



Correlation between Quenching rate, mechanical properties and microstructure in an Al-Mg-Si aluminum alloy

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DE LA RECHERCHE À L'INDUSTRIE



CORRELATION BETWEEN QUENCHING RATE, MECHANICAL PROPERTIES AND MICROSTRUCTURE IN AN AL-MG-SI ALUMINUM ALLOY

ICAA 16 – McGill University | CEA Saclay – DEN/DANS/DMN/SEMI/LM2E

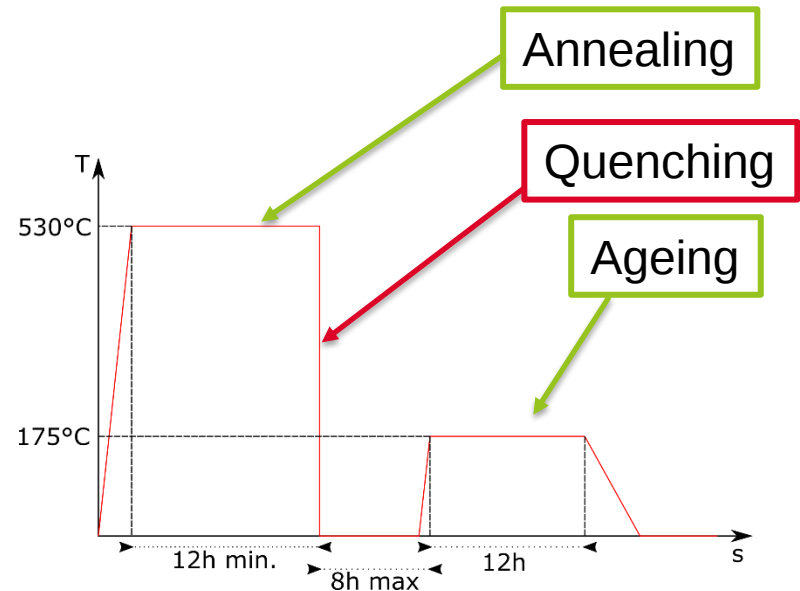
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A BRIEF REMINDER ON 6XXX ALUMINUM ALLOYS

- Good mechanical behavior
- Widely studied and used in many industries
- Specific thermal treatment : precipitation hardening
- Quenching is important while poorly documented on thick plates
- Effects on microstructures and macro properties ?
- Critical cooling rate : $V_{crit}=10^{\circ}\text{C}.\text{s}^{-1}$
- Local effects on properties ?



Quenching rate for thick plate ?
Influence above V_{crit} ?
Which impact on microstructures ?

MONITORING THE QUENCHING RATE

Monitoring and
Numerical
Simulation

Thermocouple

Ø25mm metallographic
sample

Part of the
as received
block

98mm side cube

Ø3mm TEM sample

MONITORING THE QUENCHING RATE

98mm sides
cubes of AA-6061

Annealing,
530°C, 12h at least

Water quench

Oil quench

Air quench

$\Delta t = 8\text{h max.}$

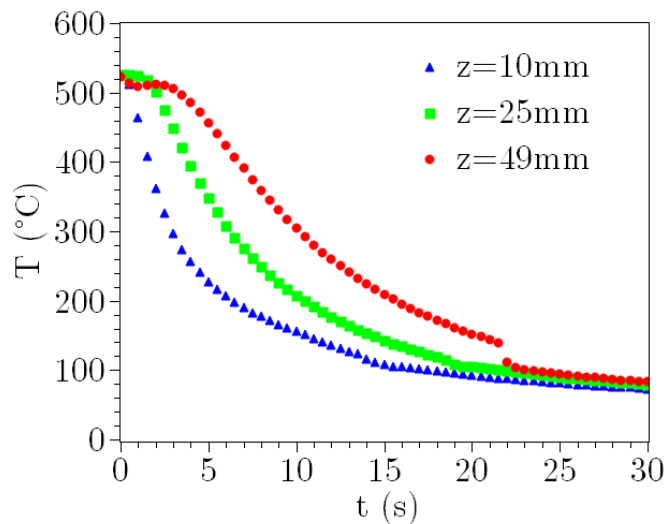
Artificial ageing, 175°C, 12h

Microstructure and mechanical behavior
→ TEM observations
→ Mechanical tests and hardness maps

3 cubes with various quenching
speeds

MONITORING THE QUENCHING RATE

Water Quench



→ Complex quench

→ Numerical simulation

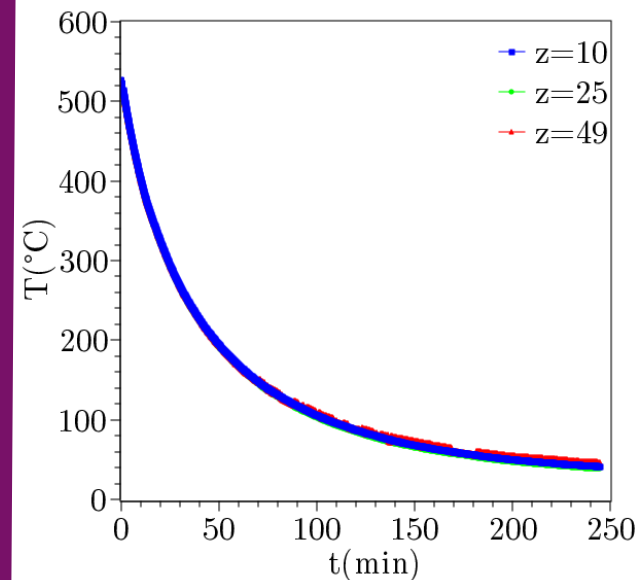
→ $40^{\circ}\text{C.s}^{-1} < V < 25^{\circ}\text{C.s}^{-1} < V_{\text{crit}}$

Oil Quench



No data
Thermocouples
cannot be fitted
the sealed oven

Air Quench

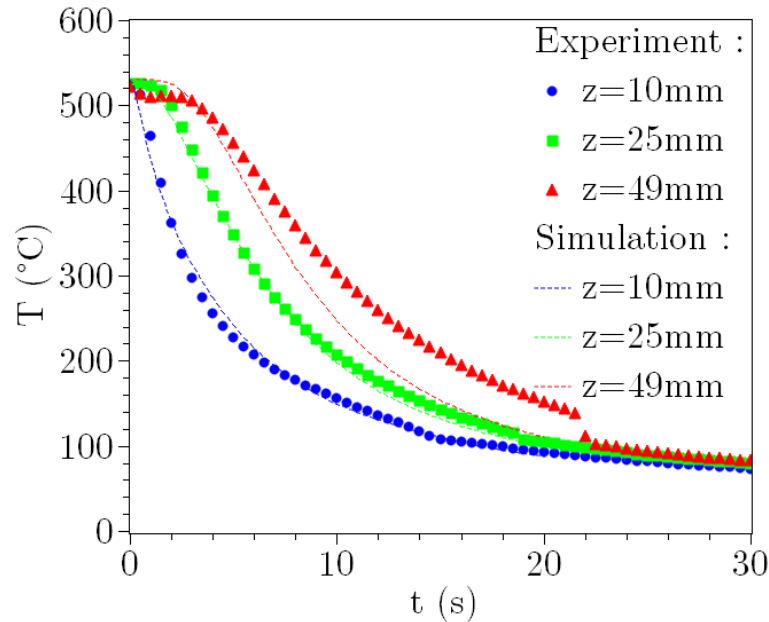


→ Same temperature curves for all positions

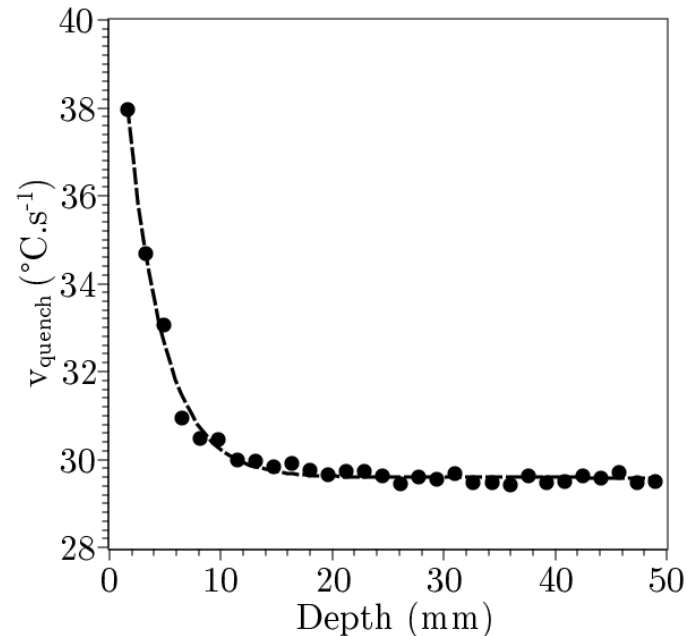
→ Homogeneous quench Rate across the plate

→ $8,6.10^{-2}^{\circ}\text{C.s}^{-1} < V_{\text{crit}}$

QUENCH SIMULATION : WATER QUENCH



$T=f(t)$: Experimental vs Simulation



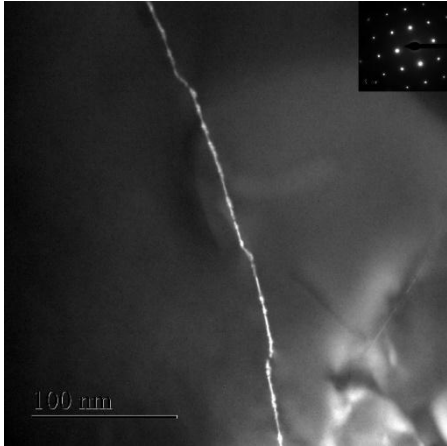
Quench rate along depth

- Simulation needed to assess the local quench rate
- CAST3M, finite elements code → Conduction-convection model
- Position sensibility

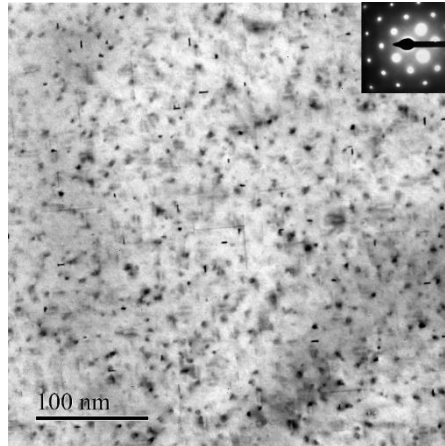
Water	Oil	Air
30 to 40 °C.s ⁻¹	?	<0,1 °C.s ⁻¹

Global overview

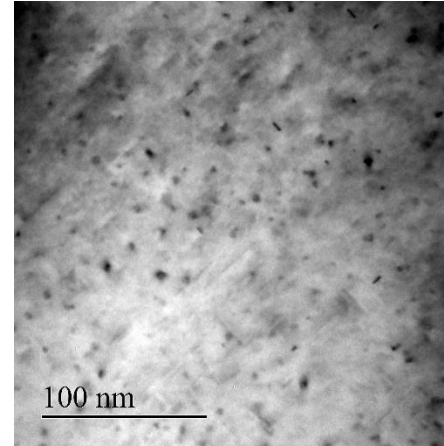
Air



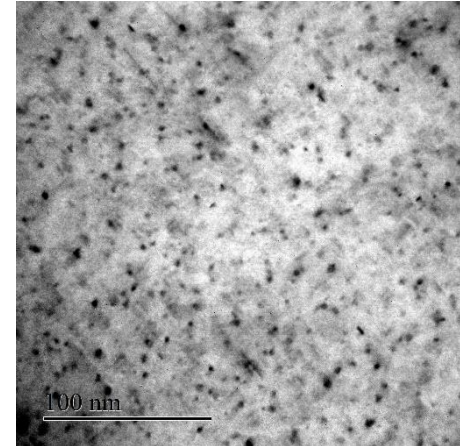
Oil



Water : mid thickness



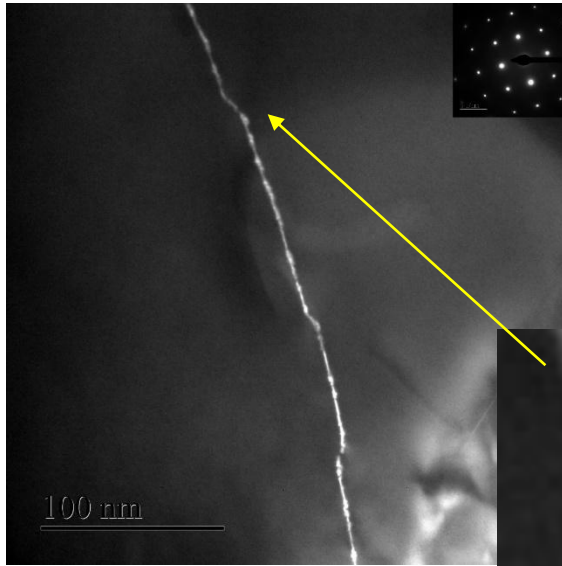
Water : near surface



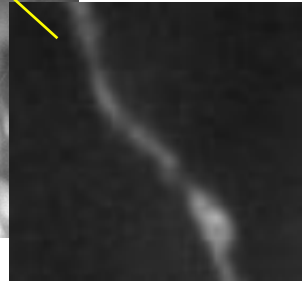
Quench rate

Density of hardening phases

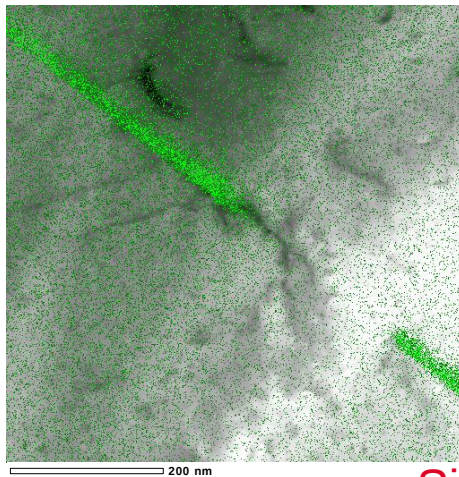
The case of Air Temper



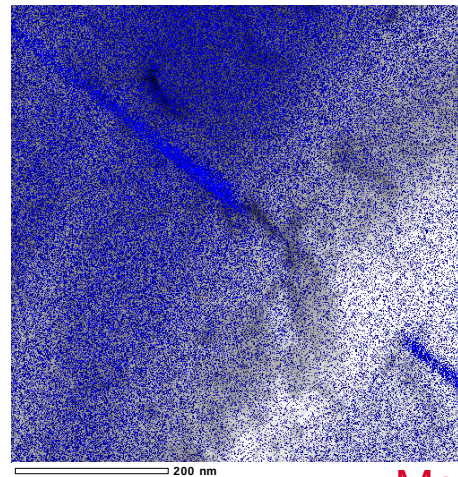
- Dark field images on $\langle 100 \rangle$ spot position
- No trace of nanoscale precipitation in grain
- Succession of nanoprecipitates



- EDX maps → Local Mg and Si enrichment
- Consistent with Al-Mg-Si heterogeneous
- Precipitation on dislocations



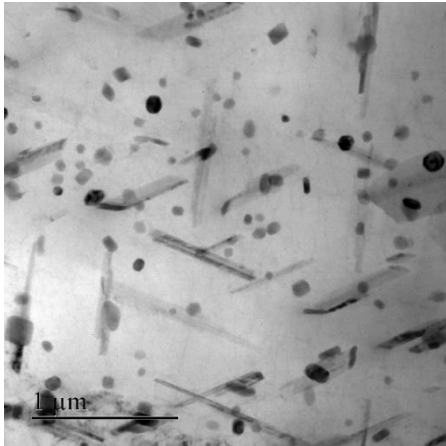
Si



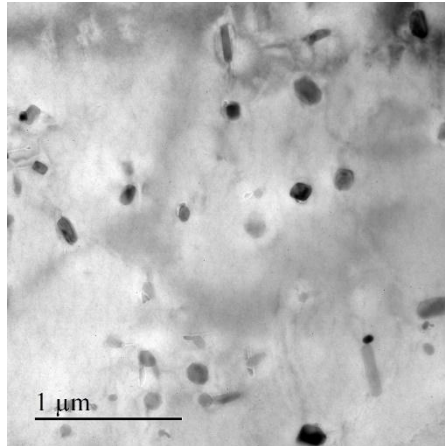
Mg

Global overview

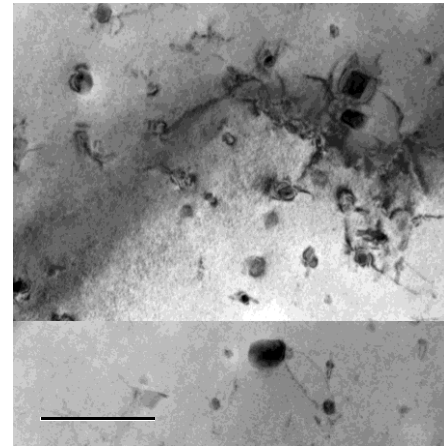
Air



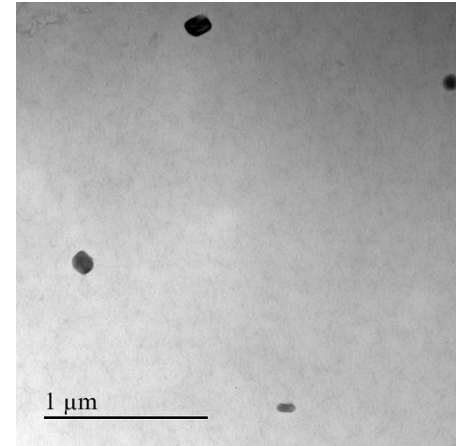
Oil



Water : mid thickness



Water : near surface

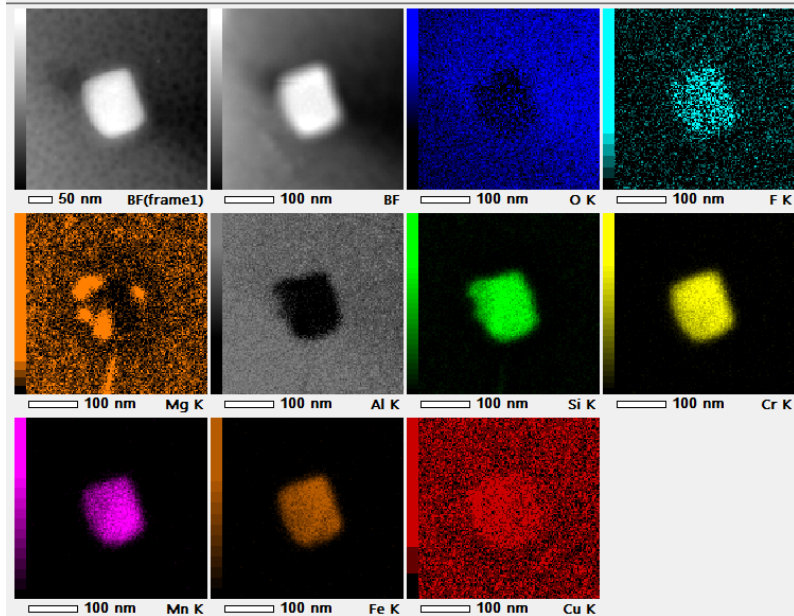


Quench rate

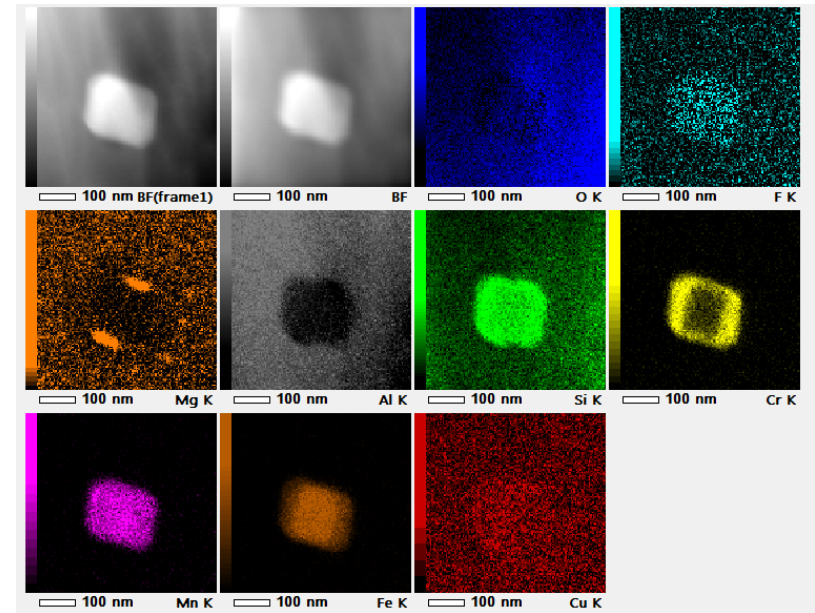
Density of submicronic particles

Water temper

EDX quantitative maps



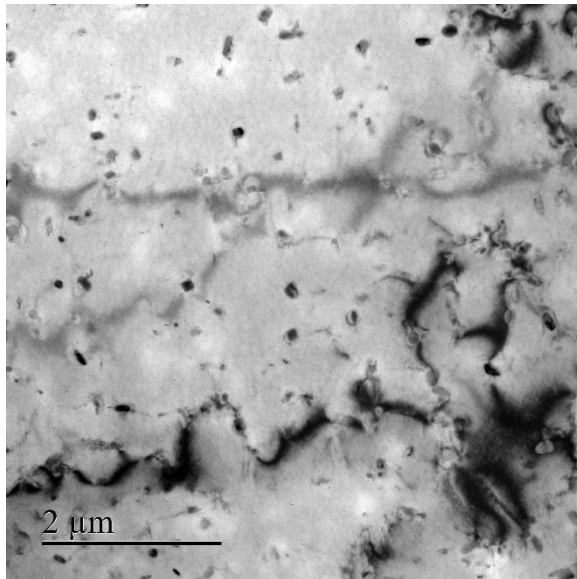
No Fe/ Cr segregation



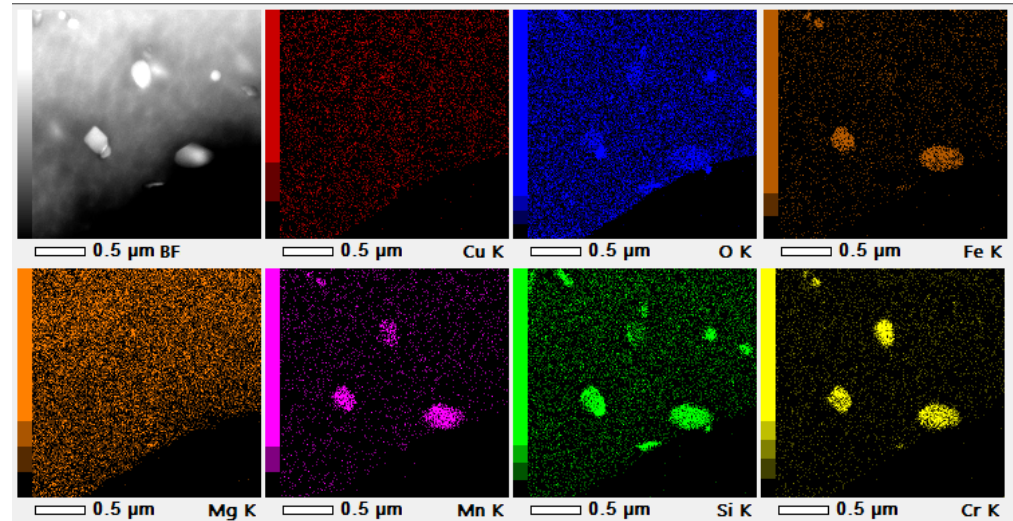
with Fe/ Cr segregation

- $\alpha\text{AlMnFeCrSi}$ phase particles as usual in 6061-T6, chemical Fe/Cr segregation occasionally observed
- Low density of particles at the surface (i.e. high quenching rate)
- High density of particles at mid thickness (i.e. lower quenching rate)
- Quench rate → Gradient of microstructure

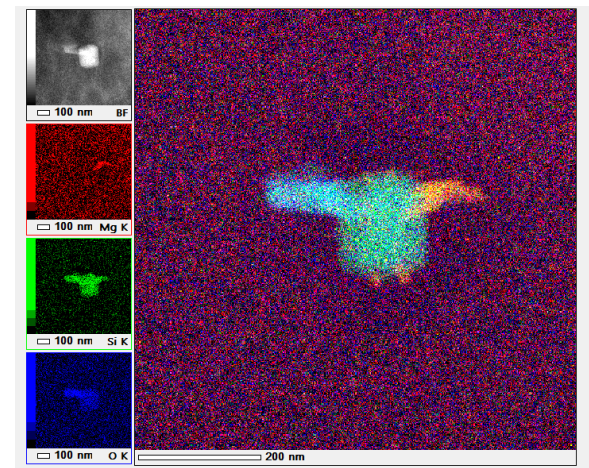
Oil temper



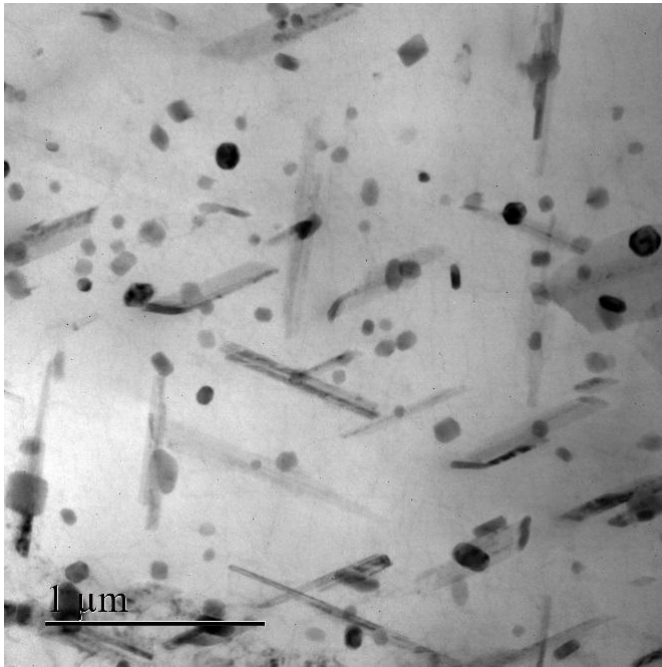
EDX quantitative maps



- α AlMnFeCrSi phase particles as usual in 6061-T6
- Homogeneously dispersed in the material
- Particles chemically heterogeneous : MgSi oxides growing on α particles
- Silicon present in all particles

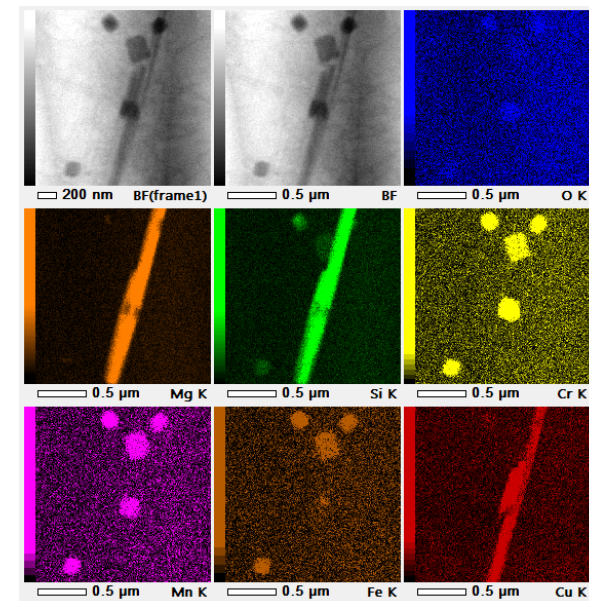
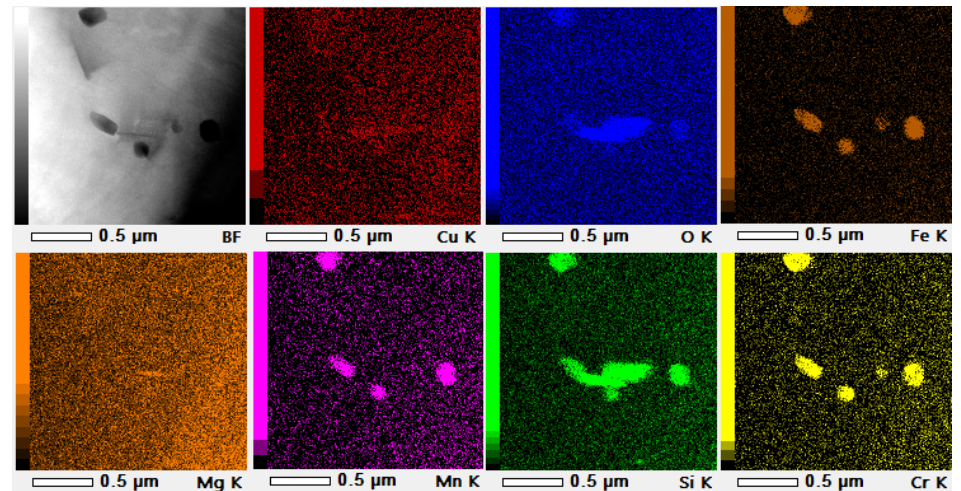


Air temper

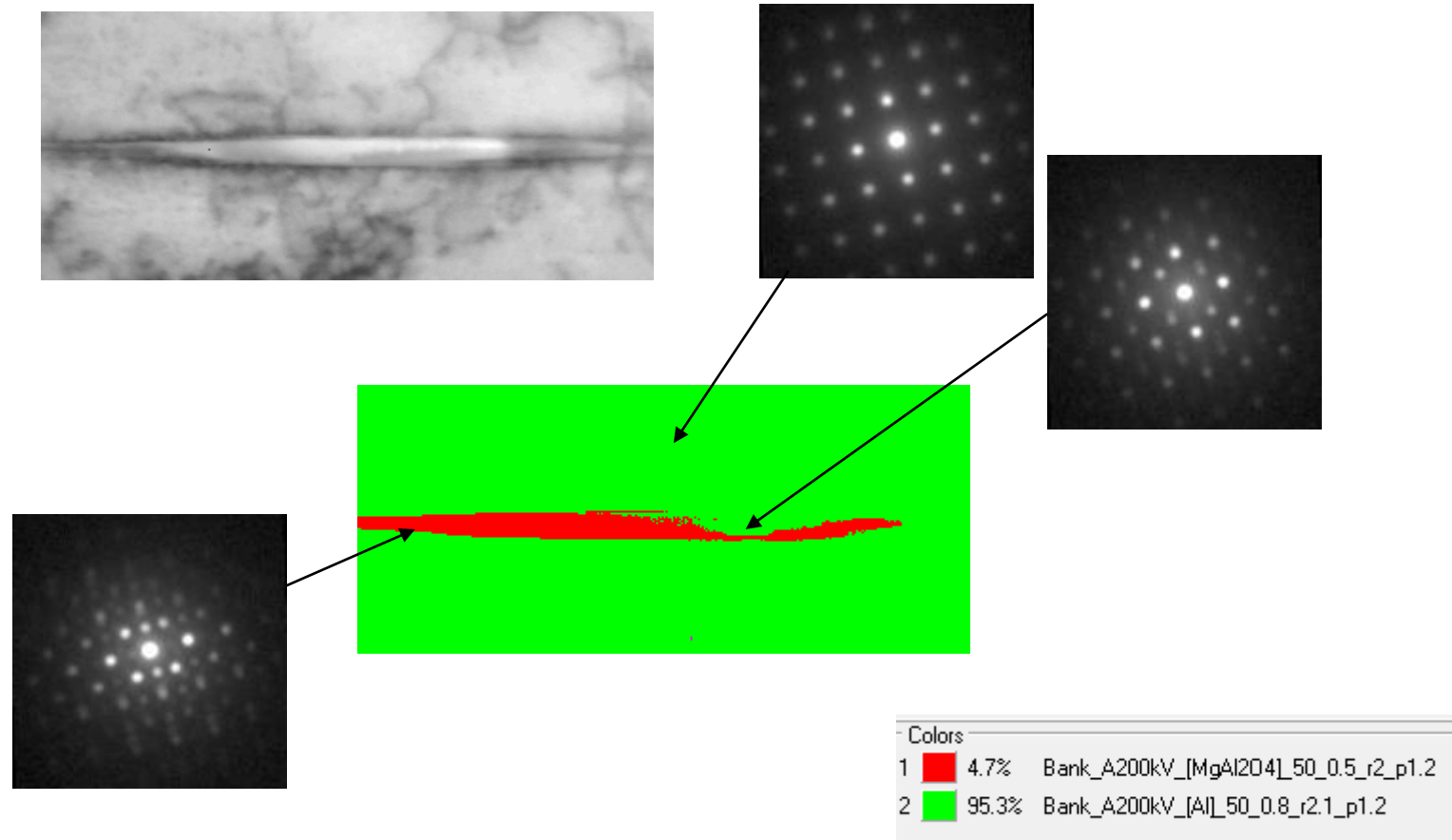


- Numerous long and thick plate shape particles
- Heterogeneous precipitation : growth of Mg-Al oxide and Mg-Si-Cu plate on α phase particles
- Silicon present in all particles

EDX quantitative maps



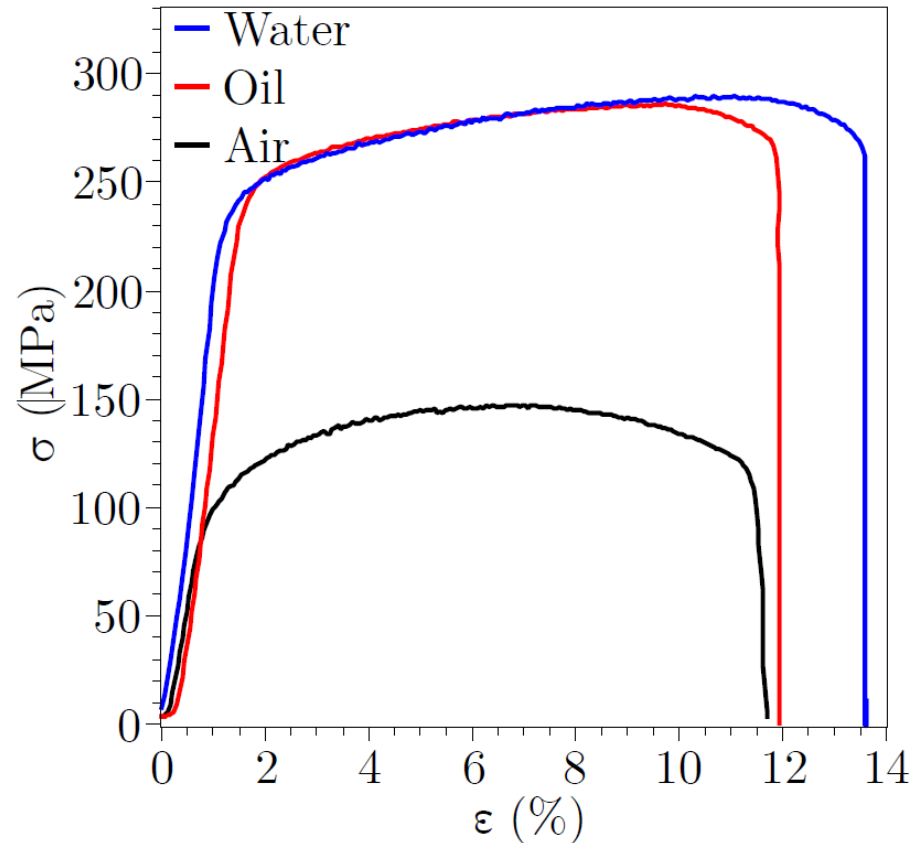
OXIDES ON AIR TEMPER : ASTAR



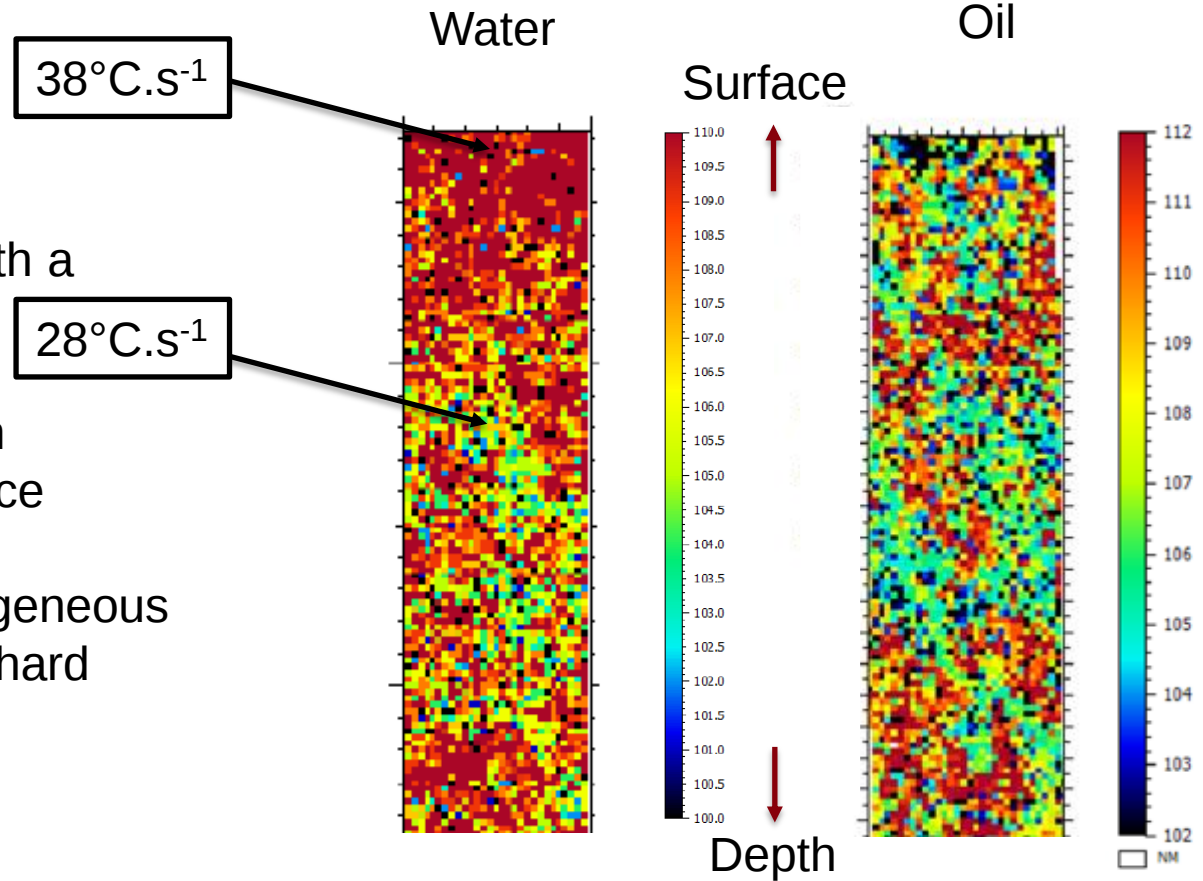
→ Complex indexation

→ Heterogeneous precipitation

- Water and Oil temper : close mechanical response. Usual hardening 6XXX T6 alloy behavior ($V \geq V_{crit}$)
- Air temper : low mechanical behavior
- Influence of the microstructure differences ?
- More local properties ?

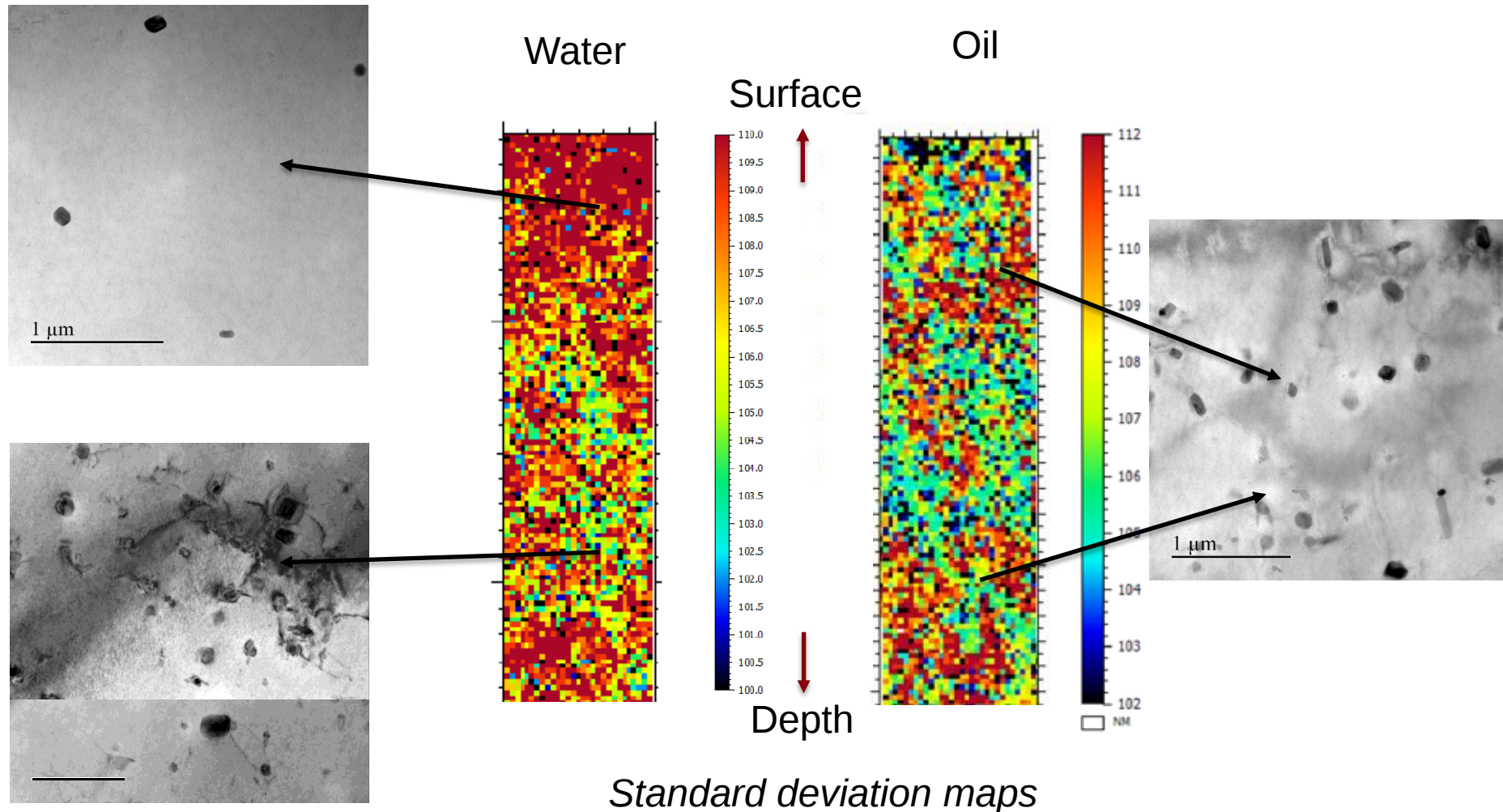


- For local information : High resolution HV 0,05 Maps with a 200 μ m step
- Water quenching : very high hardening points near surface
- Oil quenching : more homogeneous behavior but is slightly less hard
- Effect of quench rate



Standard deviation maps

ON THE MECHANICAL BEHAVIOR : μ -HARDNESS MAPS



CONCLUSIONS

Microstructure

- Submicronic scale
 - Water temper : dispersion of α -phase particles
 - Oil temper : more submicronic particles and segregation
 - Air temper : emphasized on oxide particles
- Nanometric scale
 - Usual T6 hardening precipitation in oil and water temper

Mechanical behavior

- Macro scale
 - Usual T6 hardening behavior for water and oil temper
 - Air temper : low mechanical properties
- Local scale
 - Oil temper : homogeneous response
 - Water temper : “hard zones” corresponding to the skin effect

Nanometric precipitation → influence on macro scale properties
Submicronic precipitation → influence on micro scale properties
Going above $10^{\circ}\text{C.s}^{-1}$ improves the local mechanical behavior

QUESTIONS ?

Acknowledgements

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Direction of Nuclear Energy
Department for Researches on Irradiated Materials
Section for Researches on Irradiated Materials

QUENCH SIMULATION

→ Homogeneous quench for the air

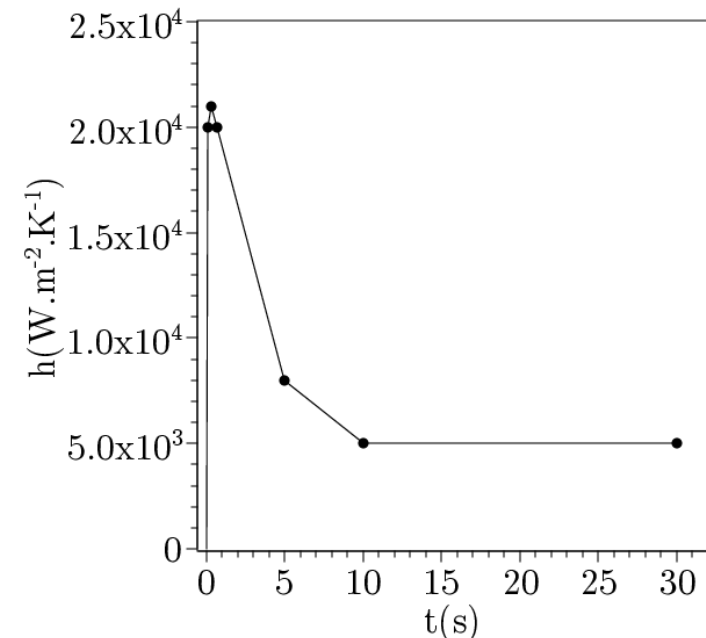
→ Complex quench for water → Necessity of simulating to understand the local quench rate

CAST3M Code → Conduction-convection model

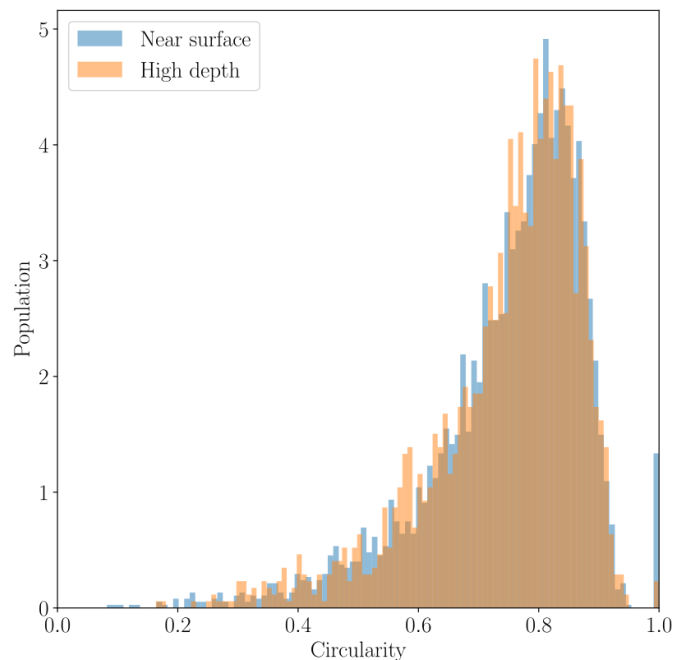
Conduction → material dependant

Convection → time, material and shape dependant

$$h(t) = \frac{\rho V C_p}{A(T_s - T_\infty)} \frac{\partial T}{\partial t}(t) \Leftrightarrow h(t) = k_0 \frac{\partial T}{\partial t}(t) \rightarrow$$



DENSITY ANALYSIS



	E05	(standard deviation)	E34	(standard deviation)	HX
Medium surface (mm ²)	22.61	2.29	22.25	1.14	14.47
Surface ration (%)	11.64	1.93	9.21	0.58	7.33
precipitates/picture	365.1	37	295	12	361