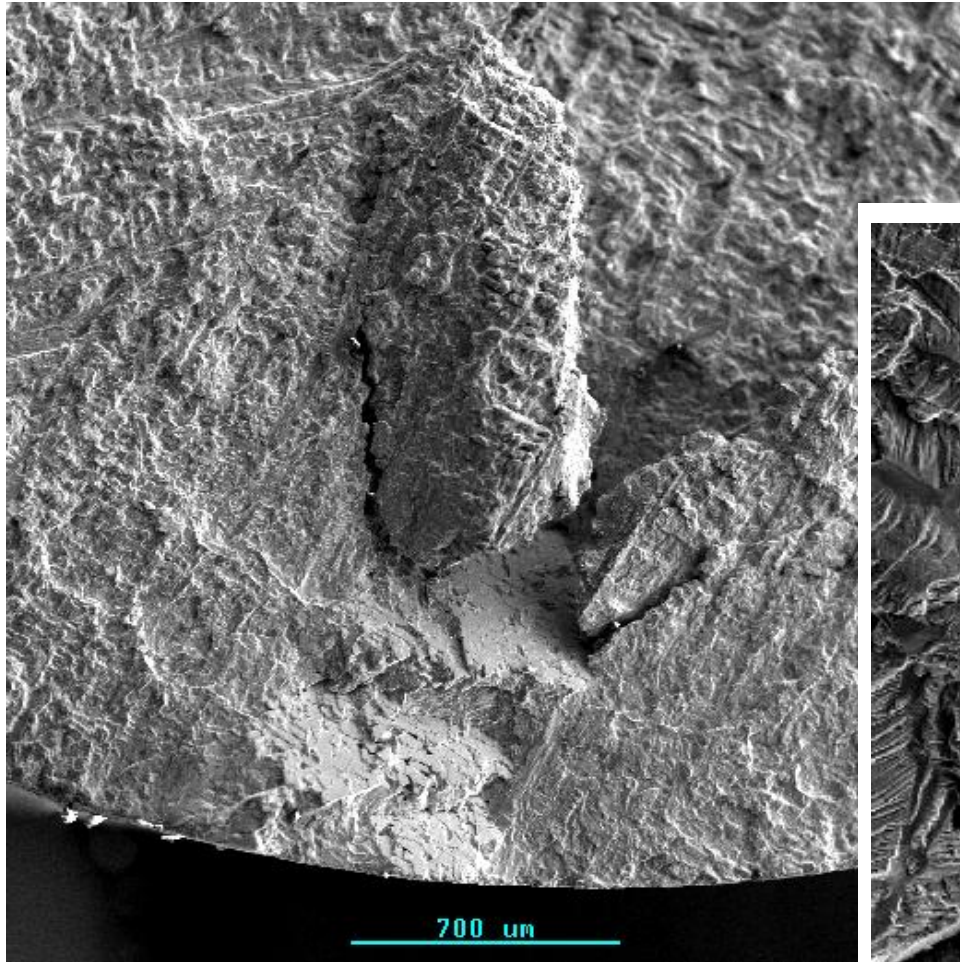
Mainly inter-dendritic fracture
and
trans-dendritic quasi-cleavage fracture

Fractography – cast sample fatigue test at 250 C



Fracture nucleation from a shrinkage defect

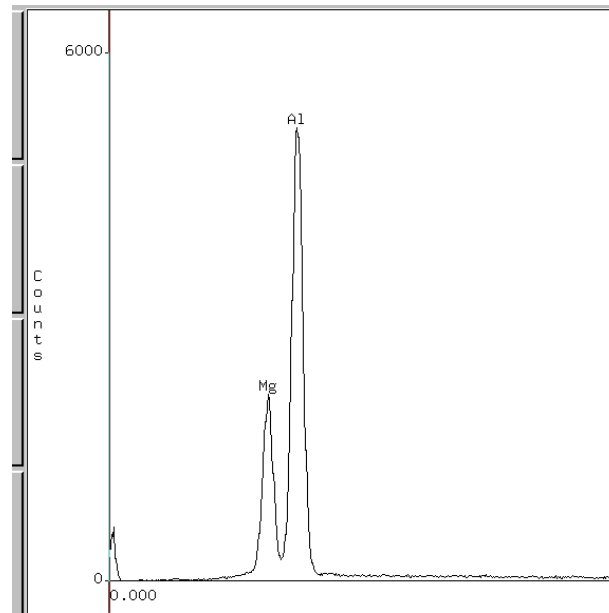
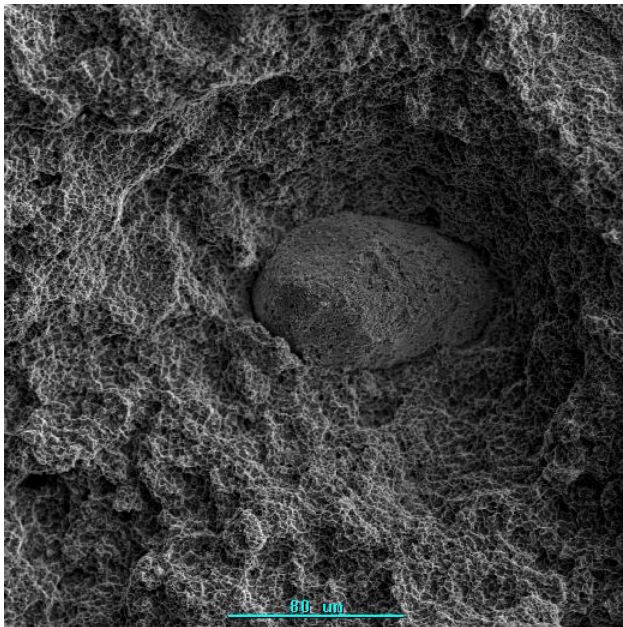
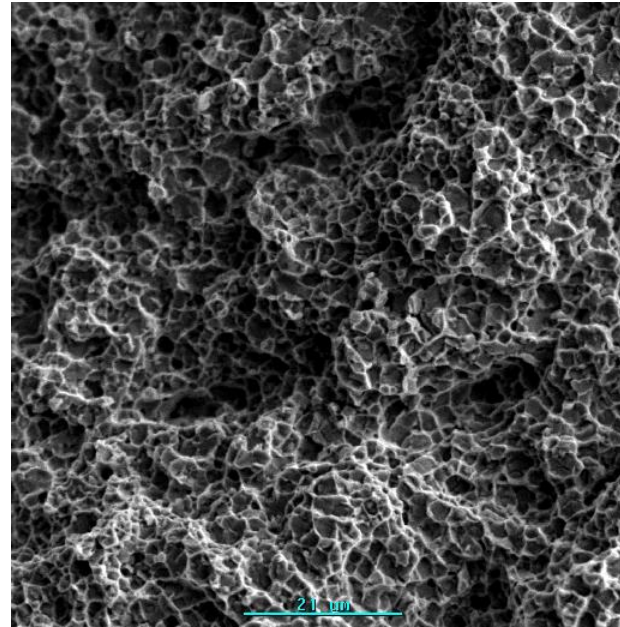
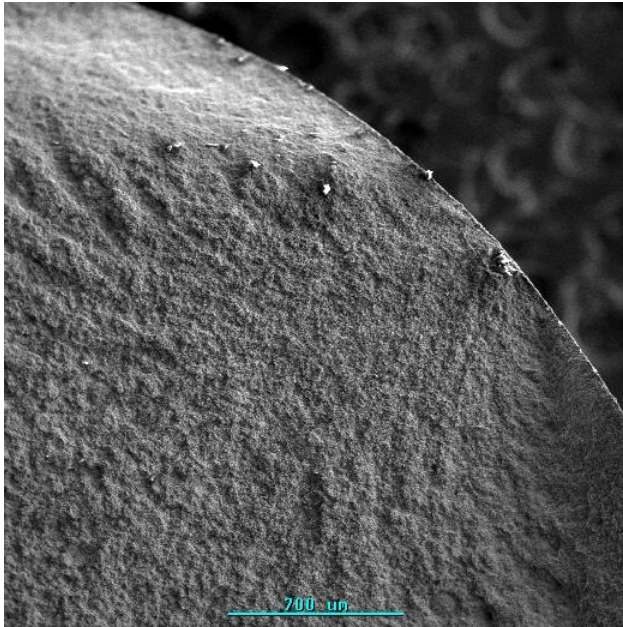
Fractography – cast sample fatigue test at 500 C



Nucleation and
propagation fatigue
fracture zones

detail of stair-step
fatigue propagation

Fractography – HIP sample tensile test fracture at 500 C



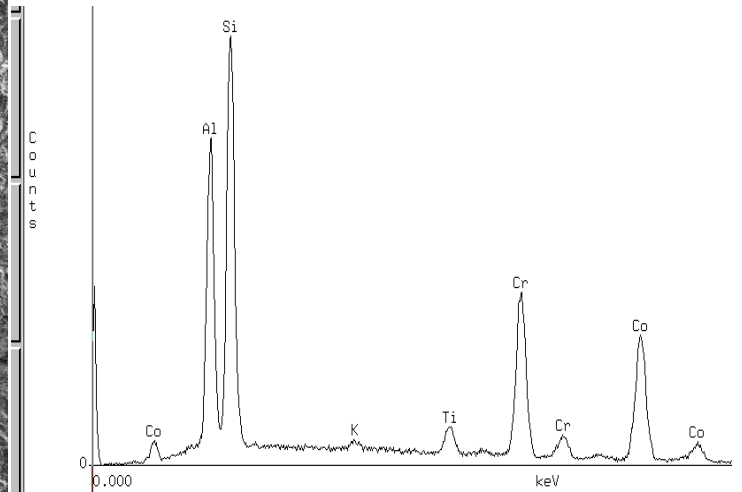
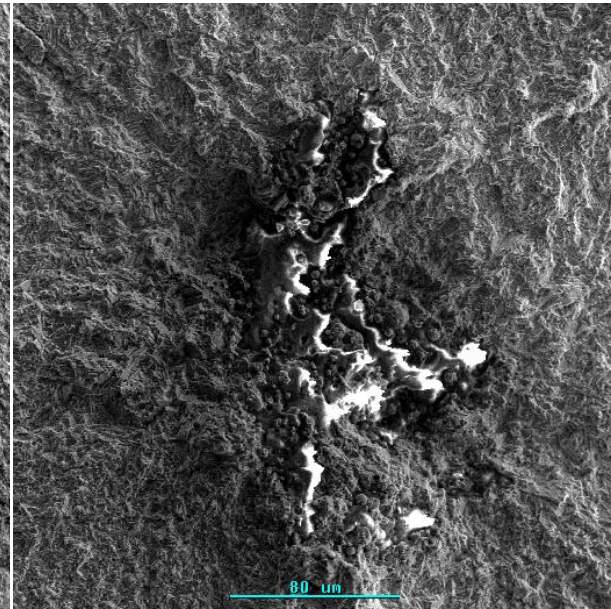
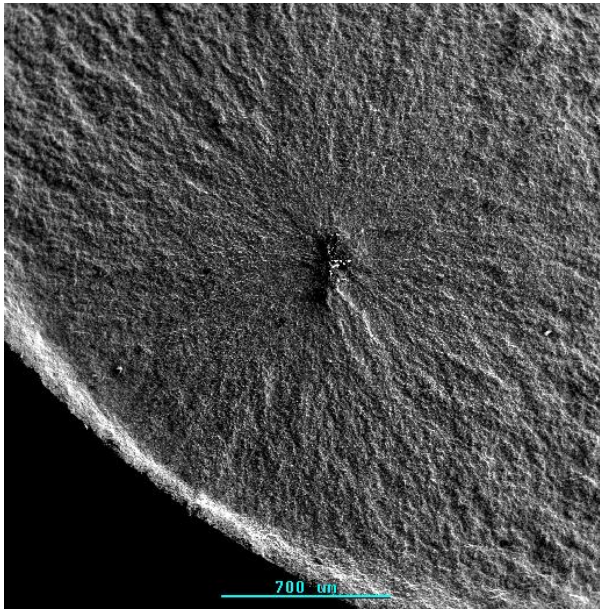
The fracture is ductile, nucleated by the presence of an inclusion

Fractography – hipped sample fatigue test at 500 C



Fracture surface observed by means of Stereo Macro-scope.

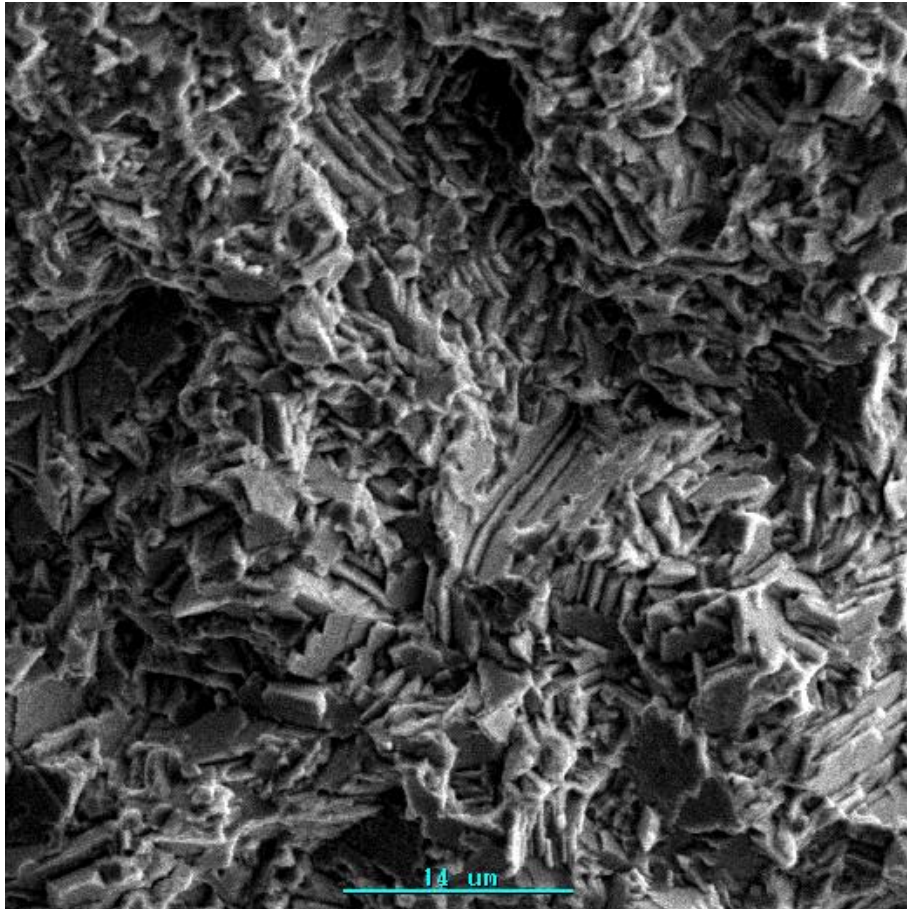
The fatigue fracture is nucleated by the presence of a defect constituted by an Al-Mg oxide.



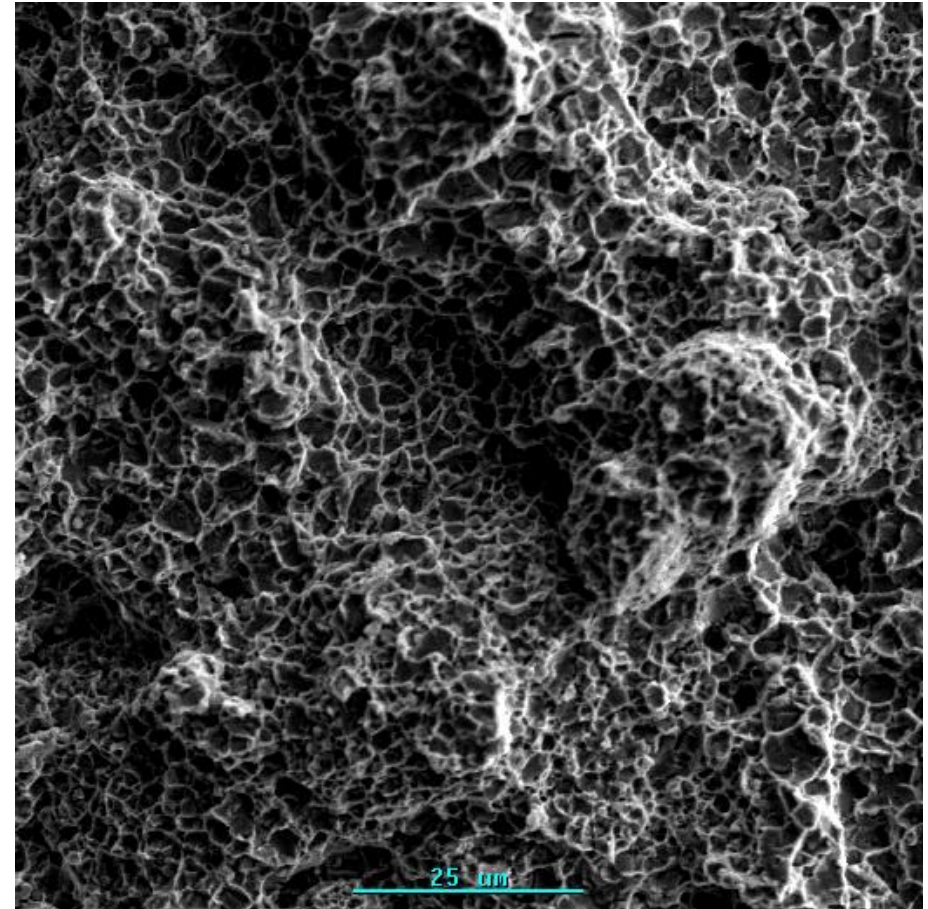
Nucleation zone (detail)

Defect EDS

Fractography – hipped sample fatigue test at 500 C



Fatigue propagation zone



Final fracture zone characterized by ductile morphology

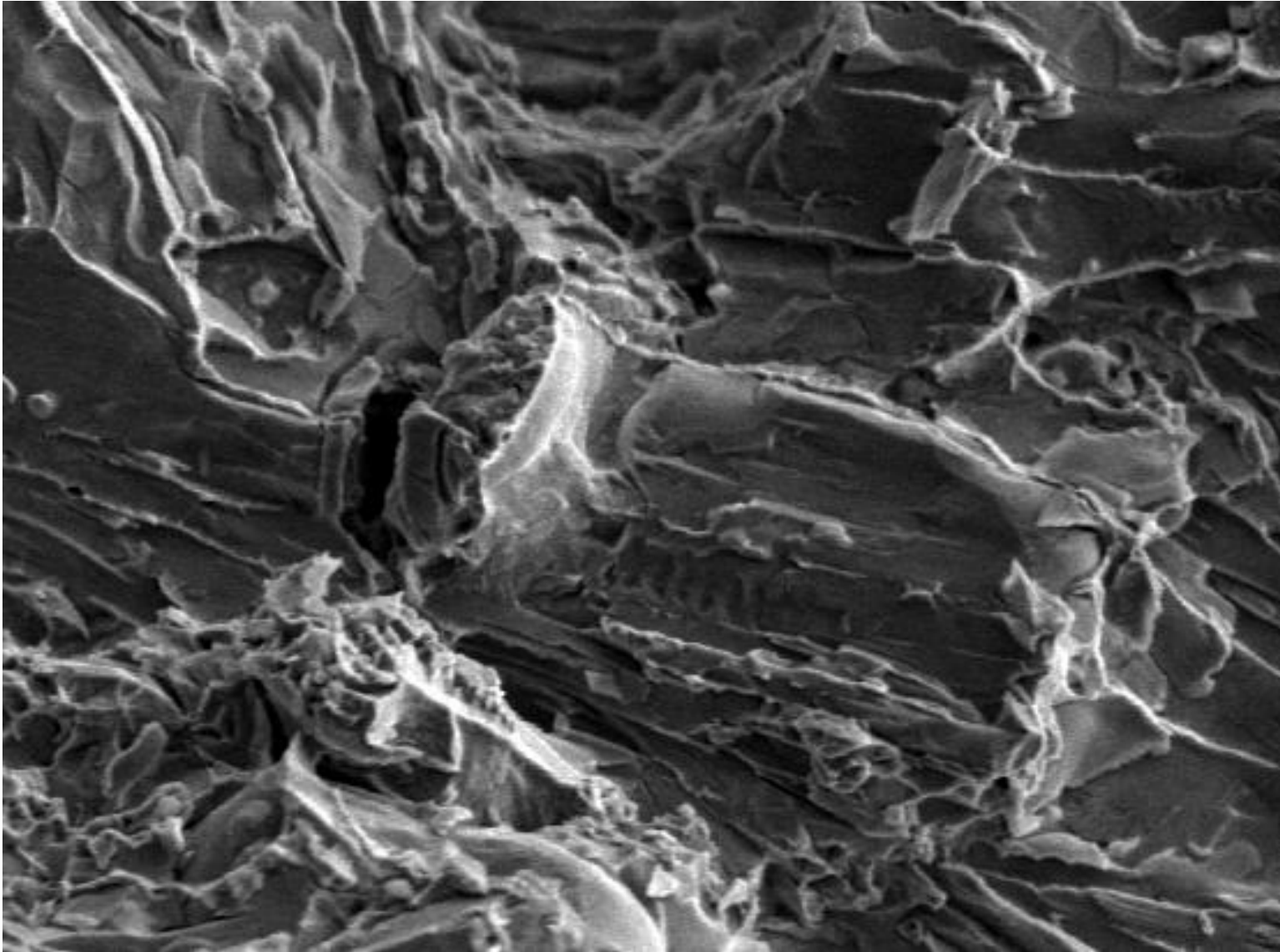
Discussion and conclusions (I/II)

- ★ Cast samples are constituted by cobalt rich primary dendrites and lamellar inter-dendritic zones (eutectic mixtures) with high carbides content.
- ★ Dendritic matrix is constituted by a solution of the alloying elements in FCC Co. EDS micro-analyses have evidenced two carbide types: one with high Cr content, the other with high W content.
- ★ Hipped 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 .
- ★ XRD analyses have shown shallow and partially overlapped peaks (e.g. 40-65 $^{\circ}$ range) with the probable prevalence of Co_{FCC} in respect to Co_{HCP} and the presence of mixed carbides. The cast sample show a phase evolution changing the test temperature, not observed for hipped samples.

Discussion and conclusions (II/II)

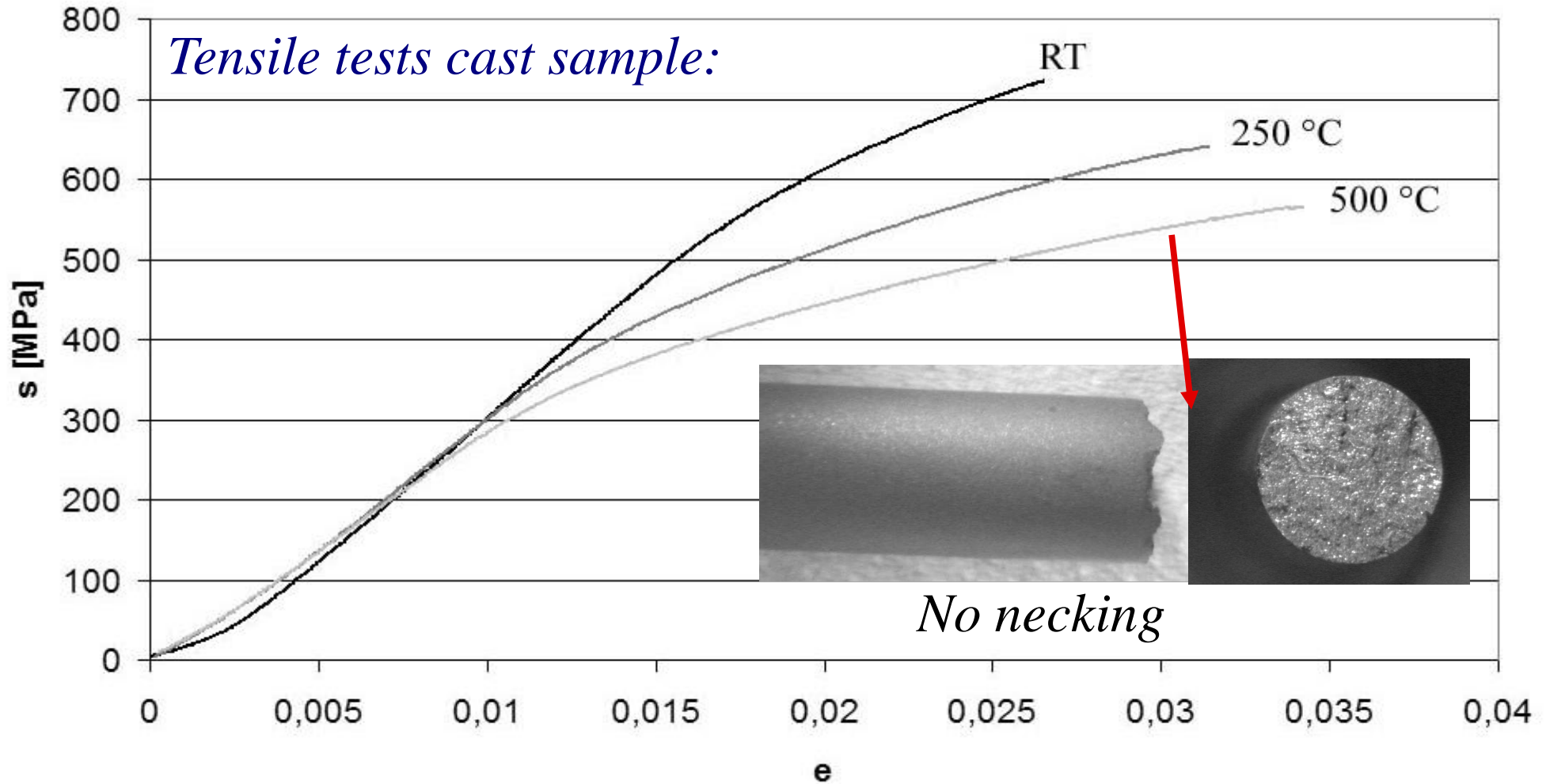
- ◆ The best performance both in tensile tests and in fatigue tests was observed for the hiped samples
- ◆ The effect of temperature on tensile and fatigue properties is limited; particularly, the observed fracture mechanisms do not change varying the temperature between 250 and 500 °C.
- ◆ In tensile test samples the fracture of cast samples is mainly inter-dendritic and only in some zones the fracture are completed by a quasi cleavage inter-dendritic fracture. In hiped samples the ductile mode fracture is nucleated by an inclusional defect.
- ◆ 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-step morphology. The crack of hiped samples is nucleated by an inclusion and the fracture is mainly ductile.

Fractography – tensile test fracture at 500 C (II/II)



quasi-cleavage

Mechanical tests



Fatigue tests:

- pulsed traction fatigue $R \approx 0$
- staircase method up to $2 \cdot 10^6$ cycles, 30 Hz, temperature 250 or 500 °C
- results obtained through 250 or 500 °C tests are similar

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	11	X	O
450	X											1	
440													
430													
420													
410		X		X								2	
400								X				1	
390			O		X		O		X		X	3	2
380										O			1
370						O							1

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 **250 C**

Strenght	Specimens results											Results	
Mpa	1	2	3	4	5	6	7	8	9	10	11	X	O
450	X											1	
440													
430		X				X						2	
420													
410			X		O		X					2	1
400								X				1	
390				O					X		O	1	2
380										O			1

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

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

HIP 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	11	X	O
740	X											1	
720													
700		X										1	
680				X		O						1	1
660			O		O								2

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

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