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Grain-boundary embrittlement in highly irradiated 15-15Ti austenitic steel

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Introduction

- Fuel cladding material for GEN-IV SFR reactor
- Optimized 15-15Ti austenitic steel designed to minimize irradiation swelling

Composition in wt%

Ti	Si	C	P	Mn	Mo	Ni	Cr
0,50	0,95	0,085	0,007	1,50	1,46	14,8	14,9

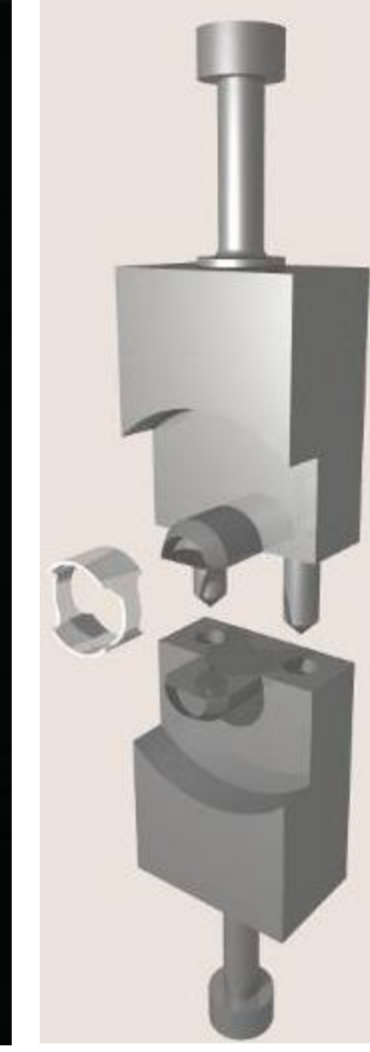
- 20% cold working after annealing treatment
- Fuel pin irradiated in Phénix SFR (110 dpa max)
- PIE performed at CEA/LECA & CEA/LECI



Phénix experimental fast reactor



Sample cutting CEA/LECA

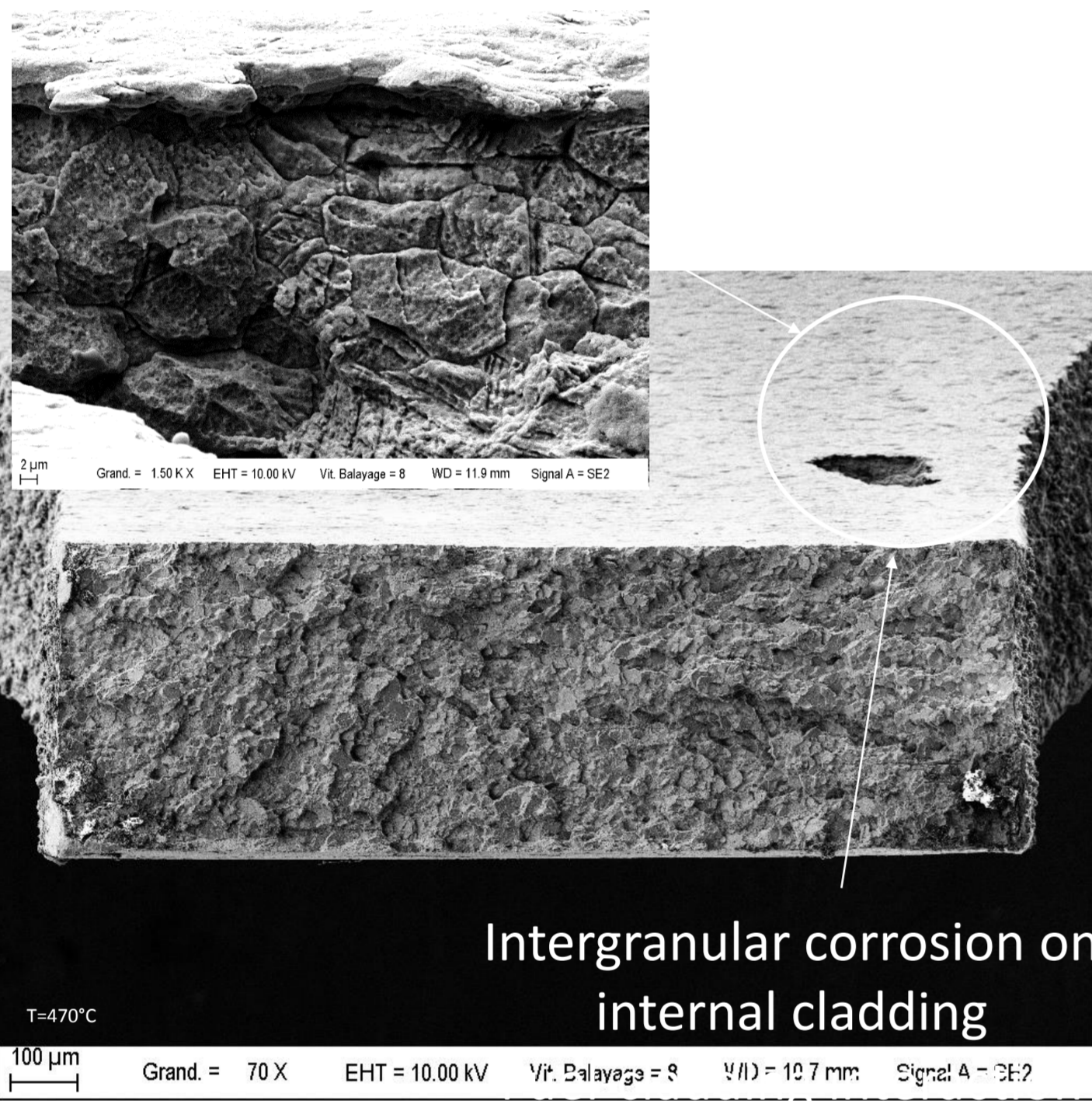


Ring tensile test CEA/LECI

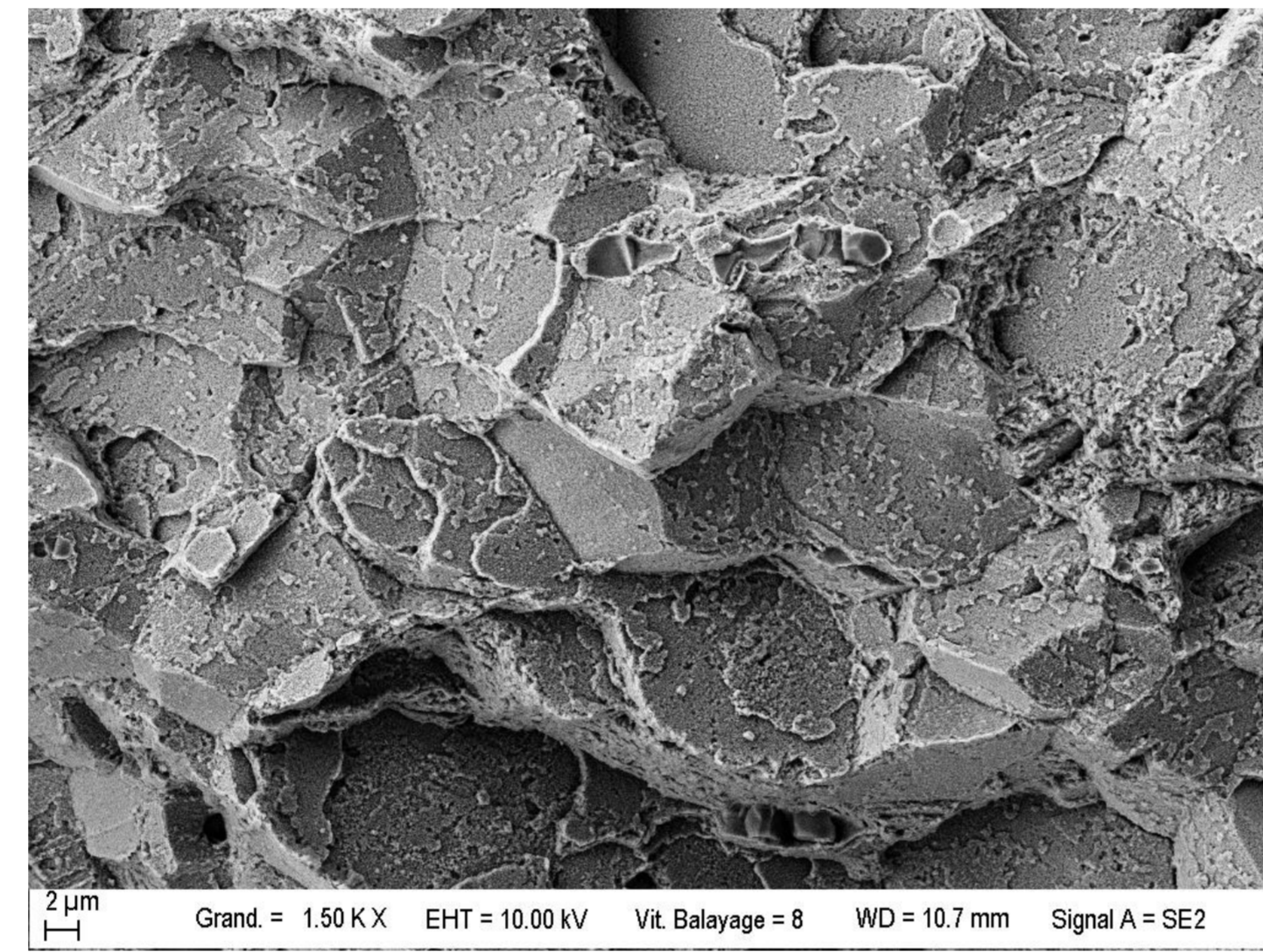
- Irradiation temp. : 470°C
- Dose : 93 dpa
- Swelling : 4.4%
- Tensile properties 20°C :
 - Total Elong. = 0.3%
 - $YS_{0.2} = 883 \text{ MPa}$
 - $UTS = 908 \text{ MPa}$

→ Low ductility

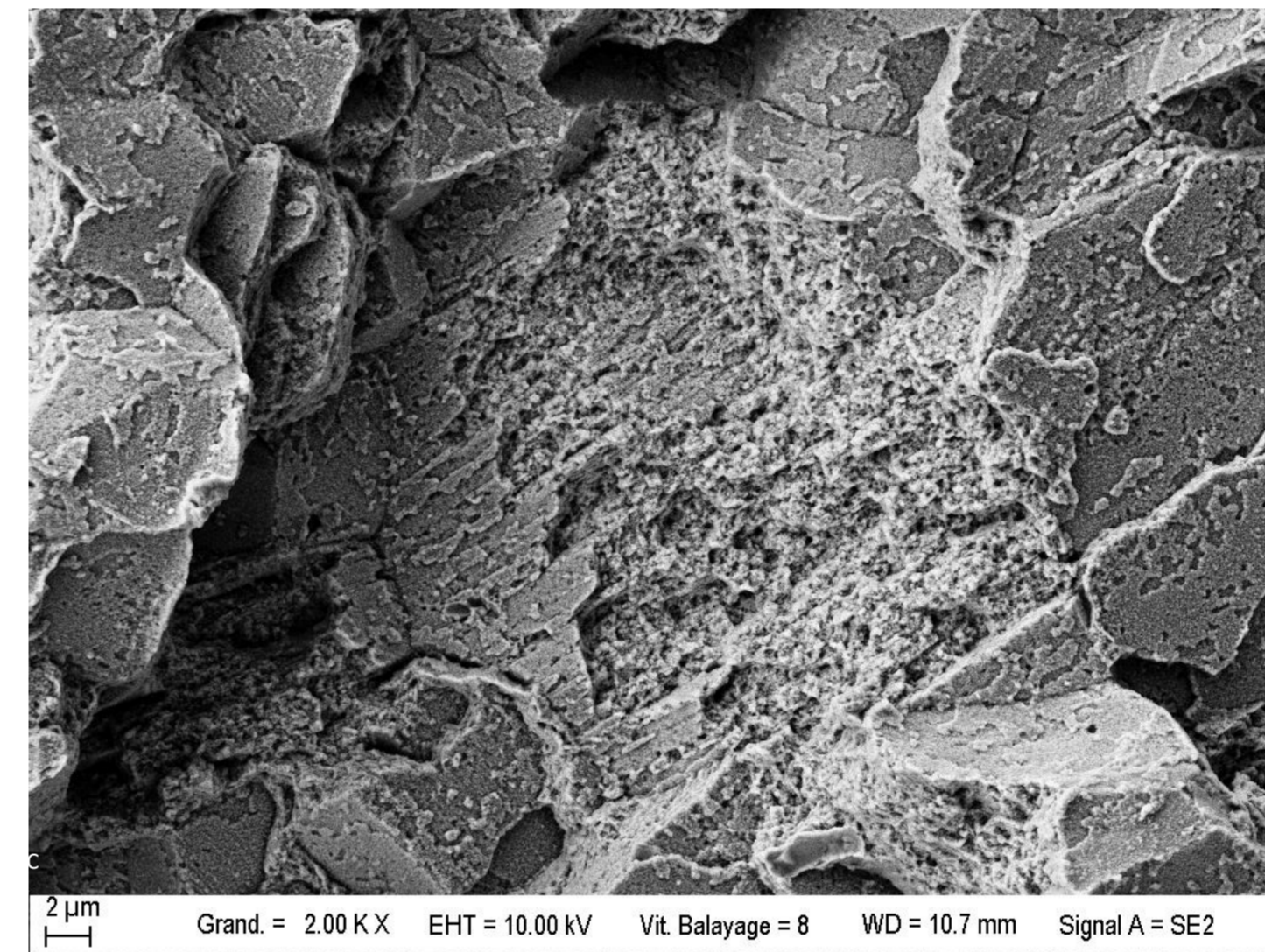
Fractography after ring tensile test at 20°C



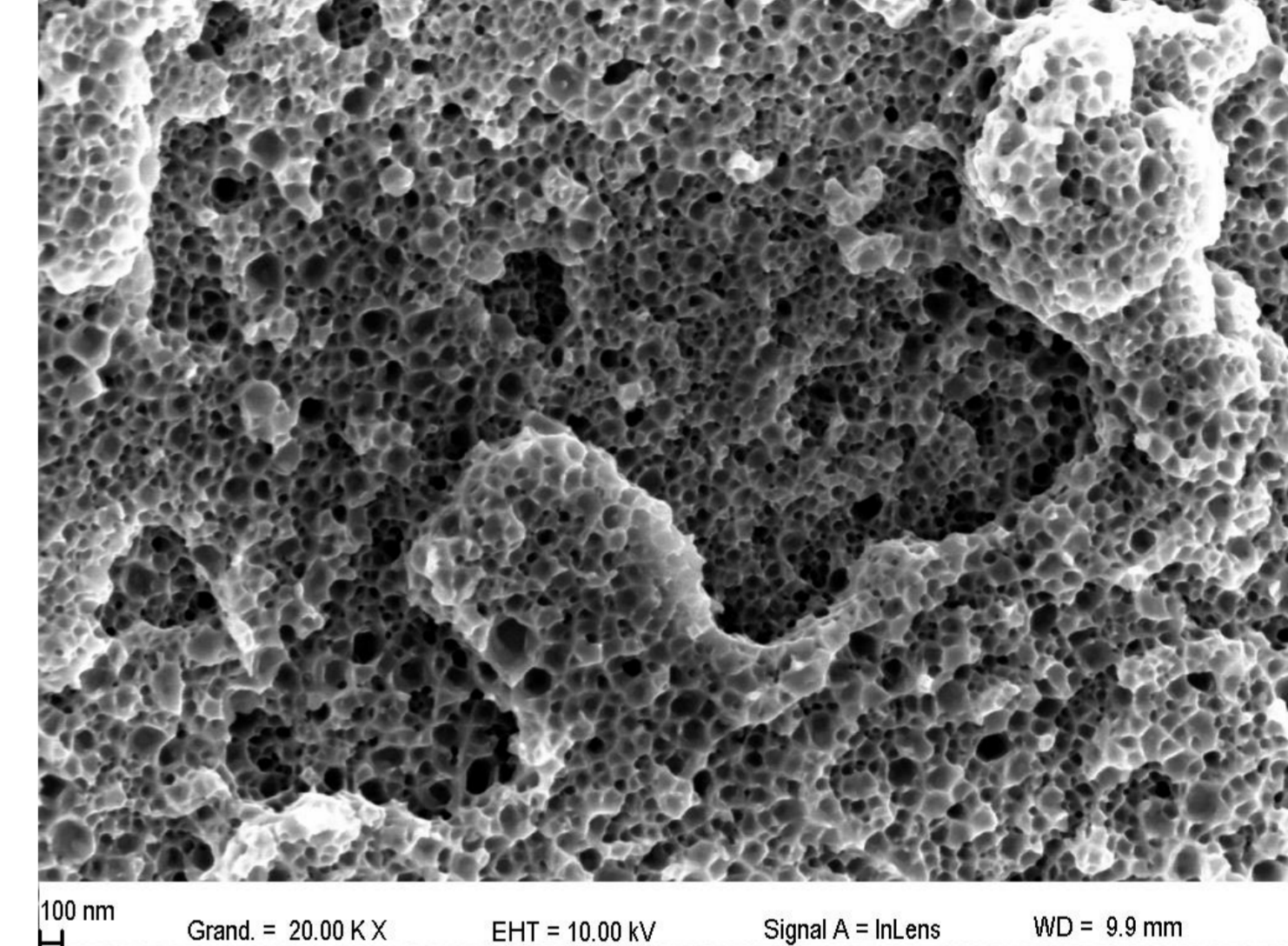
General overview



Intergranular rupture with nanodimples and precipitates at GB

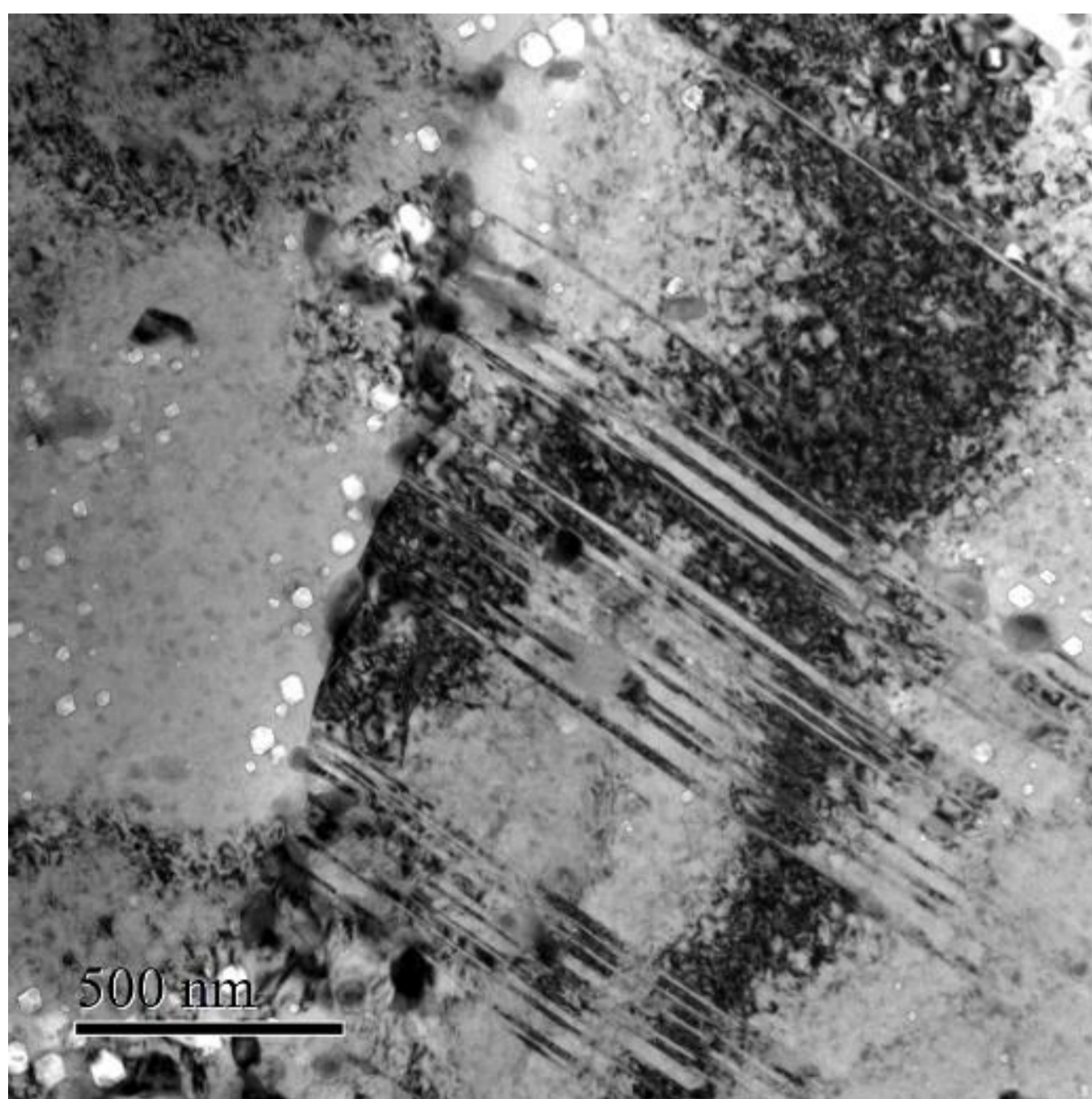


Transgranular fracture high local swelling

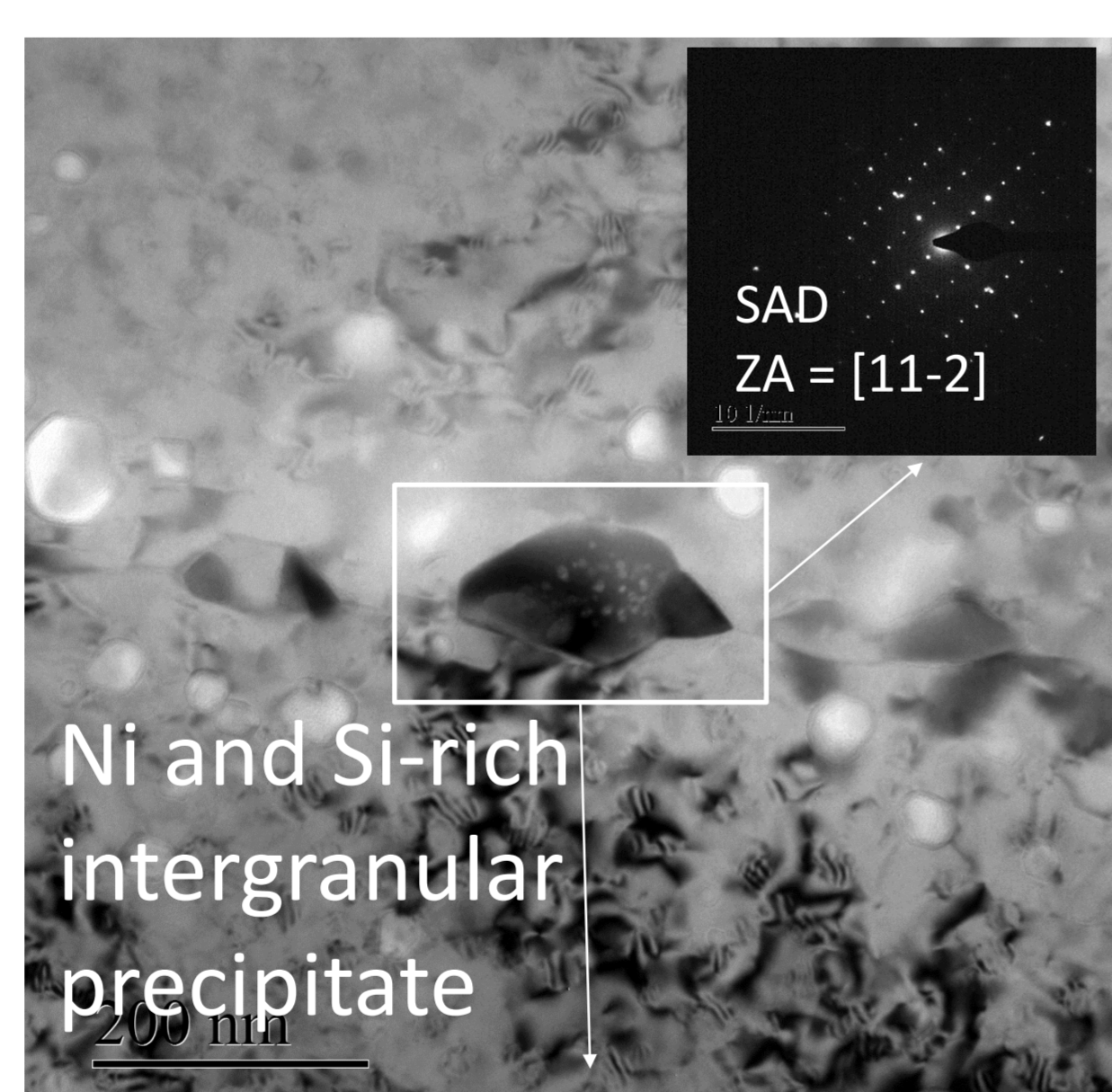


Nanodimples at grain boundary $T_{irr} = 450^\circ\text{C}$

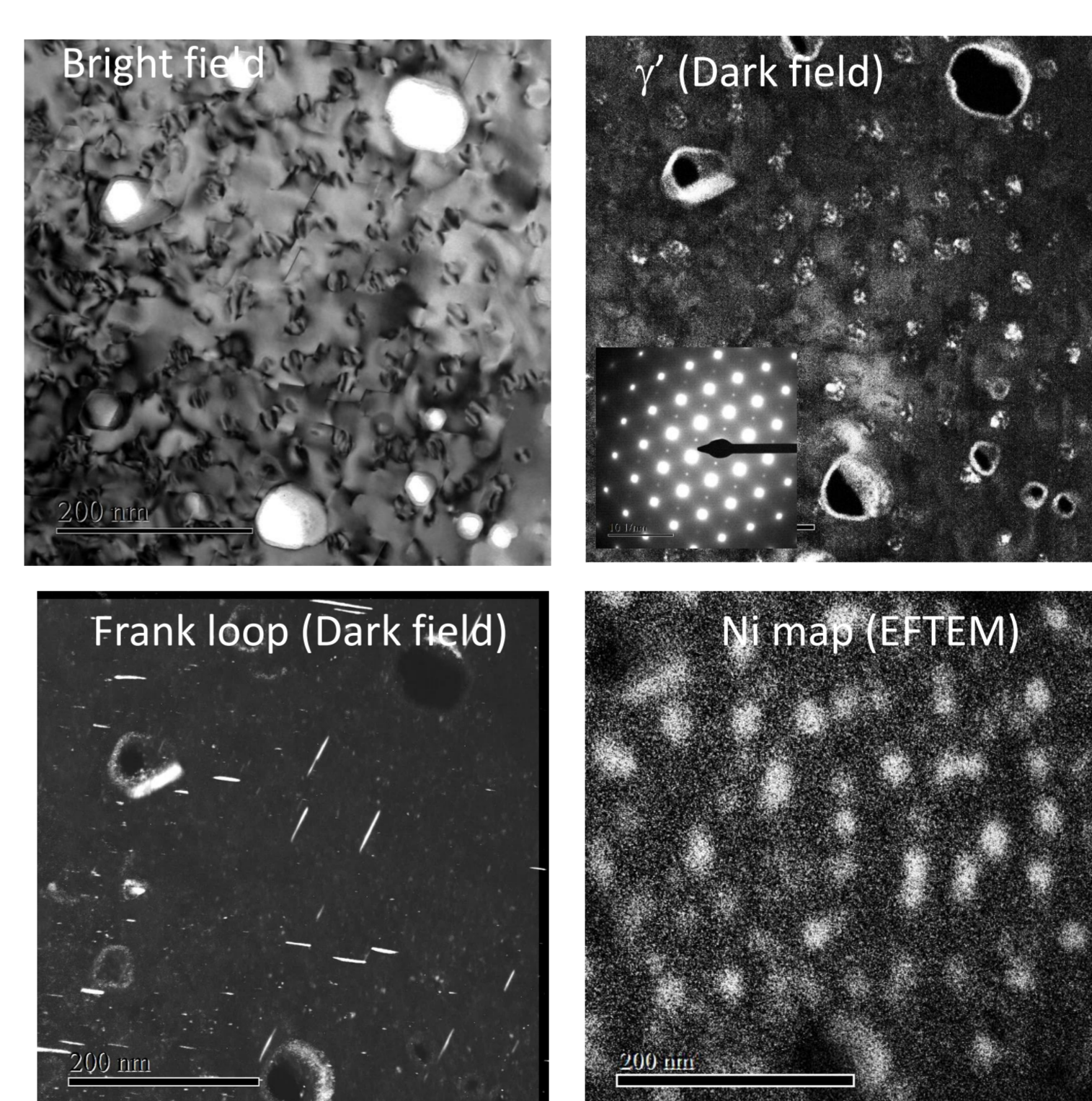
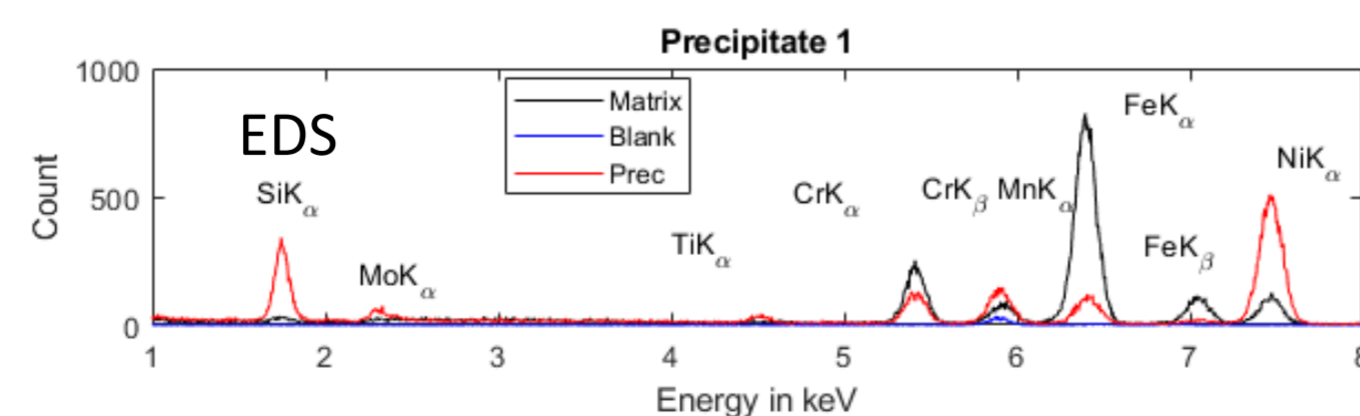
Transmission Electron Microscopy



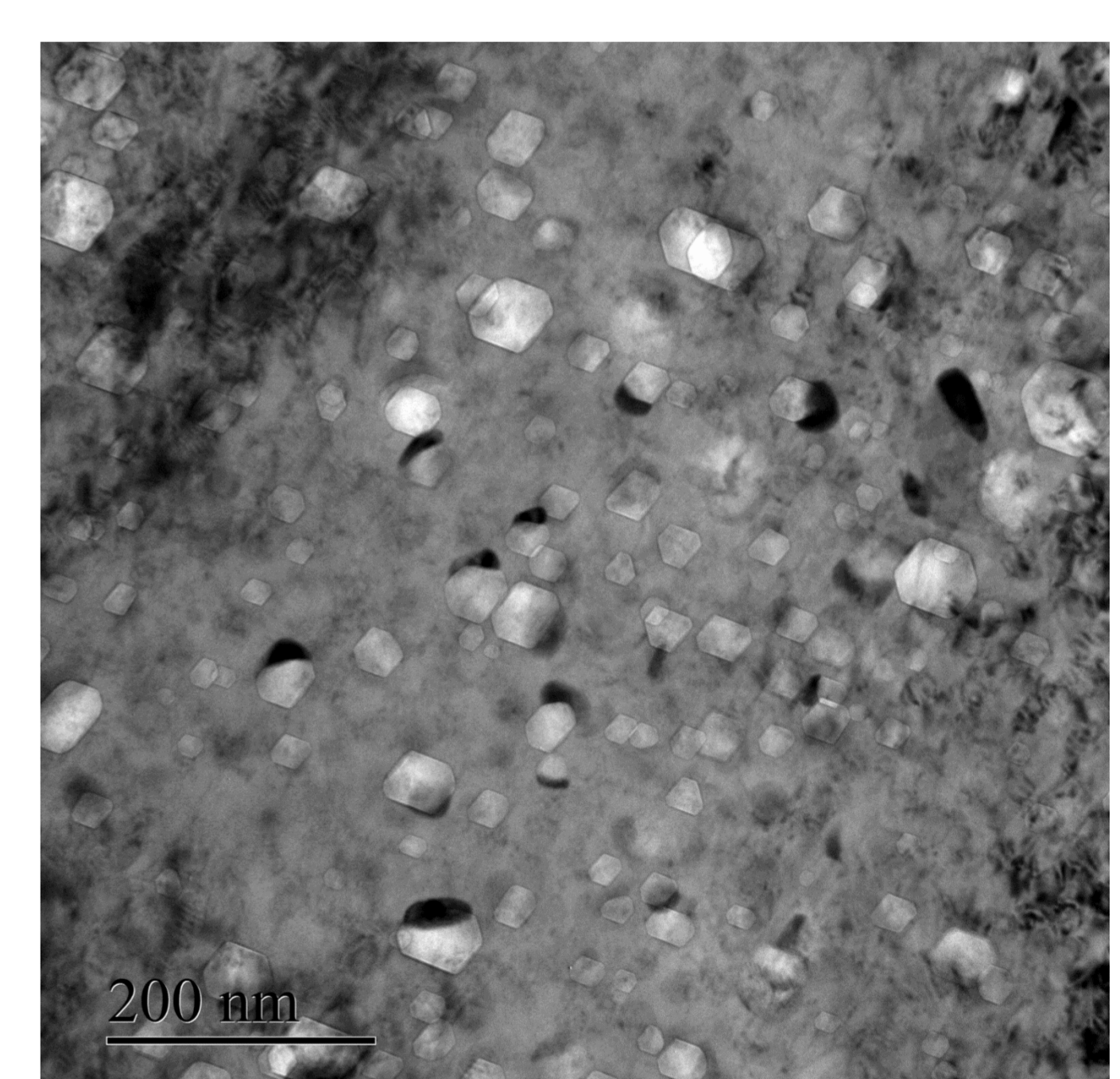
Cavities around Grain Boundary



Intergranular precipitate SAD+EDS \Rightarrow G phase



Matrix hardening : irradiation defects Cavities – Frank loops, γ'



Cavities inside grain Attached to precipitates (G phase)

Discussion on embrittlement mechanisms

- Low ductility observed in tensile test :
 - Segregation of Si and Ni and precipitation (G phase) at grain boundary
 - Low average swelling (~4,4%) but high local swelling near grain boundaries
 - Matrix irradiation hardening (irradiation defects : interstitial loops, cavities and precipitation γ')
 - Suspected Fuel-cladding interaction at low temperature $<500^\circ\text{C}$