Microstructure Evolution of 7075 Aluminum Gas Atomized Powder During Cold Spray Processing

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Thursday, June 19th, 2014, 8:00 a.m.

Addressing Microstructural Concerns

- ✓ Cold sprayed materials show low ductility due to several reasons including microstructural characteristics.
- ✓ Limited attention has been dedicated to microstructural study of different regions in cold sprayed deposits and how they may affect the local mechanical properties.
- ✓ Lack of information in the literature on formation mechanisms for the microstructural features in deposited material.

Objectives

- The main objective of this work was to study the microstructural evolution of 7075 gas atomized powder during high pressure cold spray processing.

- Specific focus on the following:
  1) development of ultra fine grained (UFG) structures.
  2) size and distribution of precipitates.
  3) solute element distribution within the microstructure.
  4) mechanical property variation in different regions.
  5) Non-isothermal heat treatment by is-situ TEM

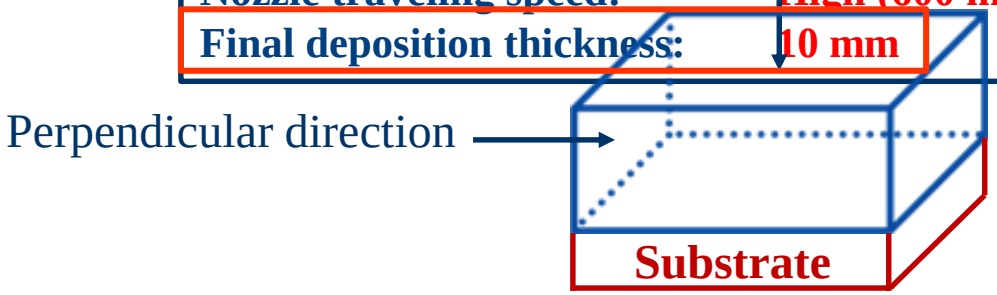
Experimental Procedure

- 7075 Al coatings were produced using commercially available gas-atomized 7075 Al powder.
- Microstructural characterization of the as-received powder and the coatings via microscopy techniques.
- Nanohardness: tests were conducted in load control mode using a maximum load of 5 mN.

Cold Spray Process Parameters

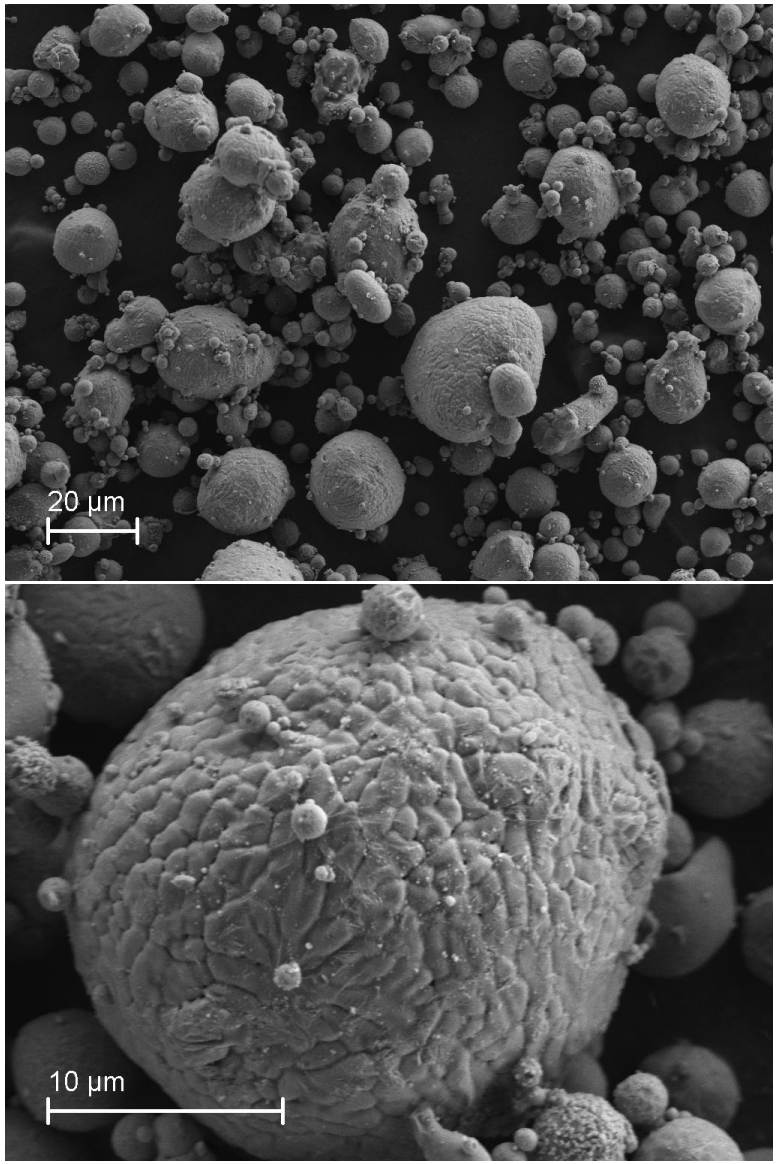
High-pressure cold spray system (CGT 4000)

Carrier Gas:	**Helium**
Gas Pressure:	**2.8 MPa**
Gas Temperature:	**450°C**
Stand-Off Distance:	**25mm**
Deposition angle:	**90°**
Powder feed rate:	**Medium (12 g min^{-1})**
Nozzle traveling speed:	**High (600 mm s^{-1})**
Final deposition thickness:	**10 mm**



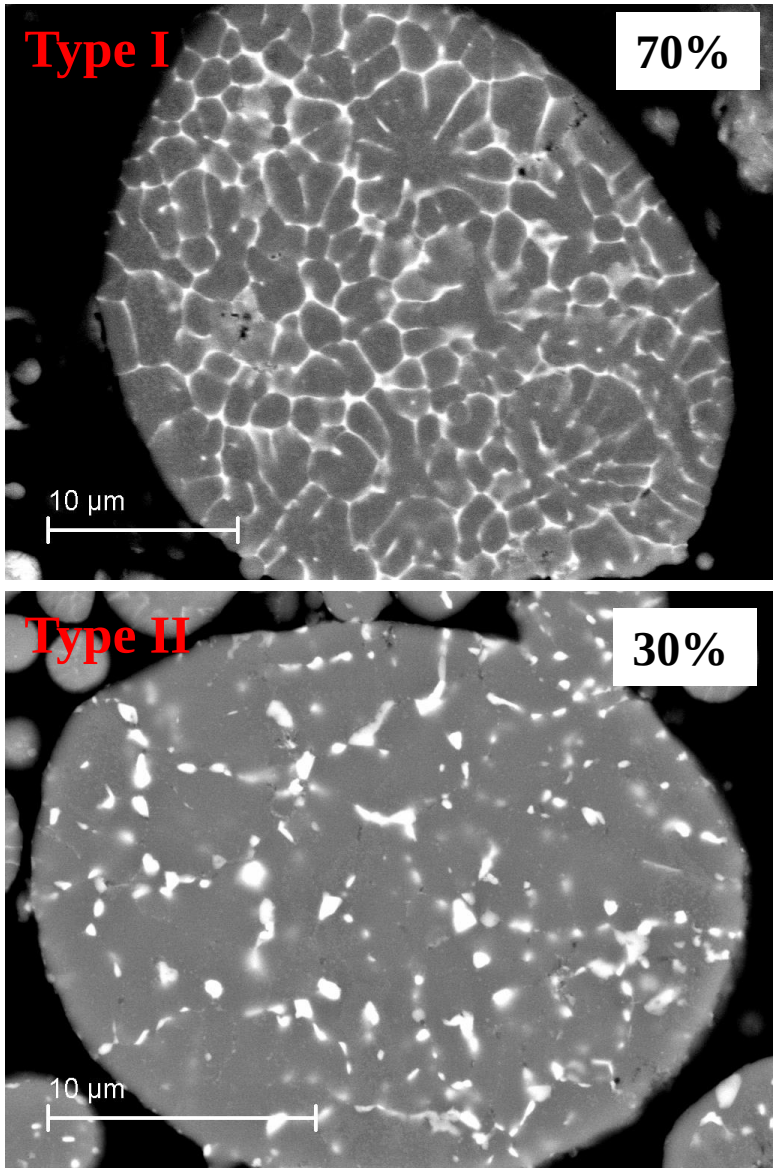
Powder Microstructure

- ✓ Relatively nonuniform particle size
- ✓ A mixture of both large particles and micro-satellite particles (less than 5 µm in size)
- ✓ particle size of 18.6 ± 8.2 µm
- ✓ The powder structure consists of grains in the range of 1-4 µm

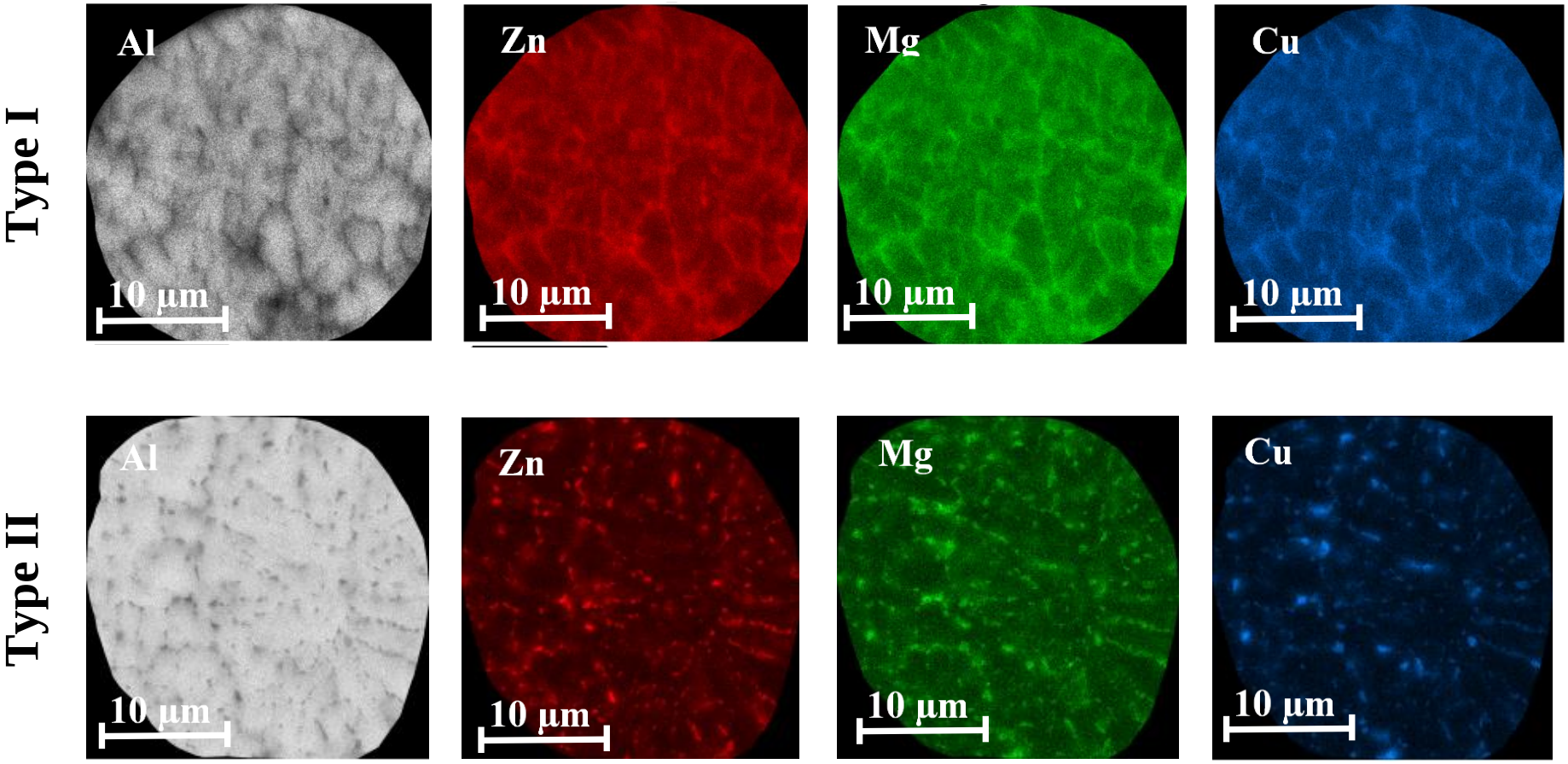


Powder Microstructure

- ✓ Two different internal grain and GB structure in the powder particles
- ✓ Type I: the same internal grain structure as that of the surface and with GB solutes segregation
- ✓ Type II: larger grain size with some precipitates at the GBs, due to lower solidification rate than that of the type I



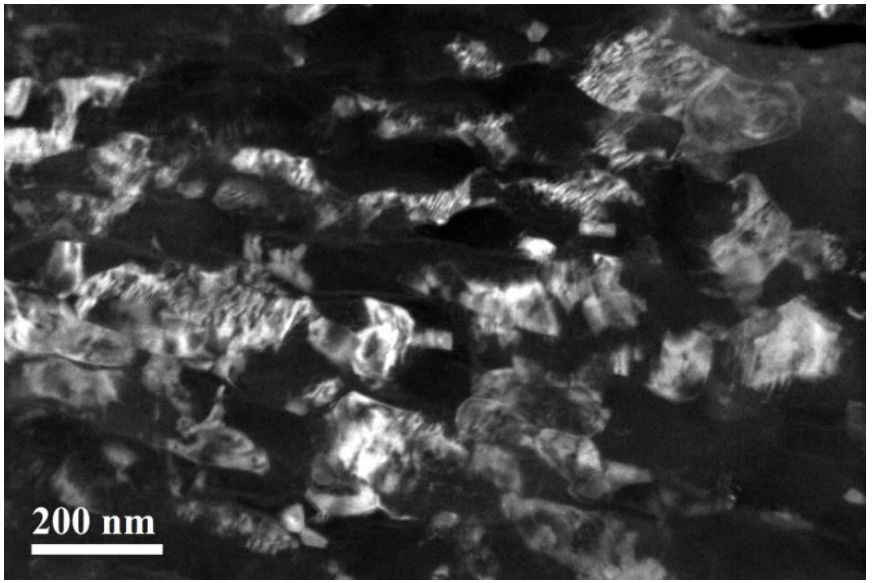
EDS map of Cross Section

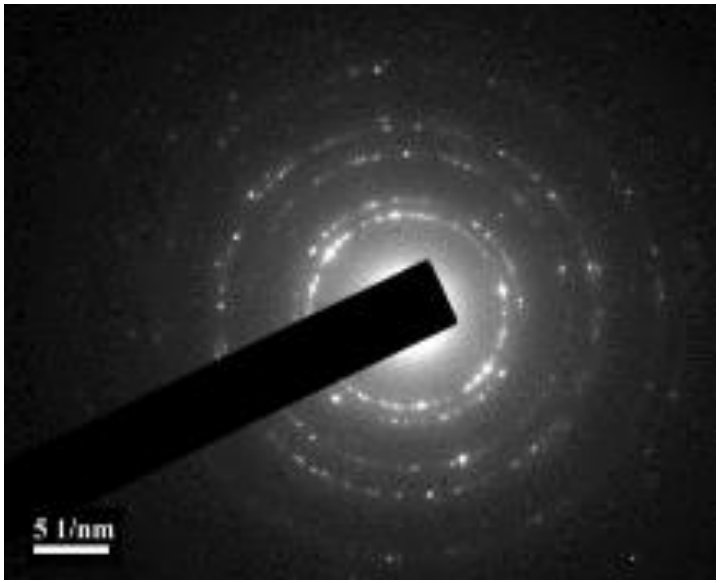


✓ Nonuniform distribution of solute elements in the microstructure

TEM study of the powder

- ✓ Internal UFG and even nano structures in powder particles
- ✓ Moderate density of dislocations and dislocation substructure
- ✓ A ring pattern in SADP
- ✓ Relatively high degree of residual stress developed through gas atomization process



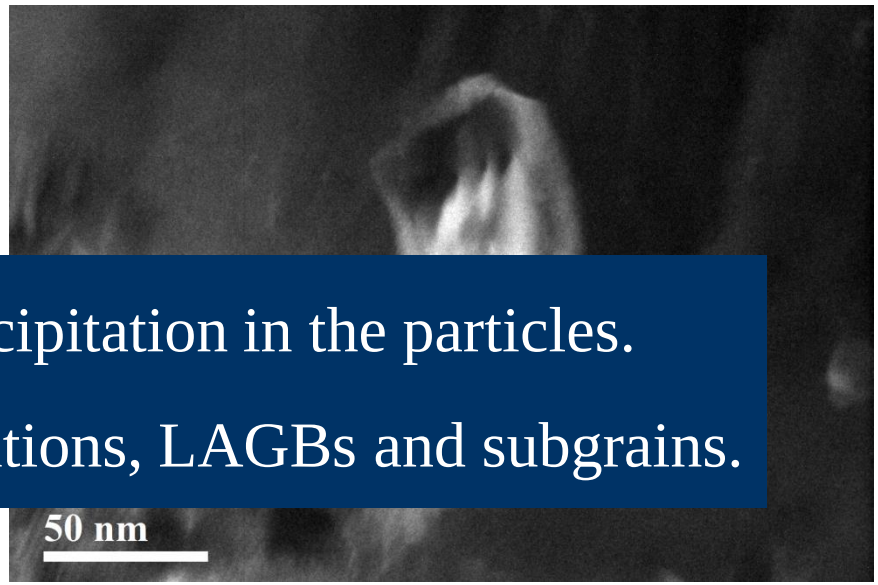


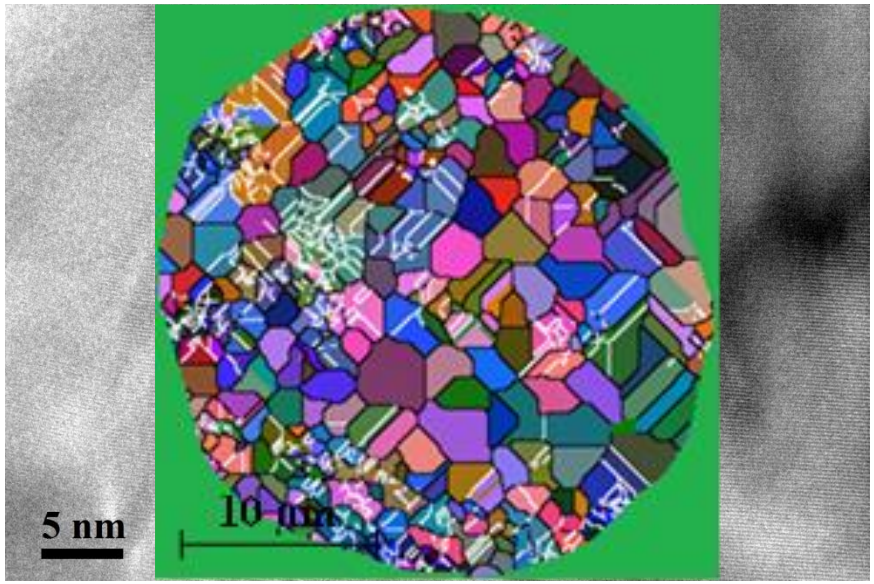
TEM study of the powder

- ✓ Presence of some nano subgrains
- ✓ The presence of dislocations
- ✓ A
  subgrain boundary
- ✓ Internal HAGBs (black lines) and LAGBs (white lines)

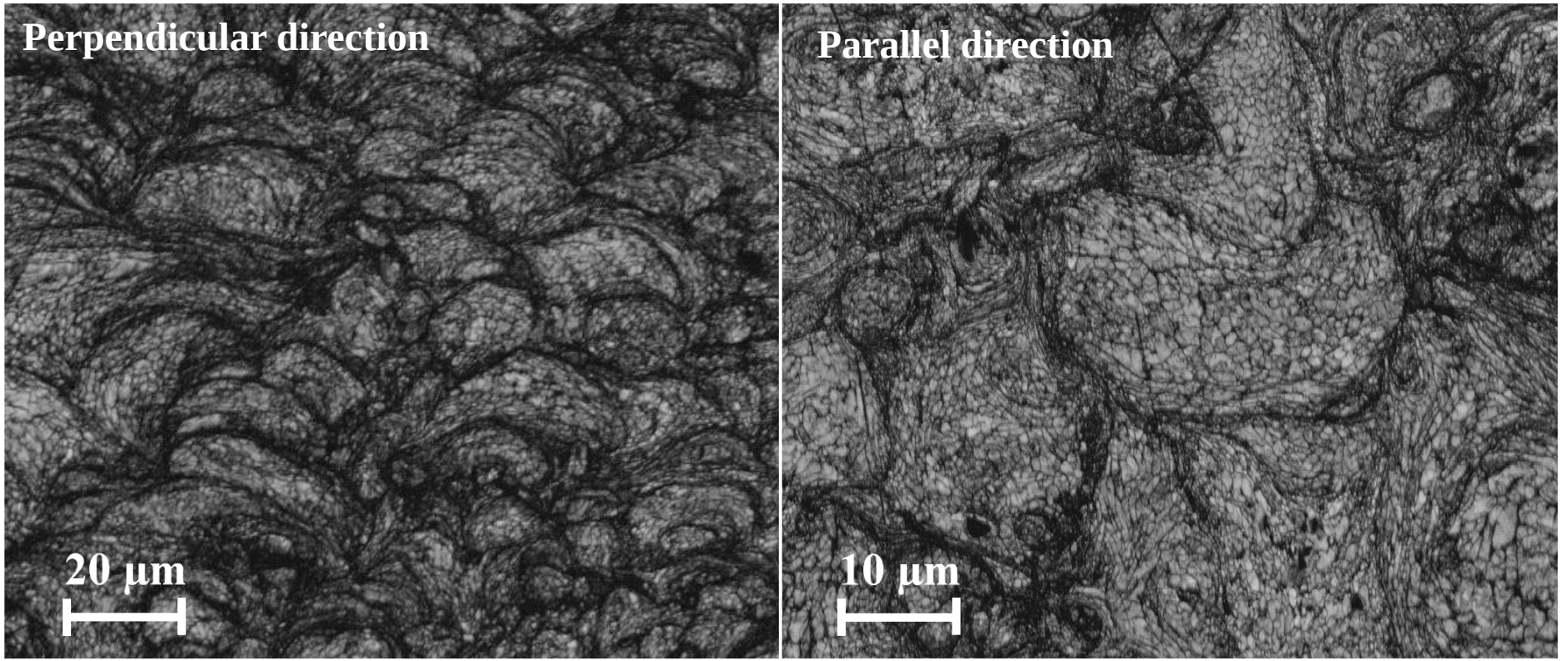
1- There is solute segregation/precipitation in the particles.

2- They also contain some dislocations, LAGBs and subgrains.



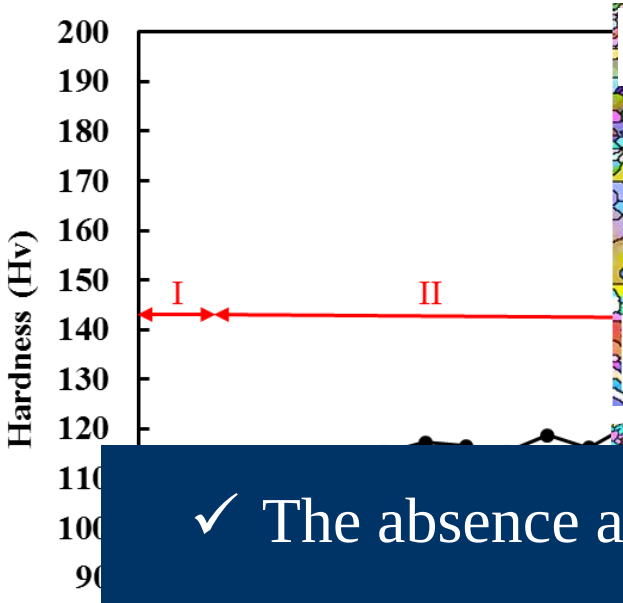


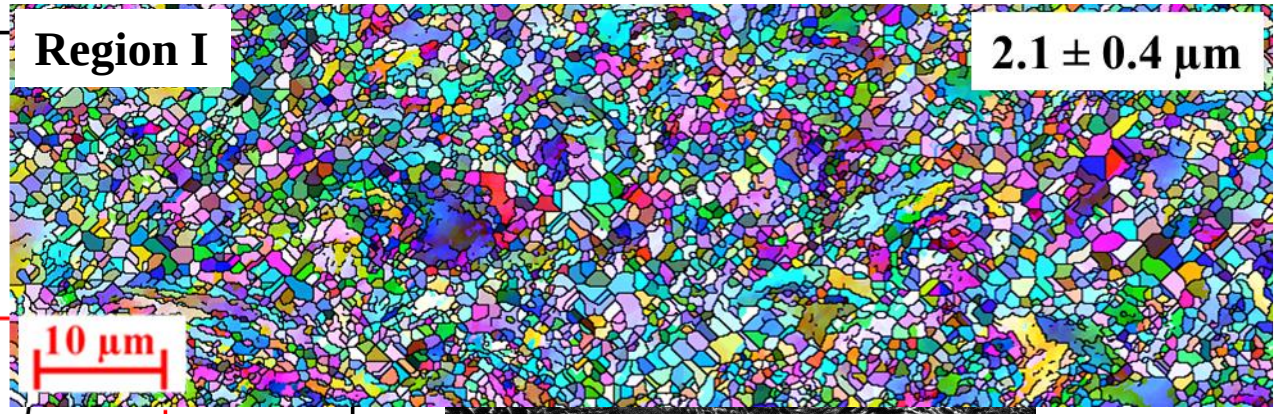
Overall structure of the CSP layer



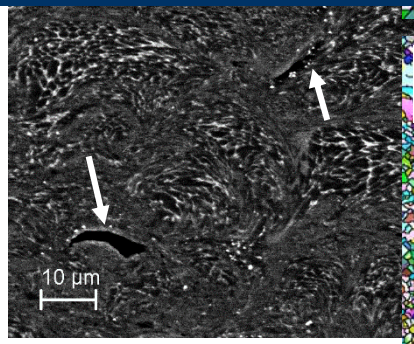
- ✓ Elongation of spherical particles
- ✓ No evidence of voids or porosity

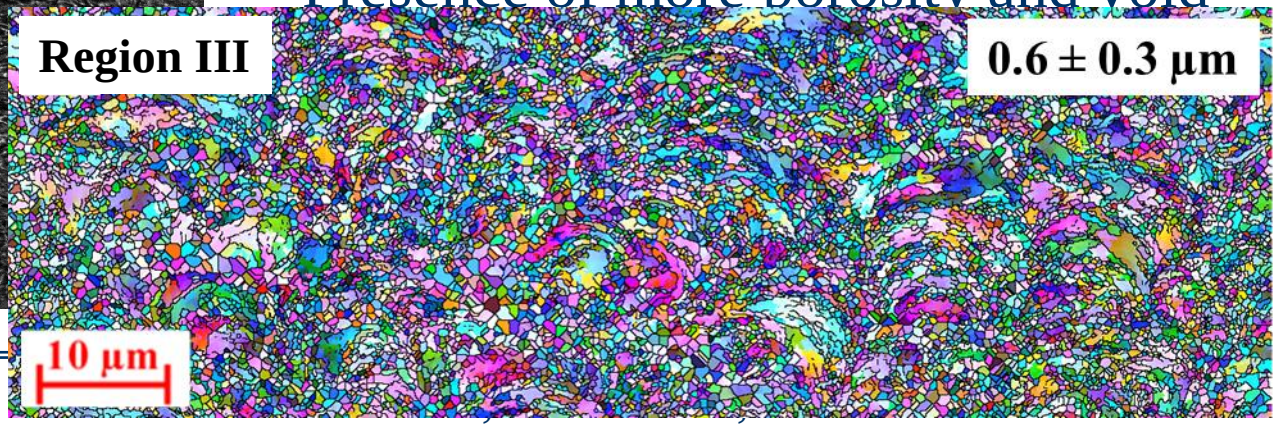
Overall structure of the CSP layer





- ✓ The absence and active presence of shot peening effect across the coating has substantial effects on the final microstructure.





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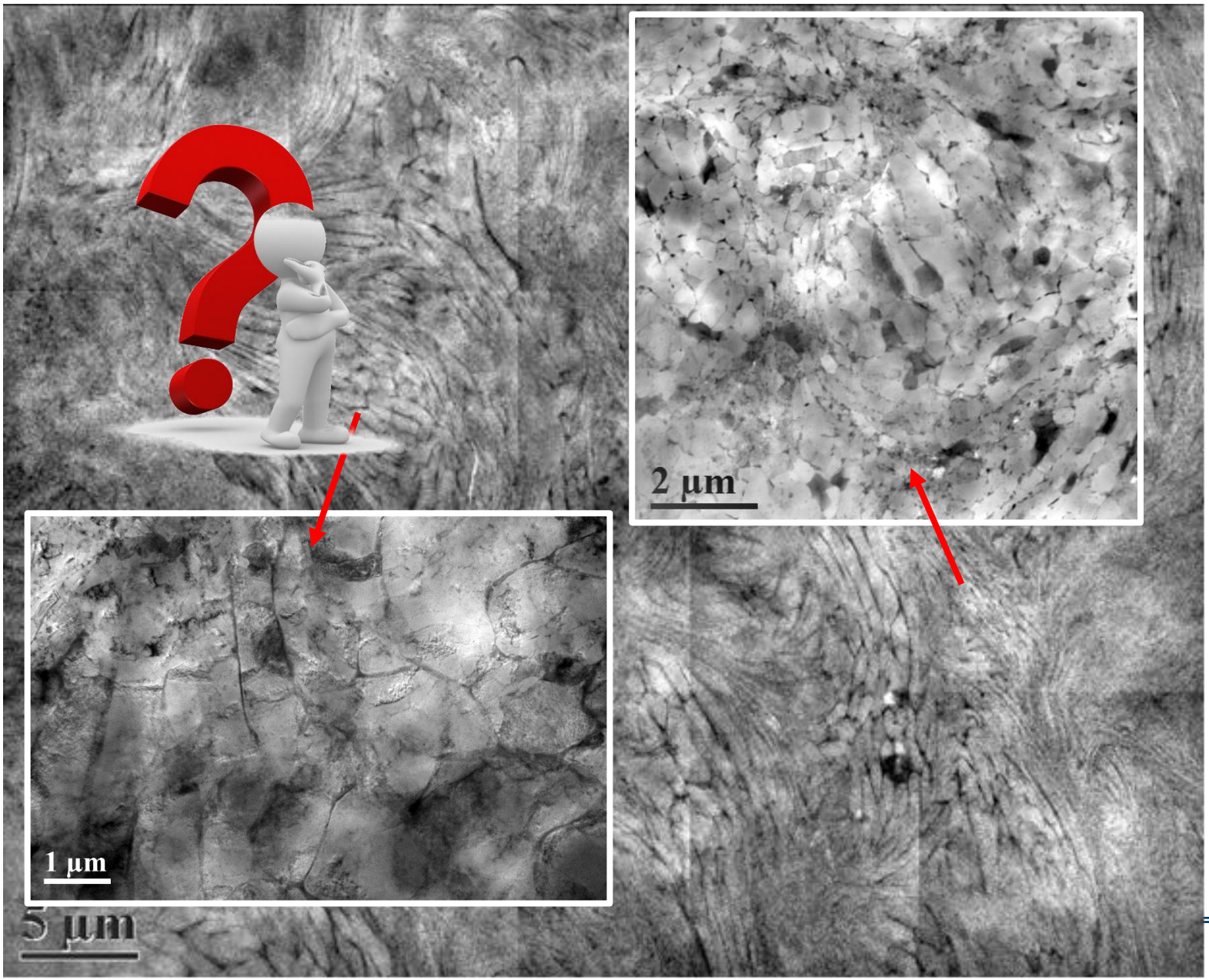
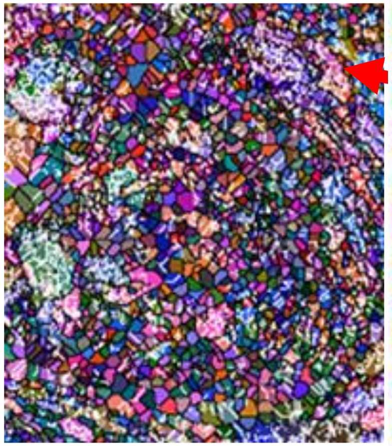
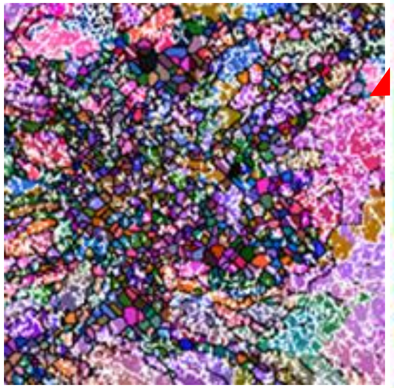
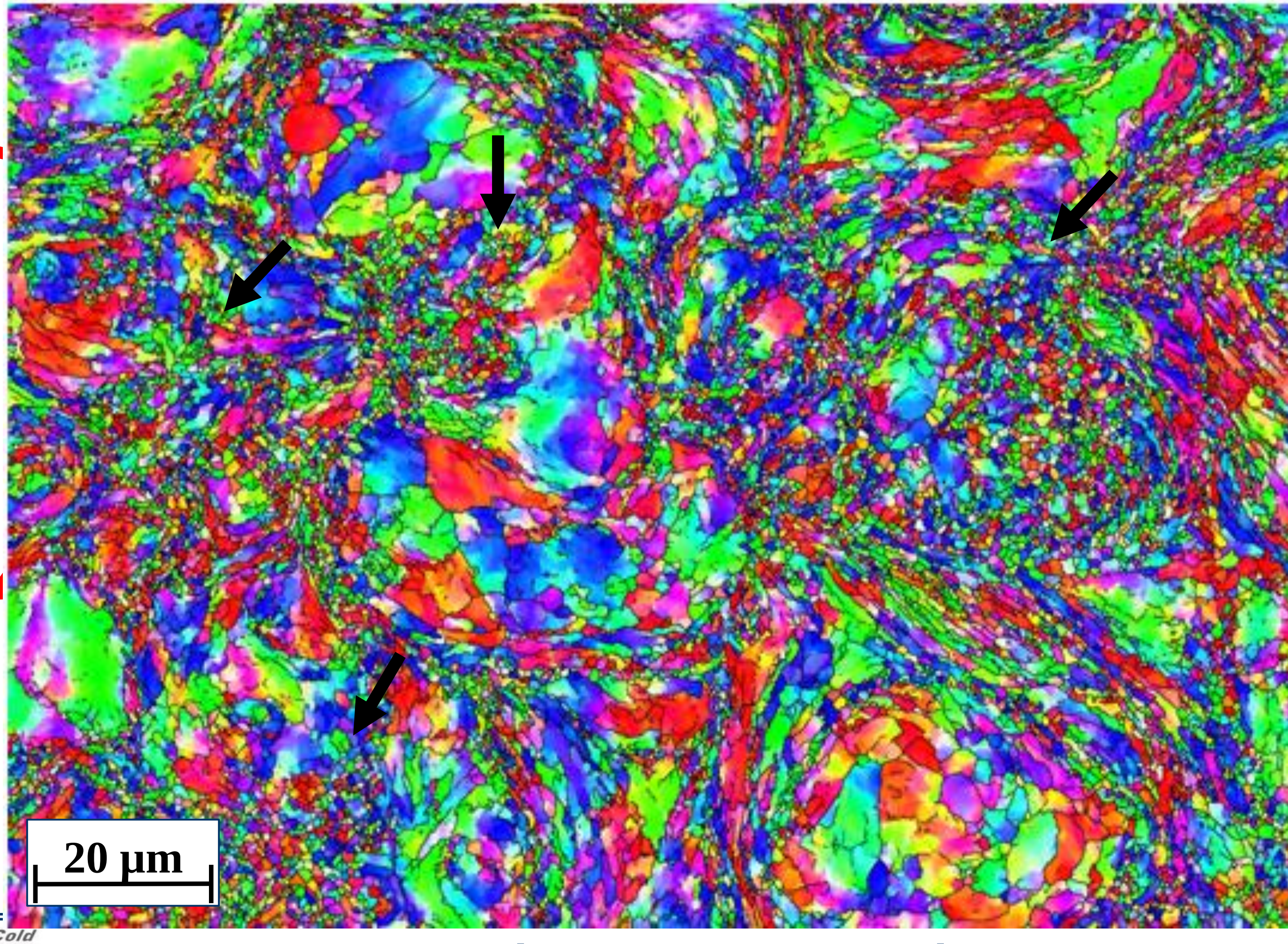


Main formation mechanisms

✓ A mechanism of **continuous dynamic recrystallization (CDRX)**: the formation of LAGBs in the first stages (dashed black arrows) and conversion of the LAGBs to HAGBs







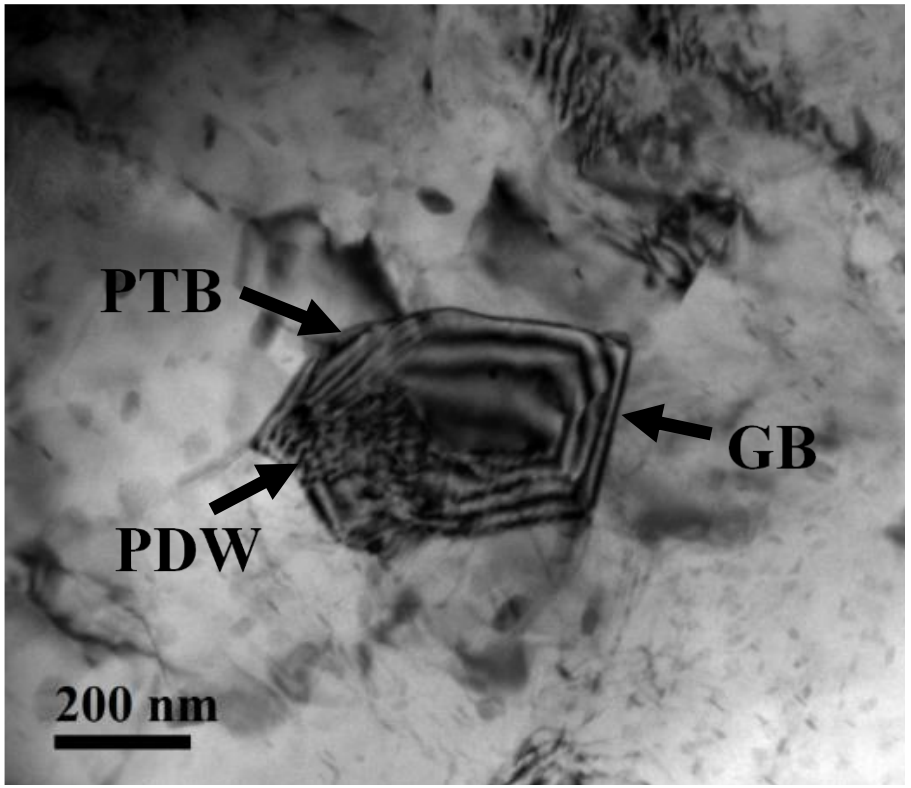
Structure Evolution of GBs

- ✓ 3 types of boundaries:

1- Polygonized dislocation wall (<1º)

2- Partially transf. boundary (1-5º)

3- Grain boundary (>15º)

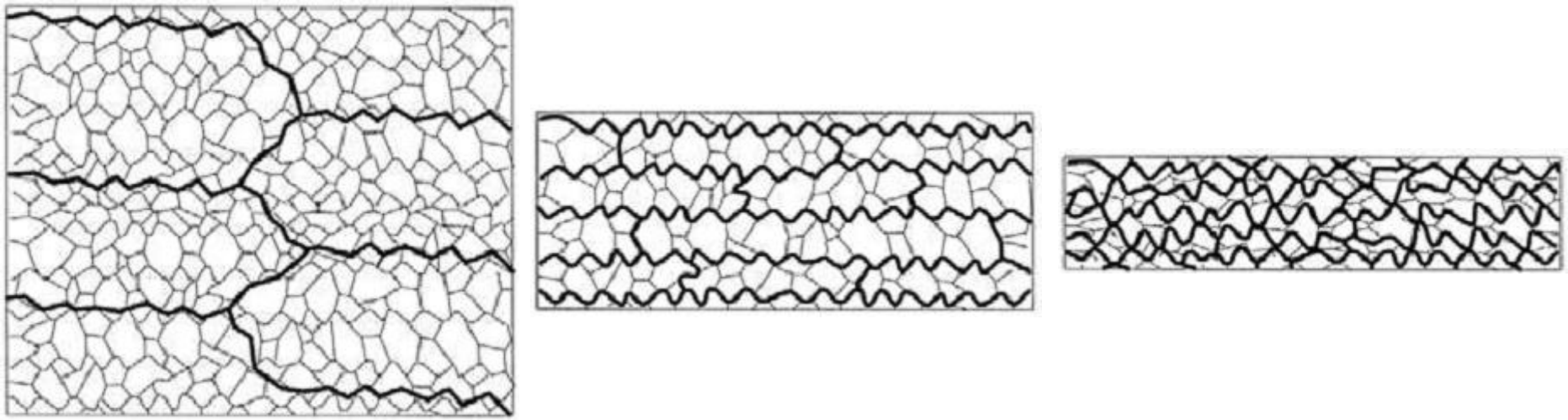


- ✓ Transformation of LAGBs to HAGBs
- ✓ Due to an increase the number of boundary dislocations during the deformation process

C. P. Chang, P. L. Sun, P. W. Kao, Acta mater. 48 (2000) 3377-3385.

Main formation mechanisms

Geometric DRX (GDRX)



1) The serrated HAGBs (thick lines) become closer.

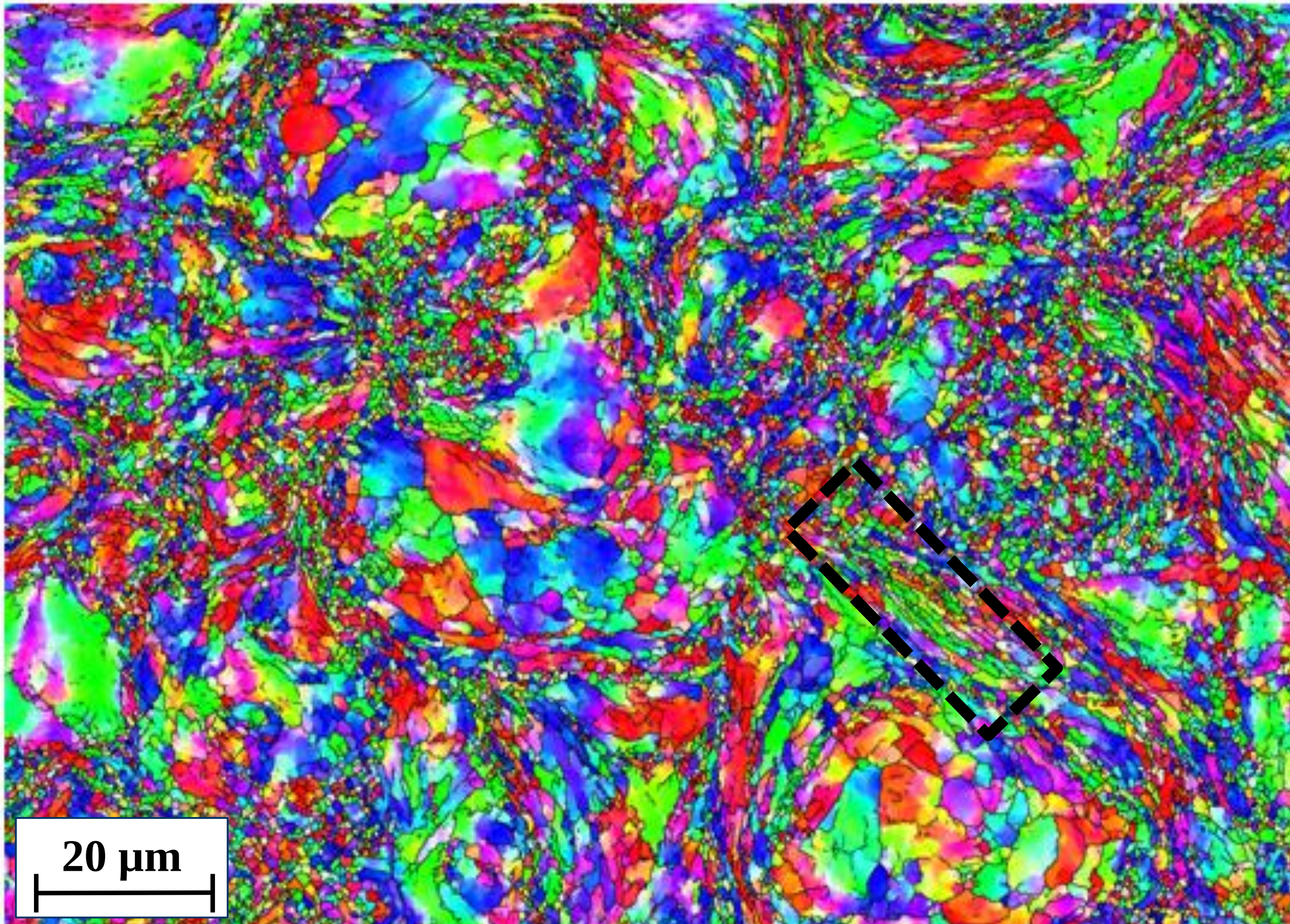
2) The subgrain size remains approximately constant.

3) Eventually the high angle boundaries (HAGBs) impinge, resulting in a microstructure of mainly UFG with HAGBs.

F.J. Humphreys, M. Hatherly, Recrystallization and Related Annealing Phenomena. Oxford, 2004.

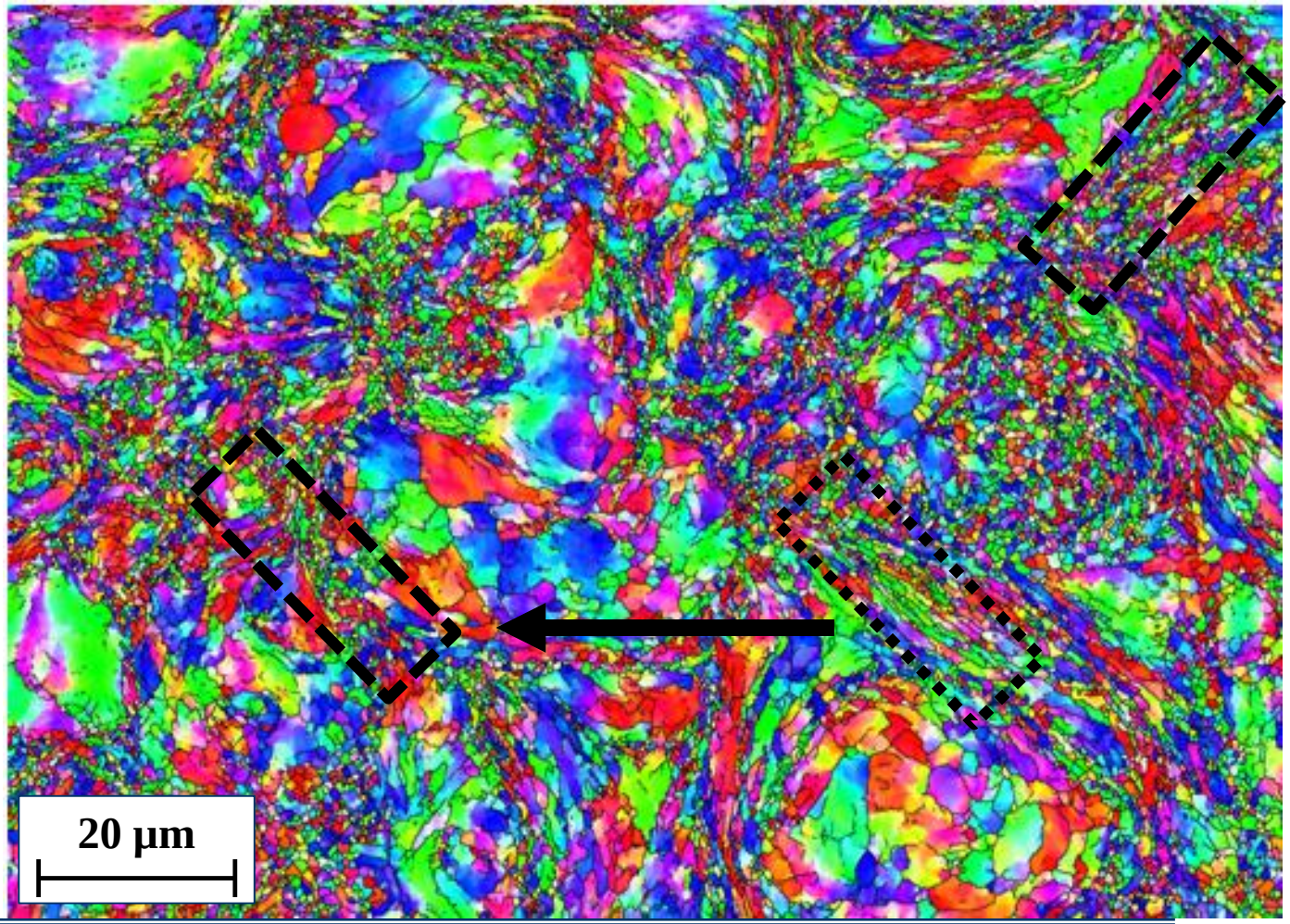
Microstructure of the CSP layer

- ✓ Some elongated grain structures at particle/particle boundaries
- ✓ Subdivided into pancaked subgrains by some LAGBs
- ✓ “Ladder-like’



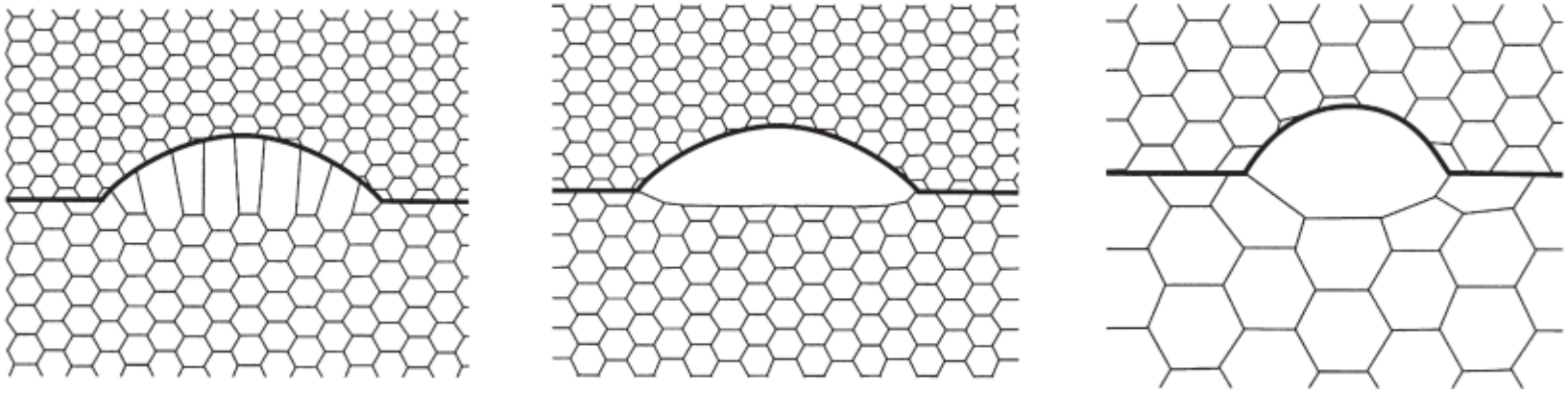
Main formation mechanisms

✓ A combination of CDRX and **Geometric DRX (GDRX)**



Other possible mechanisms

Strain Induced Boundary Migration (SIBM)



1) Bulging of part of a pre-existing grain boundary

2) Leaving a region behind the migrating boundary with a lower dislocation content

3) SIBM originating at a single large subgrain

F.J. Humphreys, M. Hatherly, Recrystallization and Related Annealing Phenomena. Oxford, 2004.

Other possible mechanisms

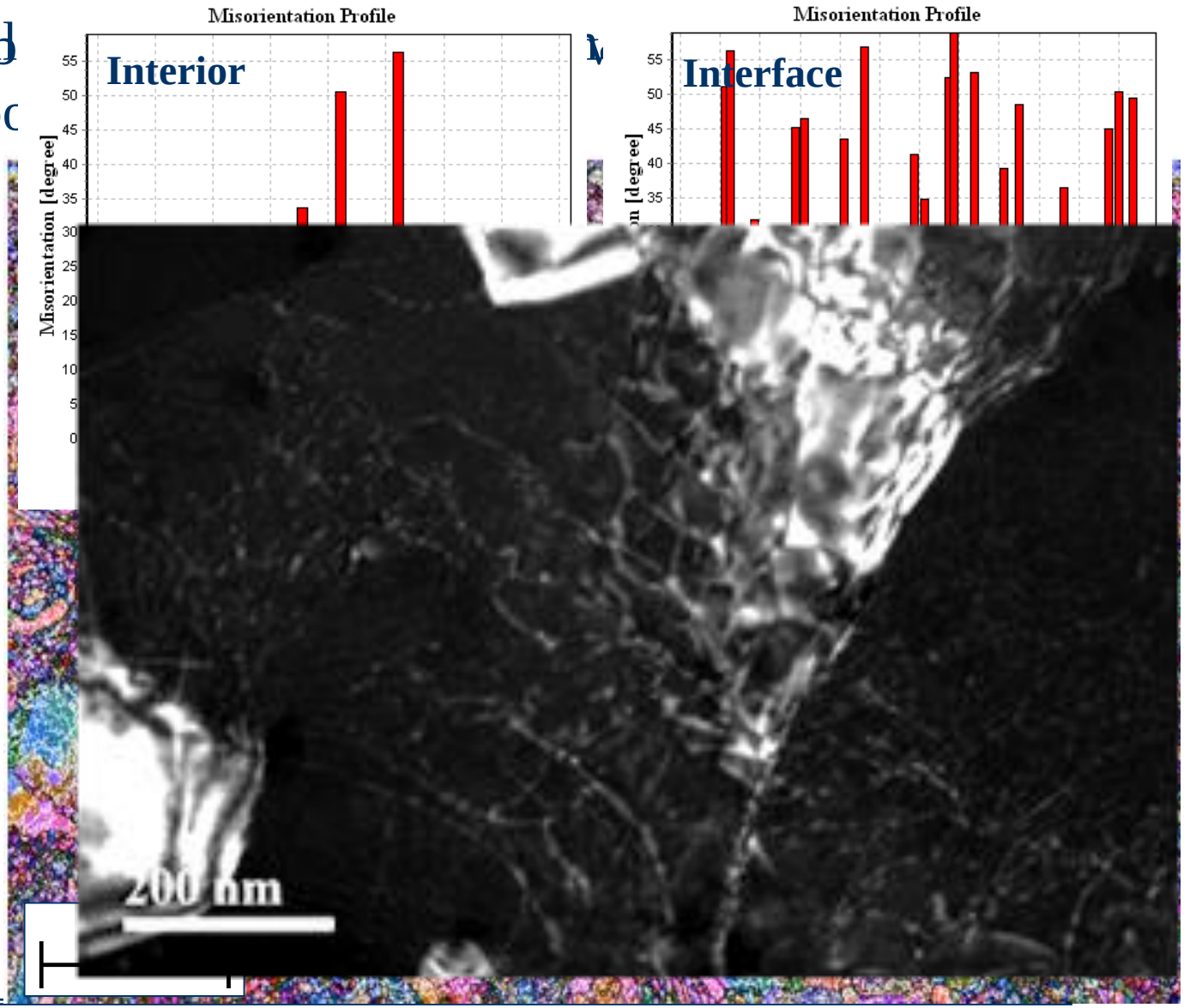
✓ Promotion of **strain induced boundary migration (SIBM)**

1- low strains and

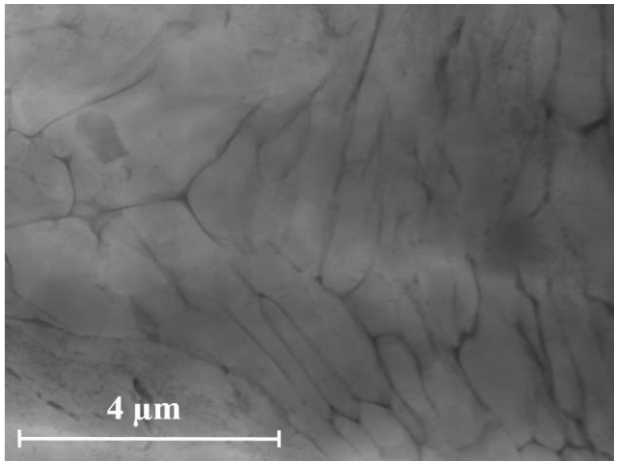
2- high temperature deformation

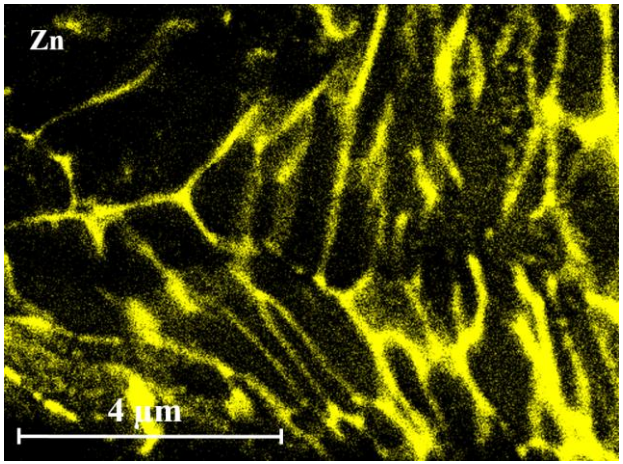
Microstructure of the CSP layer

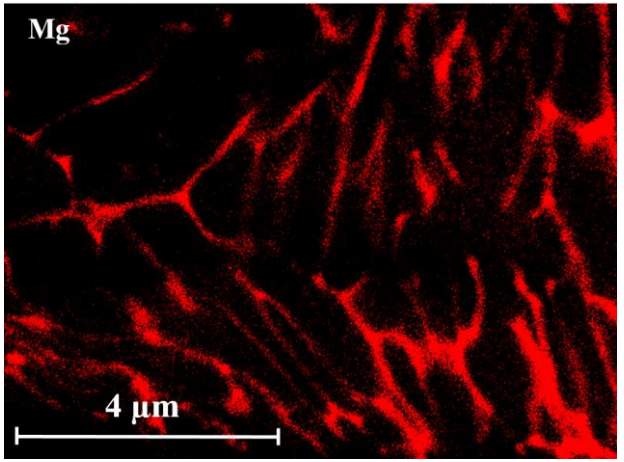
- ✓ Dislocation sub
particle/particle bo

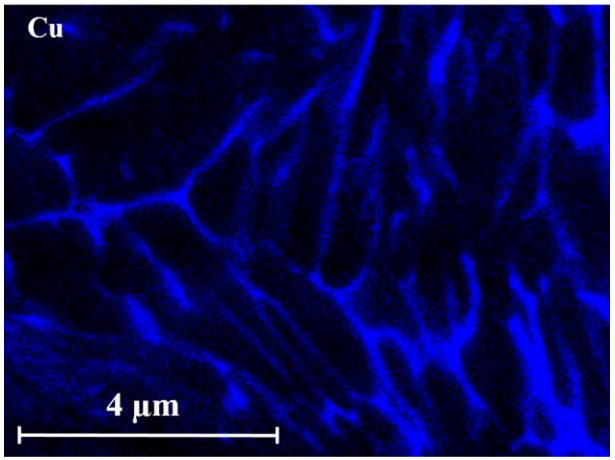


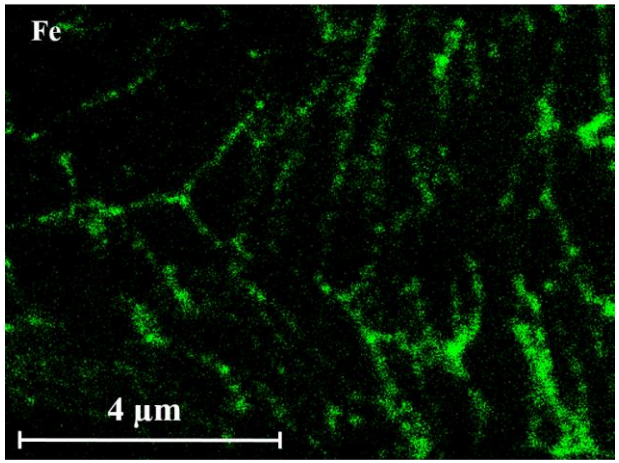
Microstructure of the CSP layer







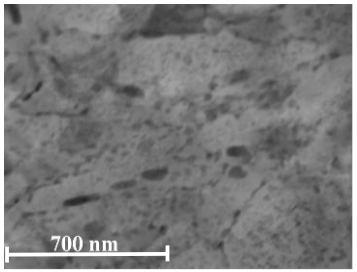


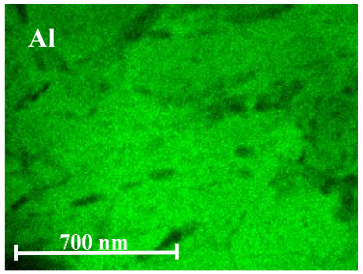


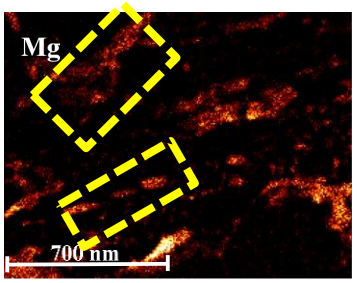
✓ Retention of solute segregation at the grain boundaries.

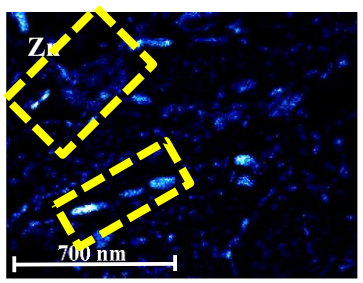
Precipitates in the Deposition

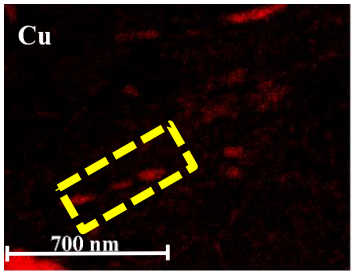
- ✓ A variety of different precipitates composed of various amounts of Al, Zn, Mg, Cu and Si
- ✓ η ($MgZn_2$) and $Mg(Zn,Cu,Al)_2$
- ✓ Fragmentation of the pre-existing precipitates

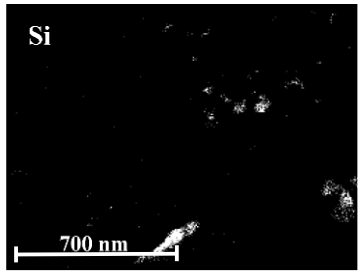


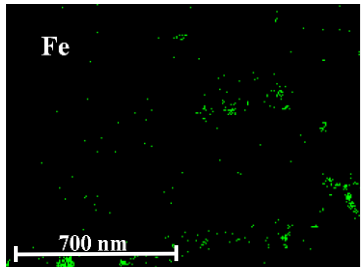






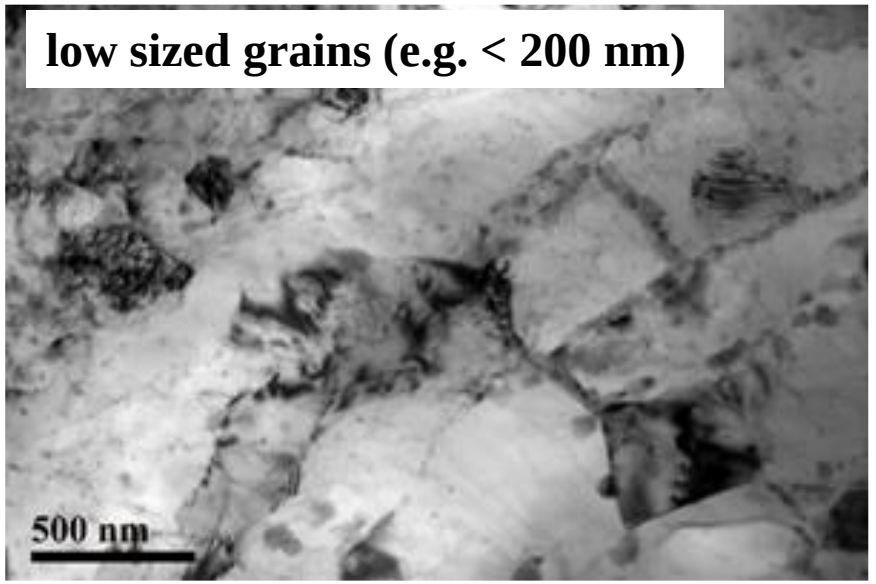


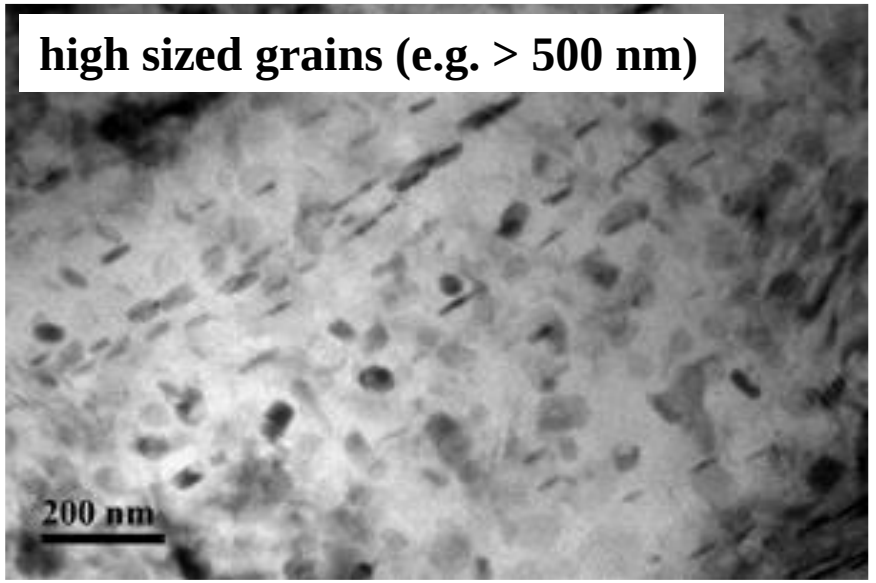




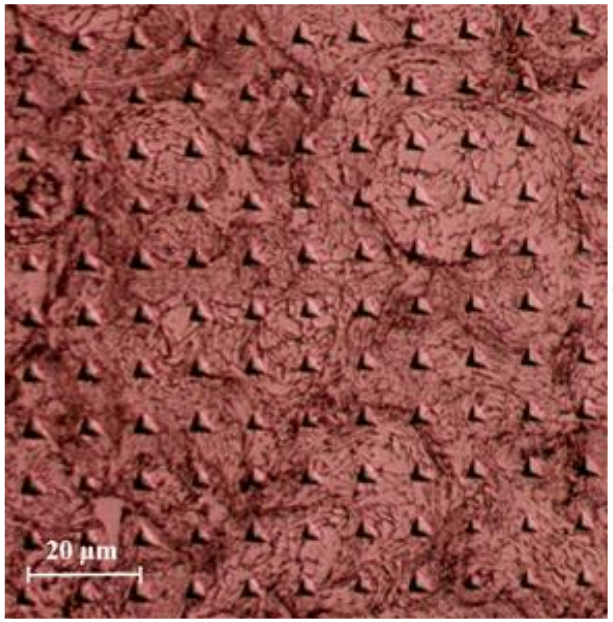
Precipitates in the Deposition

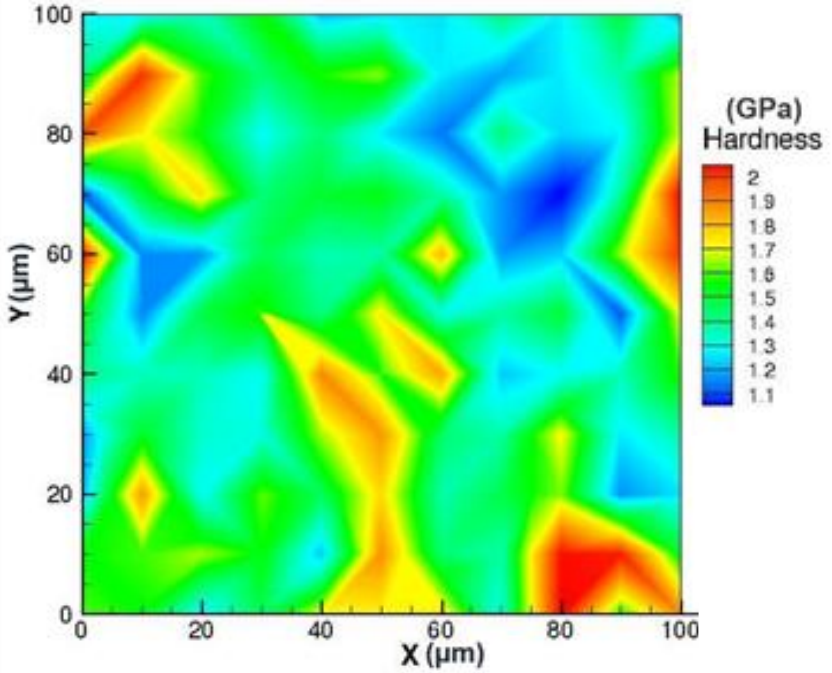
- ✓ Low sized grains: located primarily at grain boundaries
- ✓ High sized grains: distributed throughout the grain interior
- ✓ Due to volume for dislocations interaction and more nucleation sites





Mechanical Properties

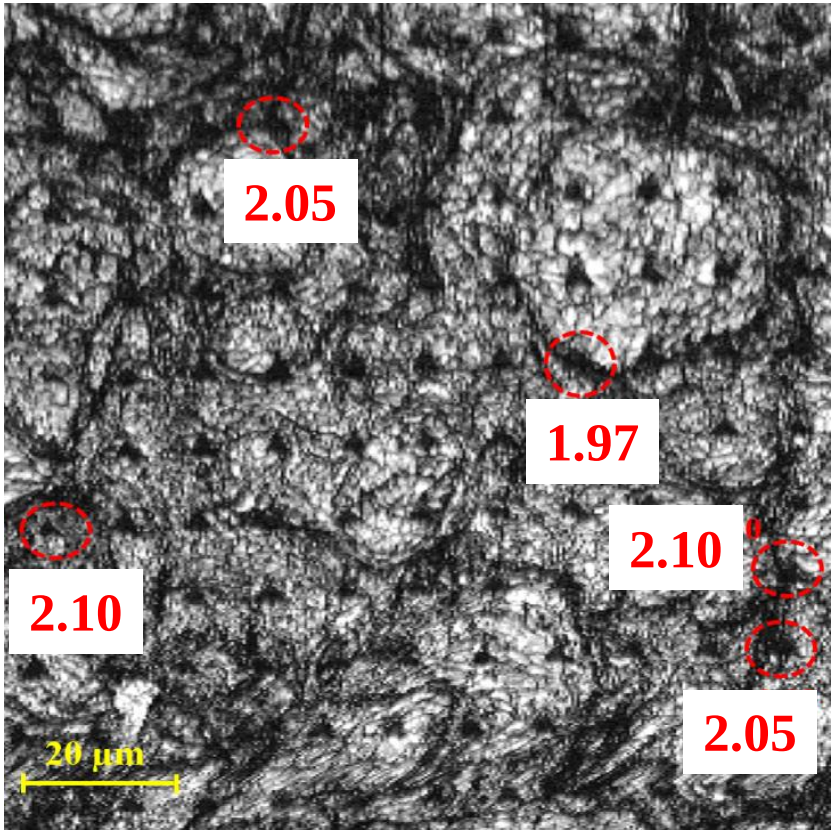


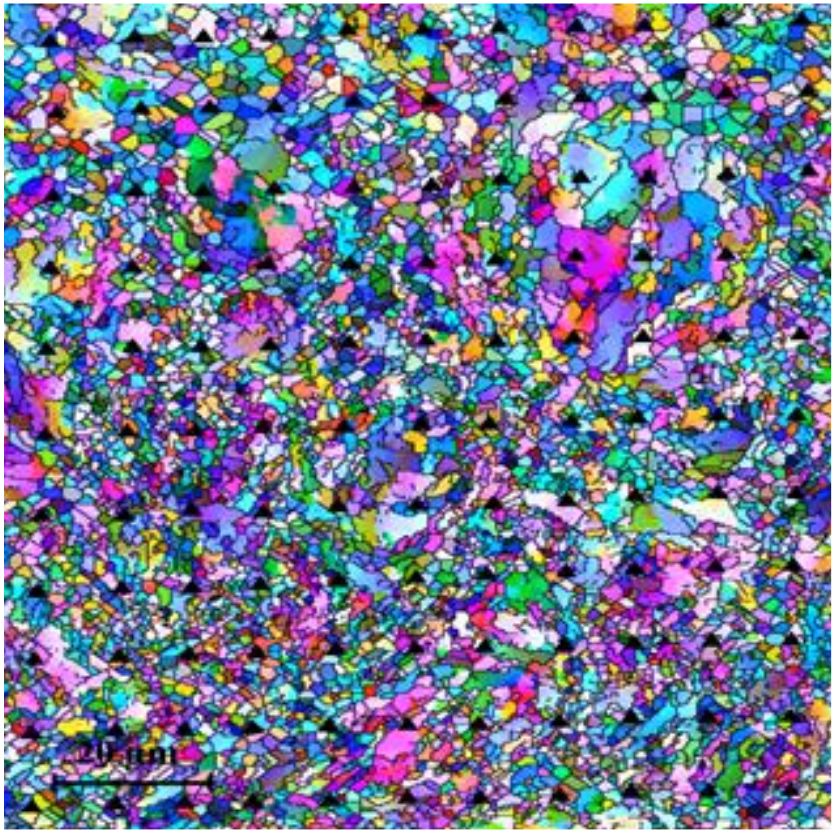


Material	CSP 7075	
Hardness (GPa)	particle interior	particle interfaces
	1.53±0.30	2.01±0.09

- ✓ Square array of nanoindentations (121 indents) in different regions
- ✓ Regions of high and low hardness

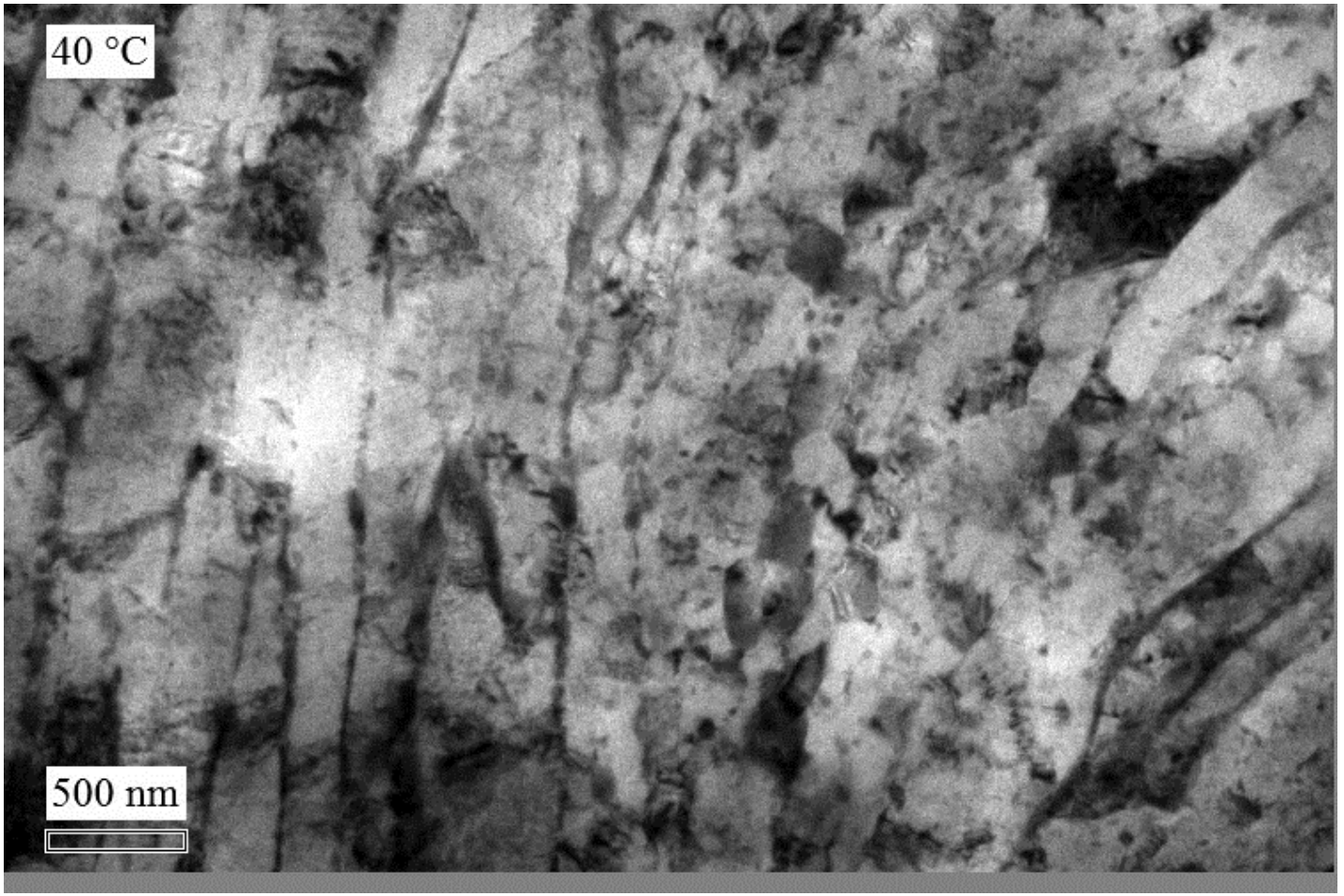
Mechanical Properties





- ✓ Submicron sized grain at the vicinity of the interfaces due to the occurrence of recrystallization

Non-isothermal HT



1) Dislocation movement

2) Annihilation of dislocations and substructures

3) Dislocation free microstructure/ RX

4) precipitation and Growth of precipitates

Conclusion/Summary

- High level characterization techniques were used to study microstructure evolution of as-atomized 7075 aluminum powder during HPCS deposition.
- The as-received particles compose of two different particle types, differentiated by their grain boundary structure and solute element distribution.
- HPCS resulted in the formation of a high quality deposition with limited porosity and inter-particle voids.
- The deposition was characterized by two distinct regions: particle/particle boundaries and particle interiors.

Conclusion/Summary

- Particle/particle boundaries contain an UFG structure and a low density of LAGBs. The formation of the UFG structure was attributed to a combination of CDRX, GDRX and SIBM.
- Particle interiors were characterized by larger grains containing a high density of LAGBs and dislocation structures.
- Temperatures for various microstructural phenomena were found upon in-situ hot stage TEM heat treatment.
- In future studies, these findings will be crucial for gaining a mechanistic understanding of the mechanical behavior of HPCS depositions.

Thank you for your attention!

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