Application of laser ultrasonics to monitor microstructure evolution in Inconel 718 superalloy

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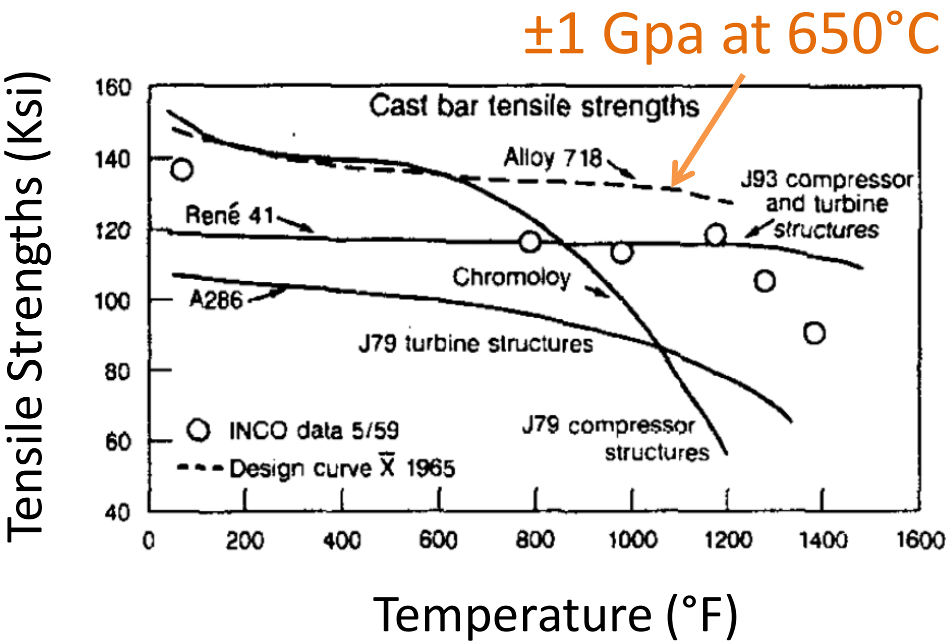
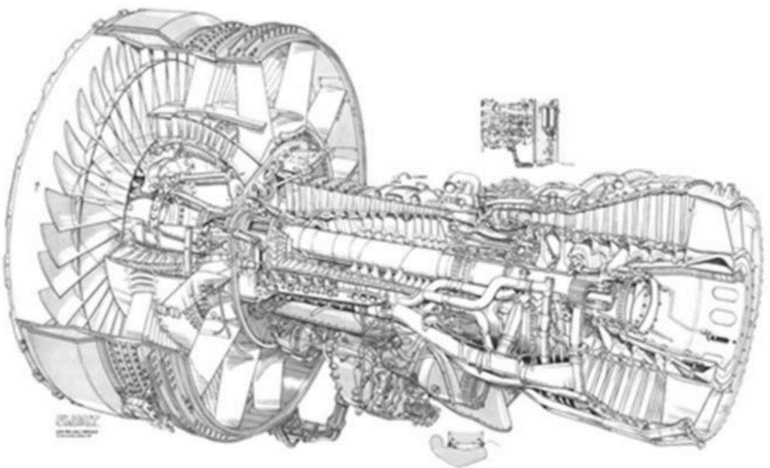
Motivation

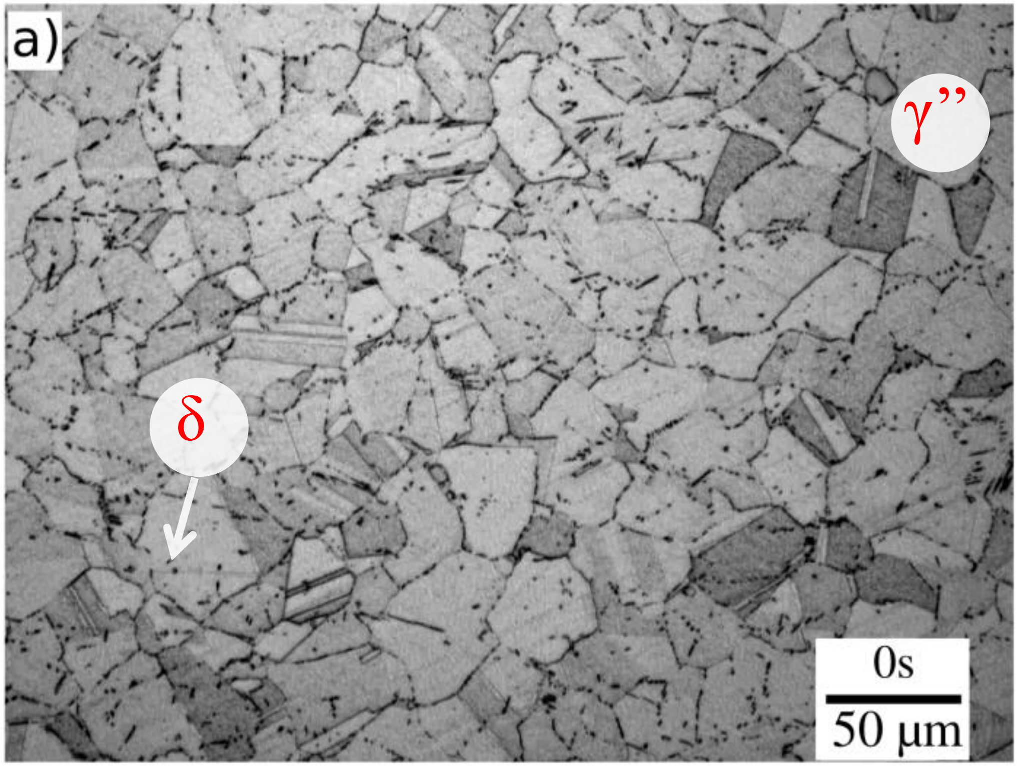
- ✓ Inconel 718 used in aviation industry
- ✓ High strength material obtained by forging process
- ✓ **Control the microstructure evolution during forging**





Initial structure prior to forging

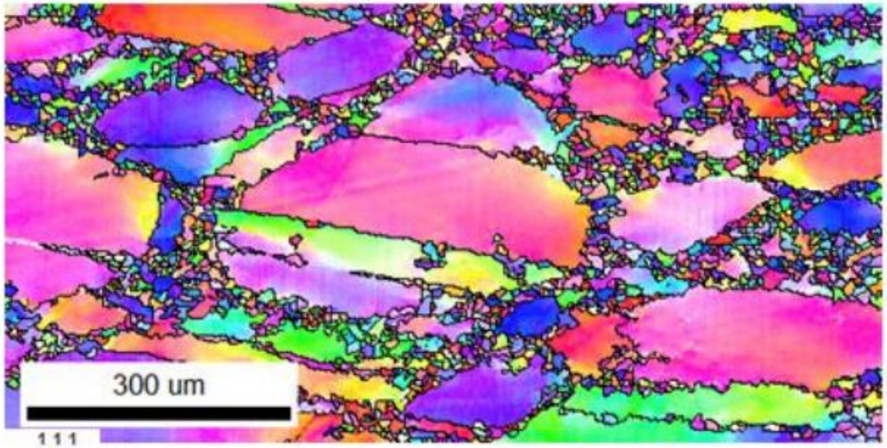
- ✓ The grain structure is optimized prior to the forging process.
- ✓ Initial microstructure composed of 20 µm polygonal grain
- ✓ + 2 to 3 % of delta phase precipitates located at the grain boundary

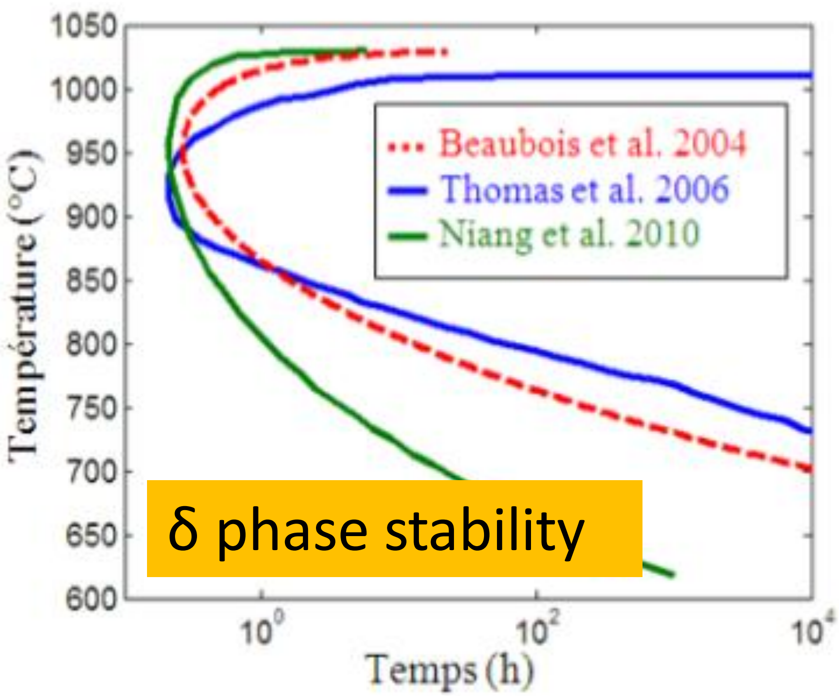


✓ Composition (Key elements wt.fraction)
0.52Ni, 0.19Cr, 0.19Fe, Mo, Nb, Ta, Ti, Al, Co

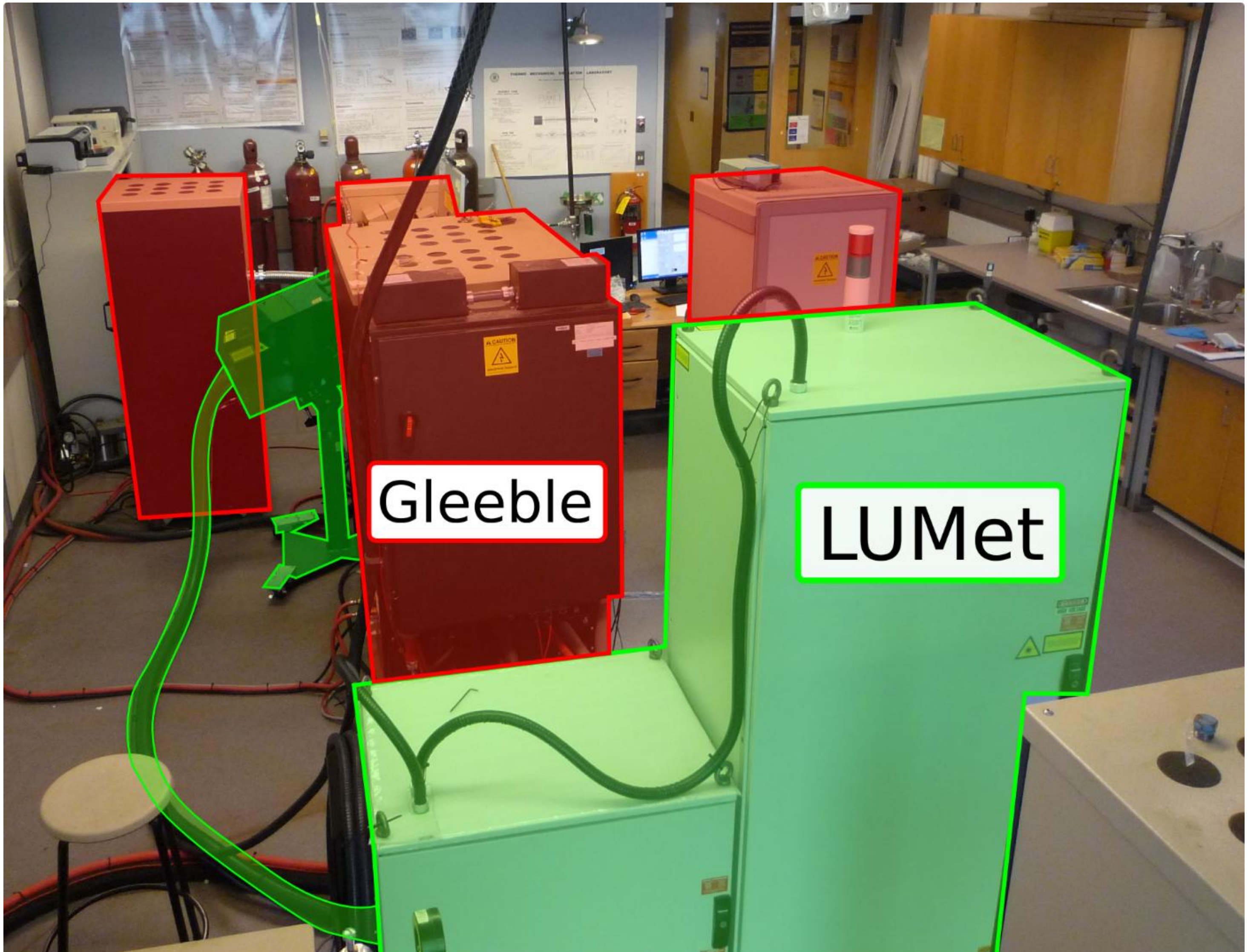
Optimizing forging process

- ✓ Forging at high temperature
- ✓ High strain and high temperature lead to dynamic recrystallization
- ✓ Delta precipitates must fully dissolve prior to forging + homogeneous grain size material
- ✓ **Goal: Identify optimum soaking time prior to forging.**
- ✓ **IN-SITU Grain size measurement**





Gleeble machine with LUMet



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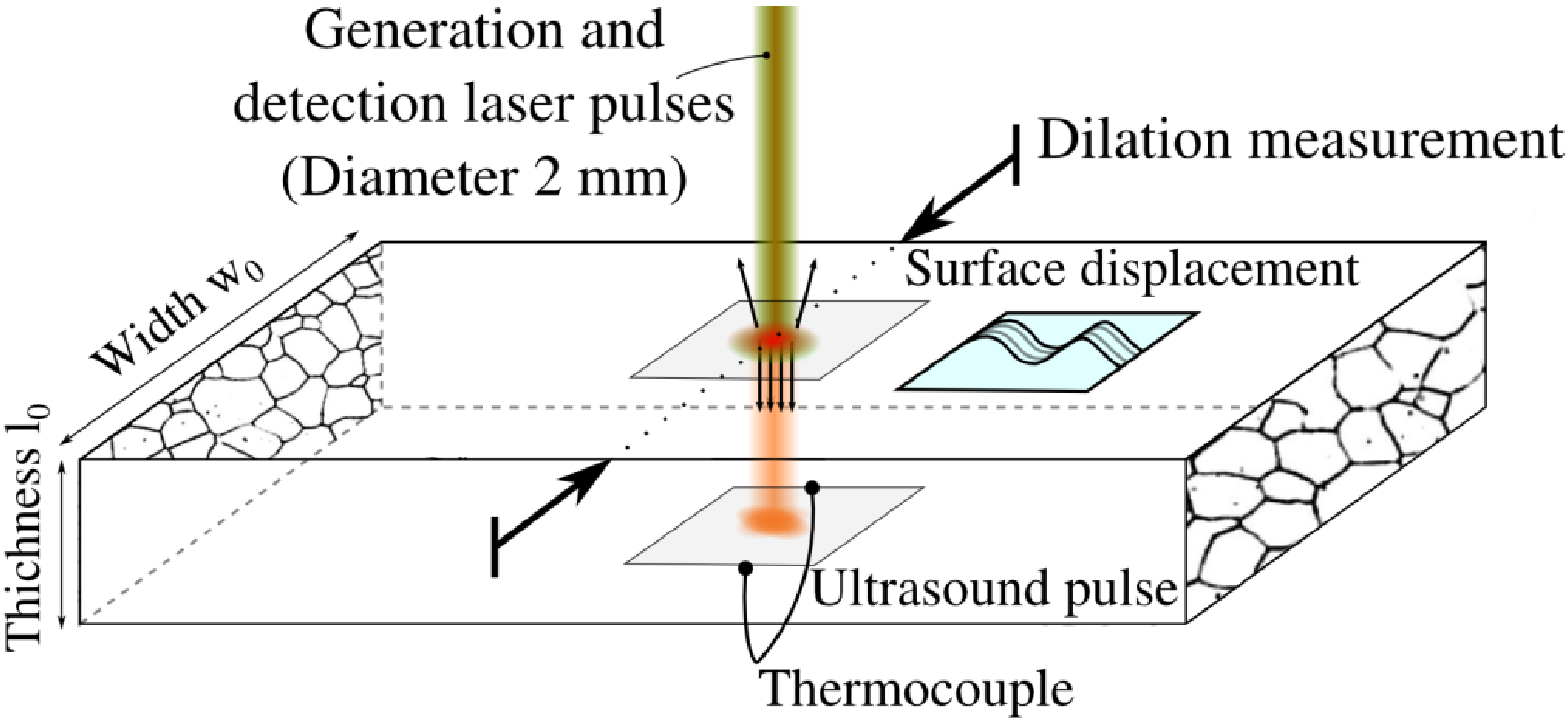
Laser ultrasonics in Gleeble



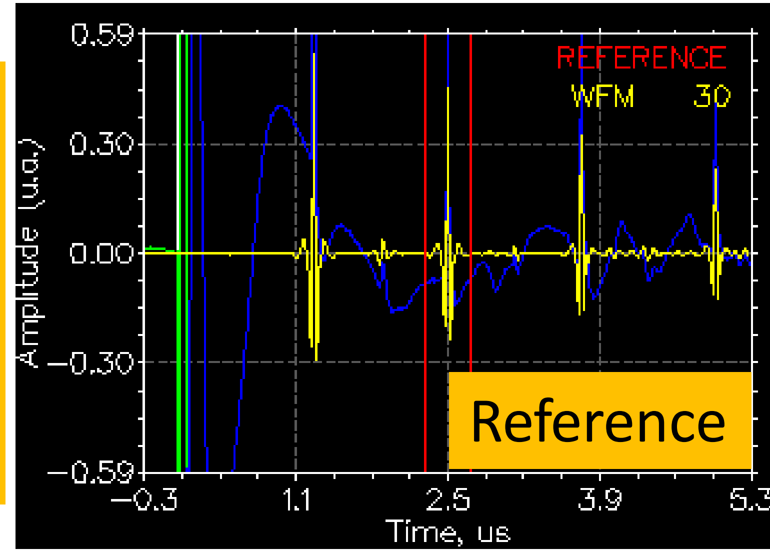
Evaluation of ultrasonic attenuation

- ✓ Measure of an ultrasonics waveform in a reference state (Grain size is known)
  REFERENCE WAVEFORM

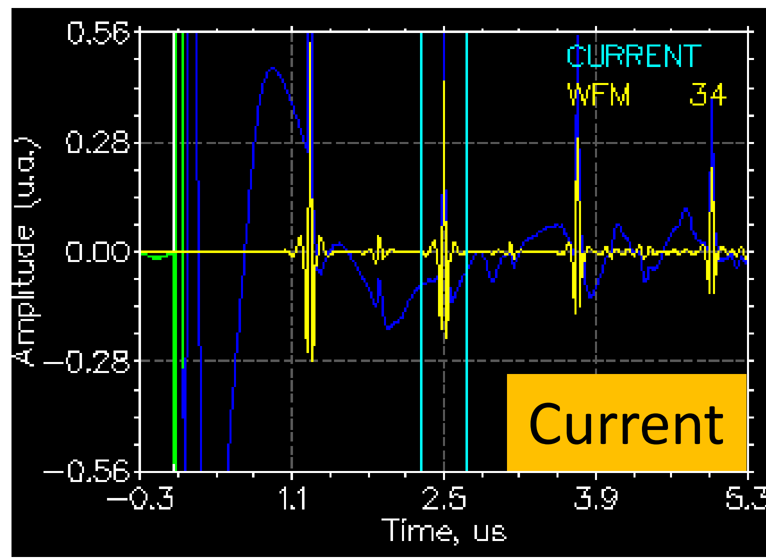
- ✓ Measure of an ultrasonics waveform during a temperature treatement
  CURRENT WAVEFORM

- ✓ Cleaning the signal by filtering and select an echo

Initial grain size



Current grain size



Evaluation of ultrasonic attenuation

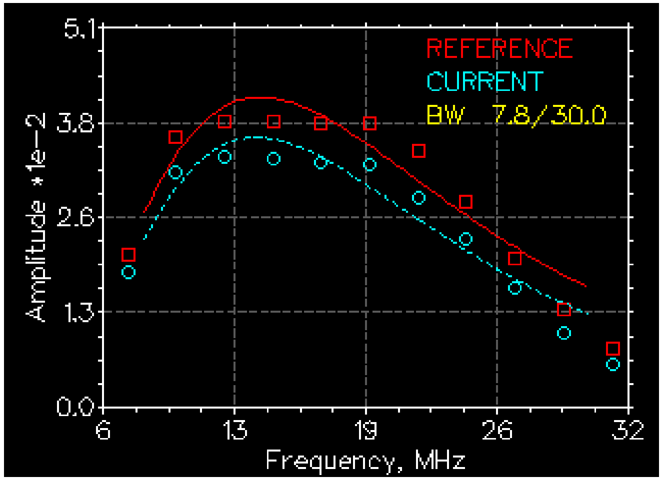
- ✓ Evaluate the amplitude of the FFT for each echo

- ✓ Ratio of the amplitude spectrum gives the **ultrasonic attenuation**

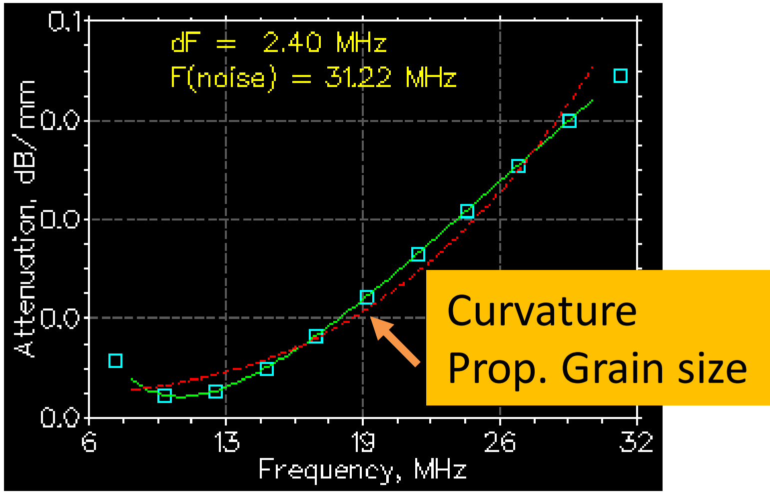
$$\alpha(f) = -\frac{20}{2d} log10\left(\frac{g(f)A_t(f)}{g(f)A_0(f)}\right)$$

- ✓ Curvature of the spectrum is related to the **average grain size**

Amplitude spectrum

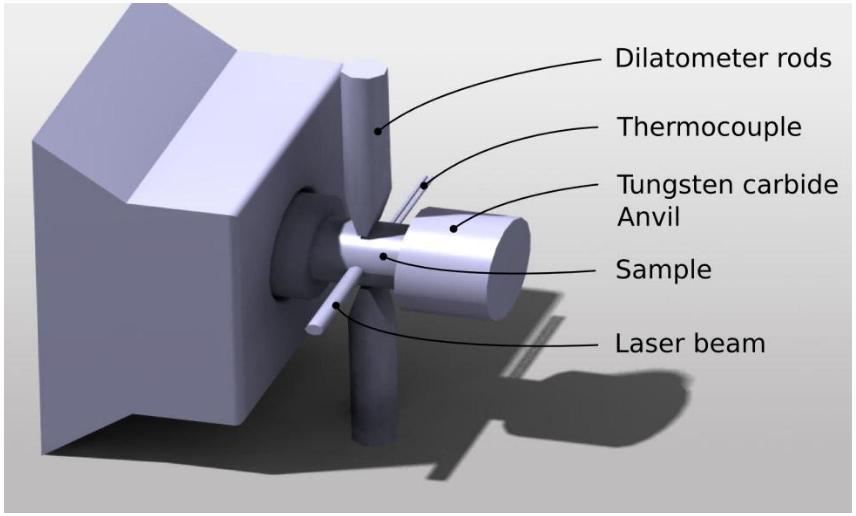


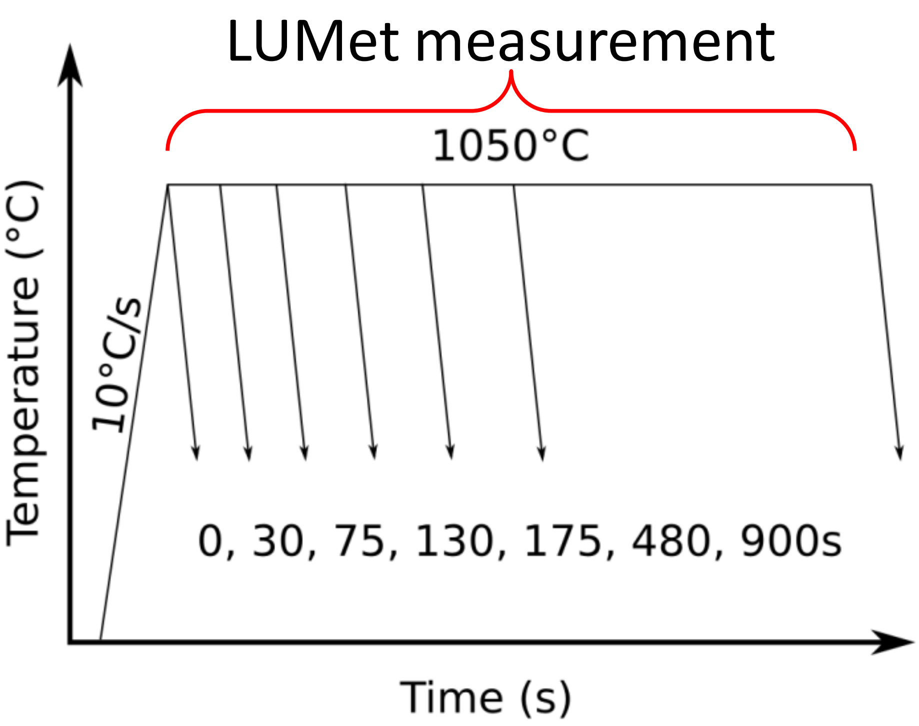
Attenuation spectrum



Experiments

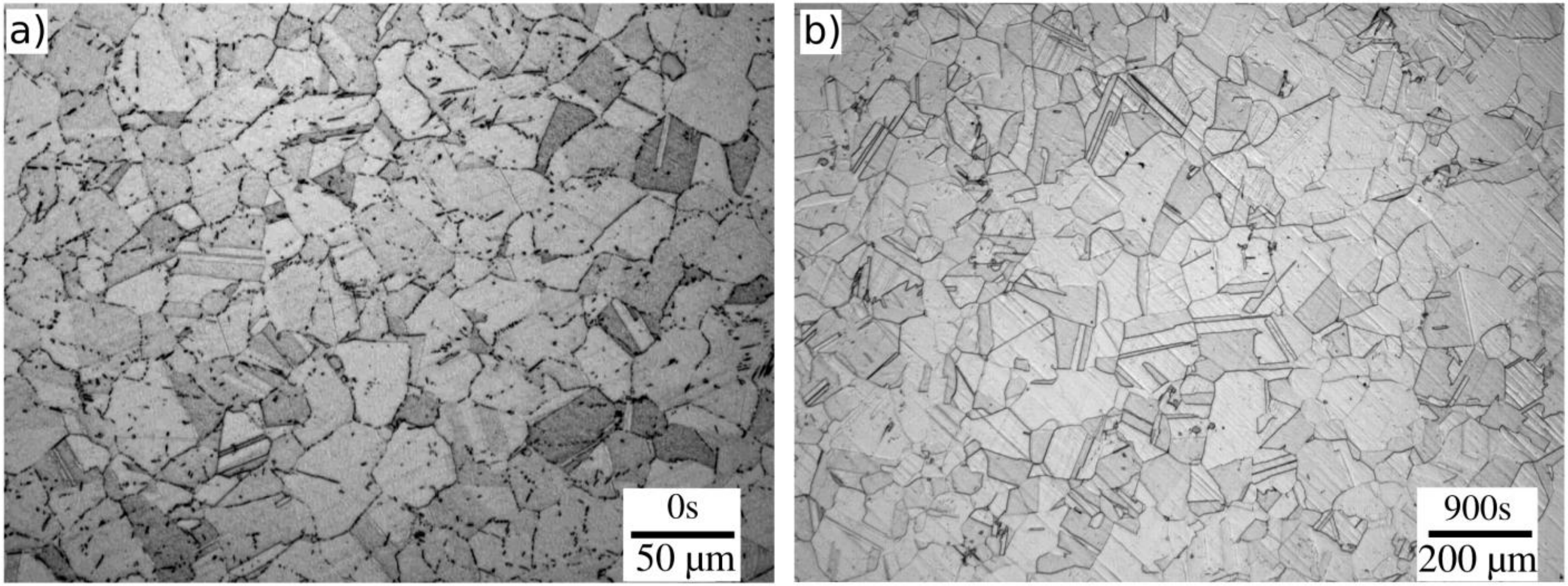
- ✓ Isothermal holding at 1050°C for various time
- ✓ Laser ultrasound measurement of average grain size
- ✓ Validation with metallography and modeling





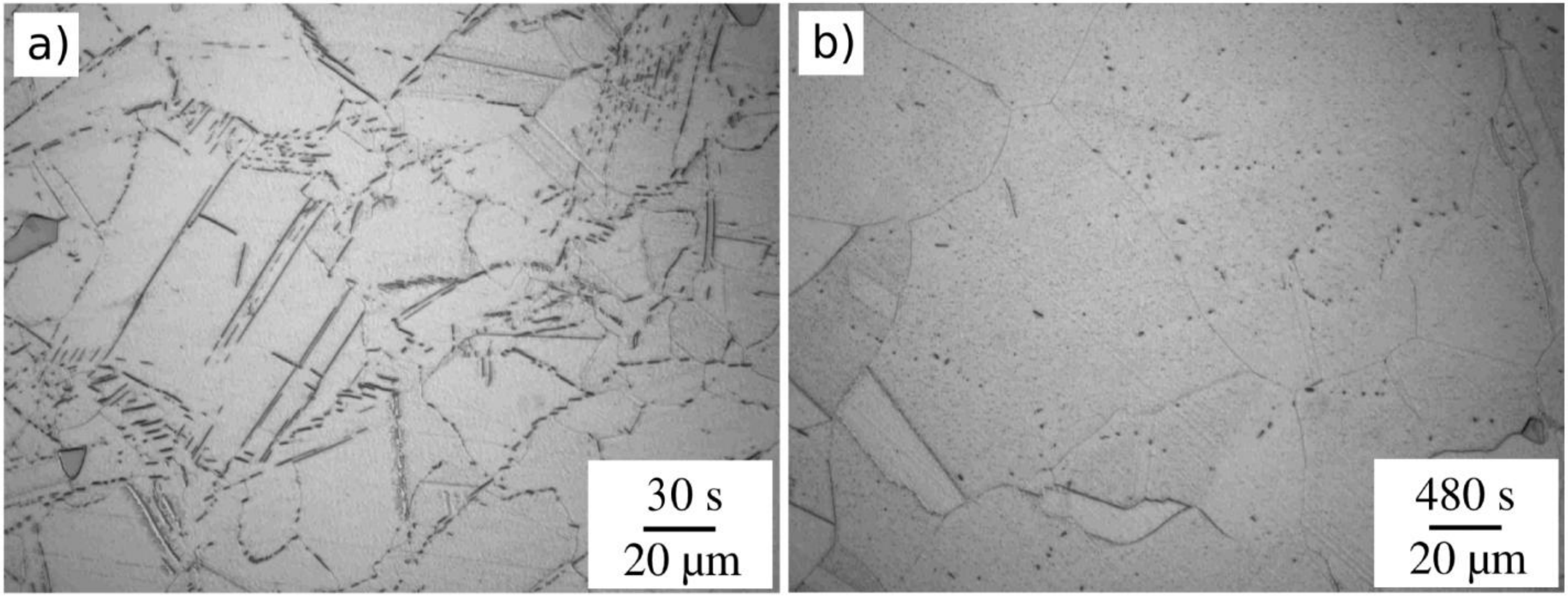
Initial and final stage

- ✓ Average grain size increases by a factor of 4 during the 15 mn annealing
- ✓ 900 s: Delta phase is almost fully dissolved
- ✓ 900 s: Formation of annealing twins



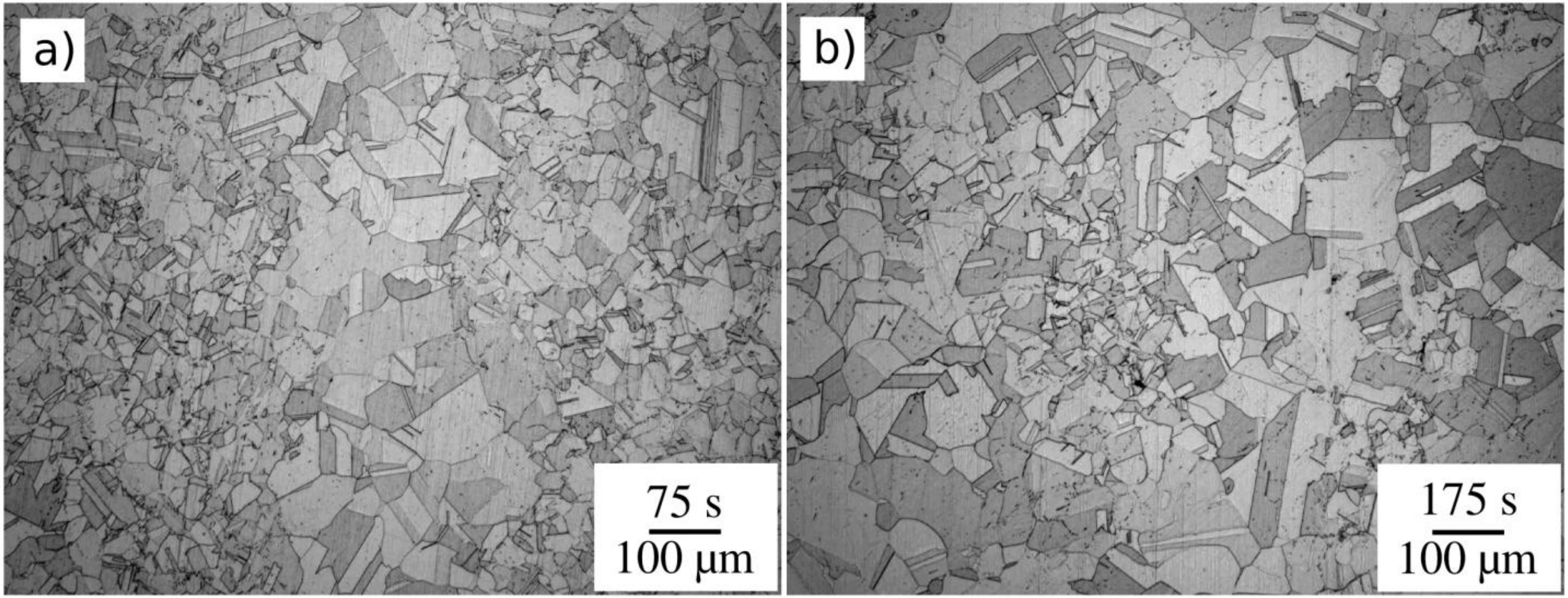
Evolution of Delta phase

- ✓ 30s : Coarsening and dissolution of delta phase
- ✓ 480s: Small fraction of delta phase remains, most GB are unpinned



Heterogeneous grain structure

- ✓ 75s : Faster grain growth in certain area of the sample
- ✓ 480s: Few zones with small grains remains



Mean grain size, distribution

✓ Equivalent area diameter

$$EQAD = \sqrt{\pi \bar{A}/4}$$

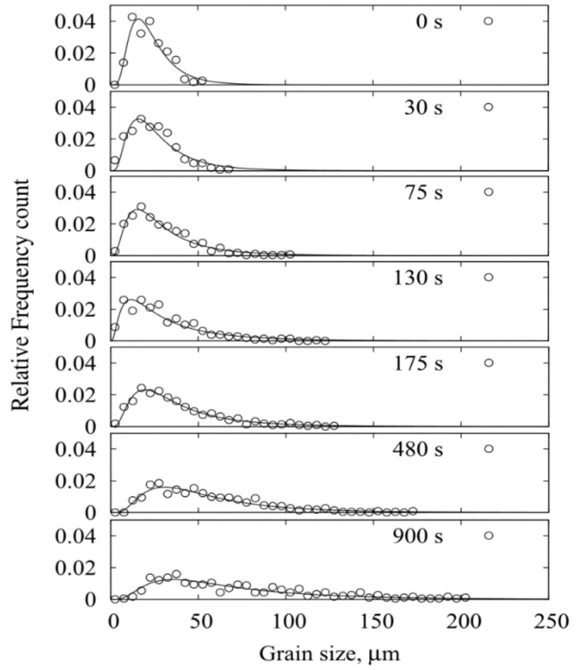
✓ Maximum grain diameter

$$Dmax = AVG(1\%\ largest\ grain)$$

✓ Average diameter from log-normal distribution M, S

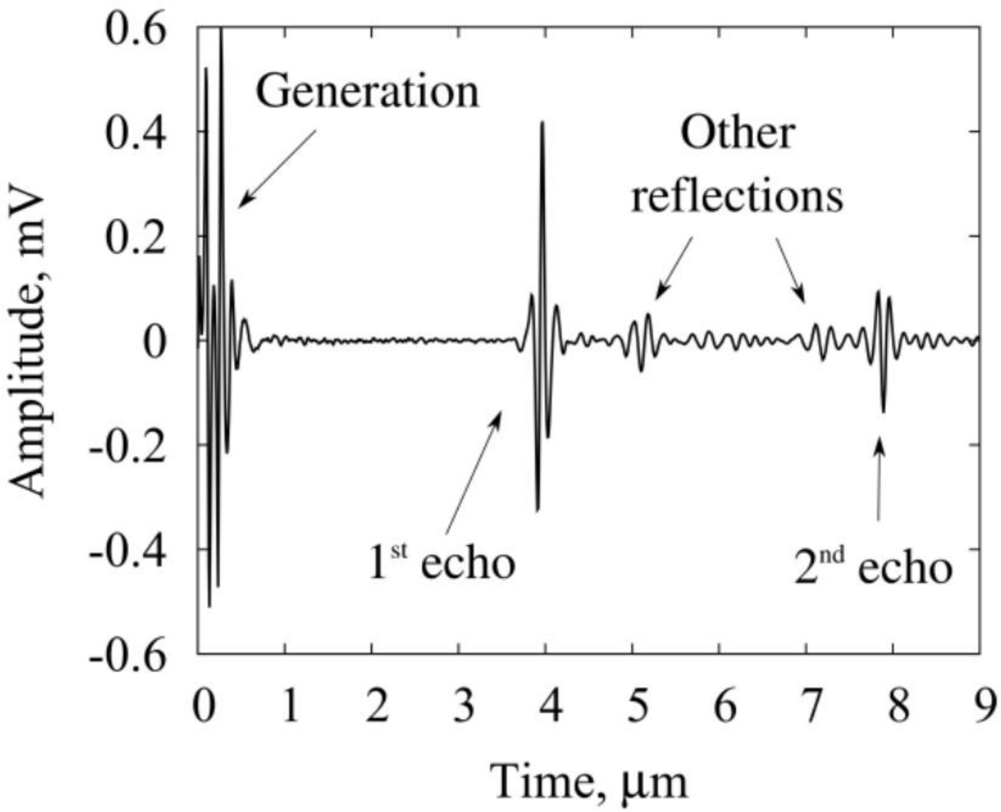
$$\mu = \exp(M + \frac{S^2}{2})$$

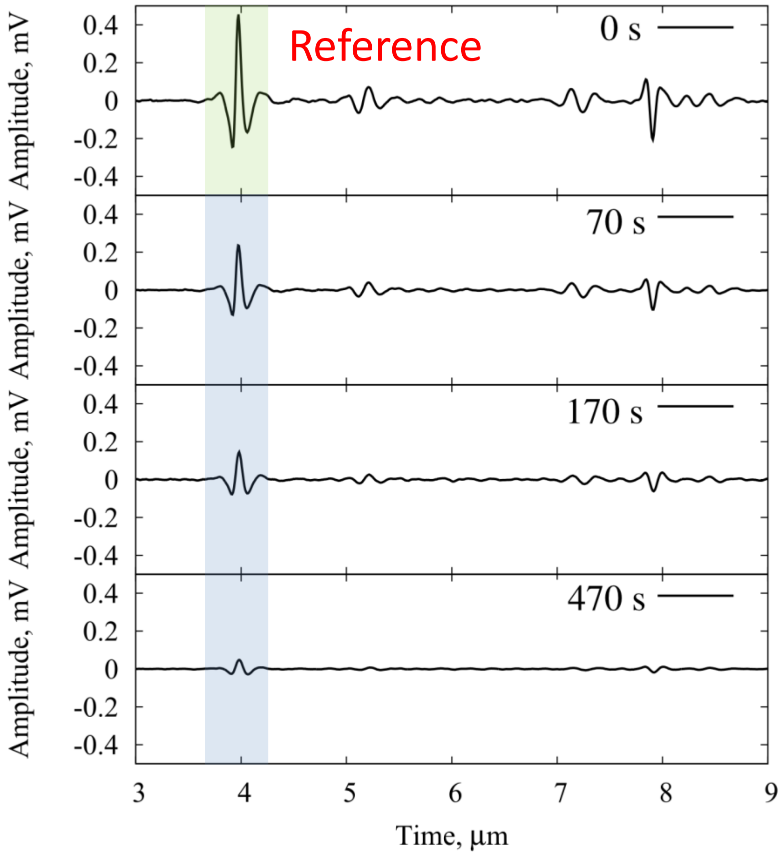
Time	$EQAD$	D_{MAX}	$D_{MAX}/EQAD$
0	24	53	2.2
30	27	65	2.4
75	33	94	2.9
130	37	115	3.1
175	44	128	2.9
230	46	130	2.8
480	62	166	2.7
900	82	199	2.4



Ultrasound signal

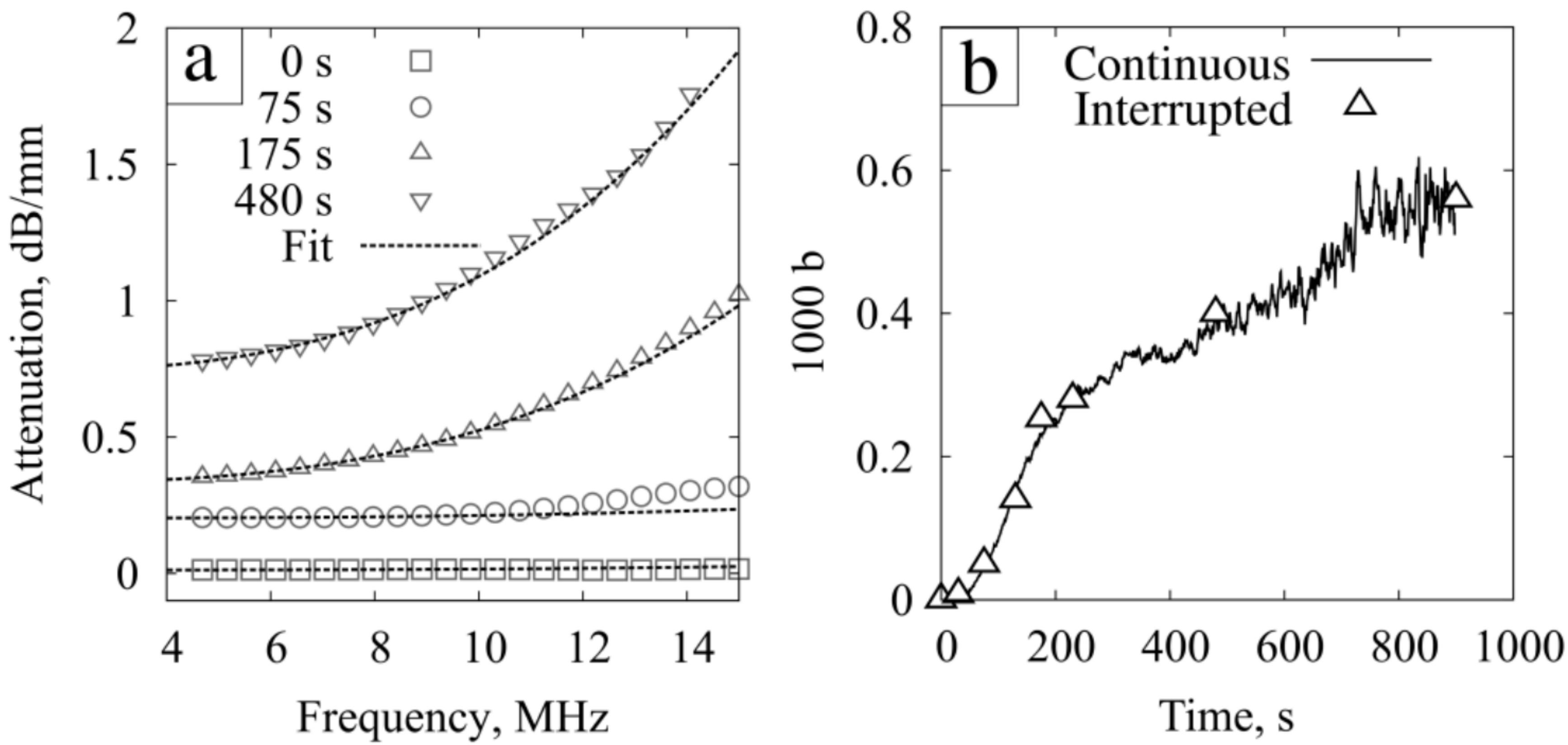
- ✓ For each waveform, analysis of the frequency content of the first echo relative to the echo measured in the initial state





Attenuation, grain size parameter

✓ Systematic evaluation of the grain size parameter b from the measured attenuation spectrum using $a+b*f^3$

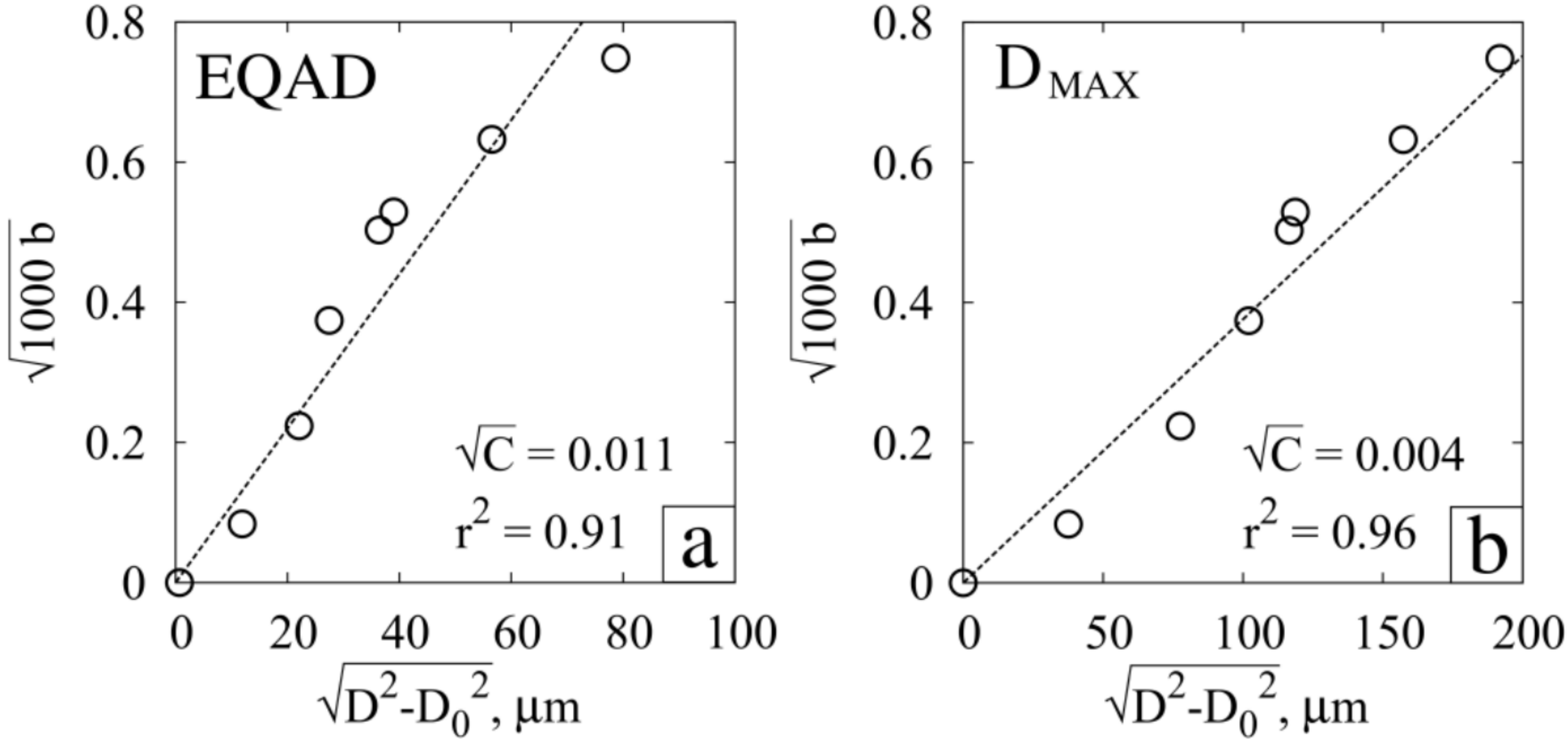


Direct quantitative correlation

$$\alpha(f) = a + CD^{n-1}f^n$$

$$\alpha(f) = a + C[D^2(t) - D_0^2(t_0)]f^3$$

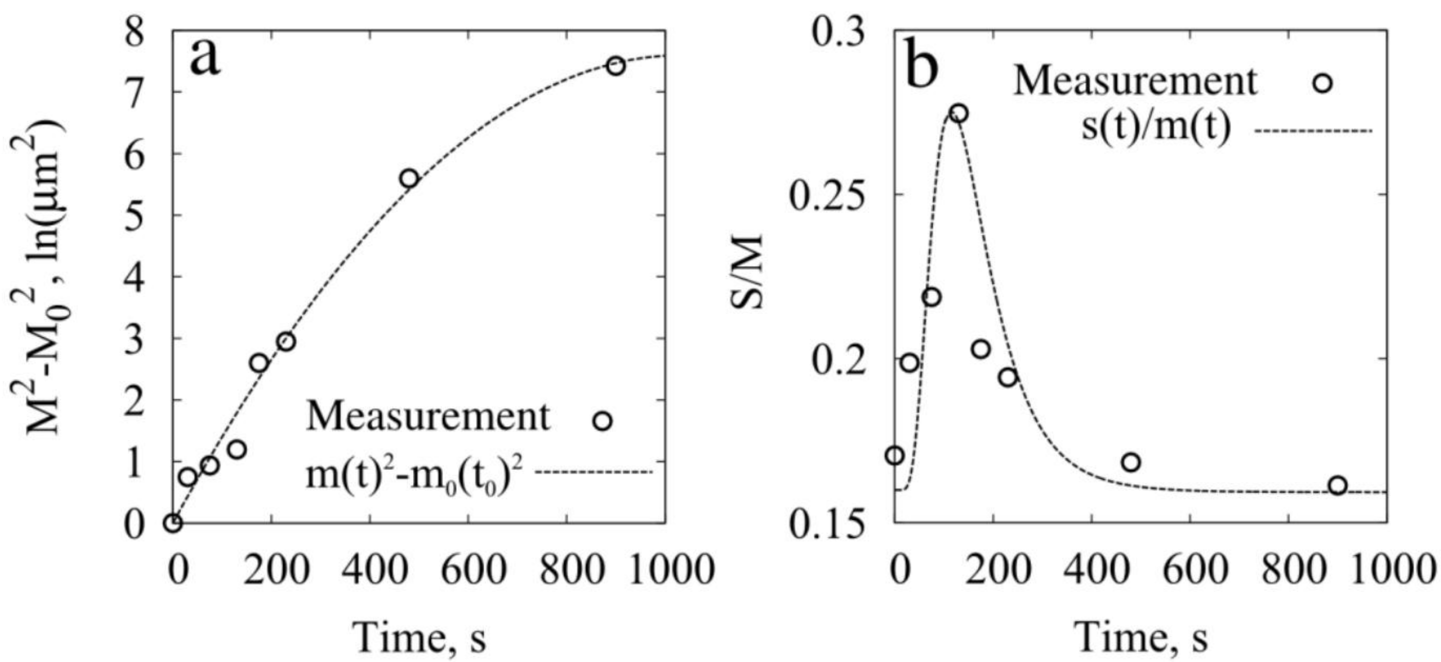
$$b(t, D) = C(D^2(t) - D_0^2(t_0))$$



Inverse method

- ✓ Stage of heterogeneous grain growth, large and small grains
- ✓ Can we predict how should b varies from metallographic investigation : Time dependant size distribution F(t,D)

$$F(t,D) = \frac{1}{\sqrt{2\pi s(t)^2}D} exp\left(-\frac{(ln(D) - m(t))^2}{2s(t)^2}\right)$$



Prediction of the attenuation

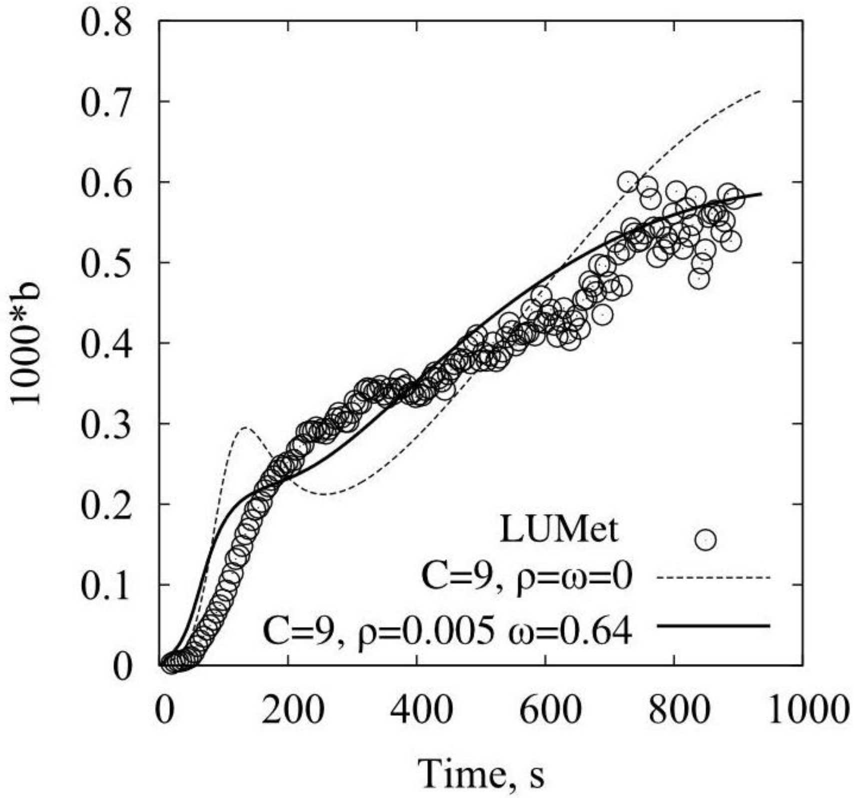
- ✓ Attenuation parameter b weighted by the distribution of grain size in the materials

Weighted average on b parameter

$$b\,(t,D) = C\int \xi(D)\,F(t,D)\,D^2\,\delta D$$

Correction function for wide grain size distribution

$$log10\big(\xi(D)\big) = -\rho D + \omega$$

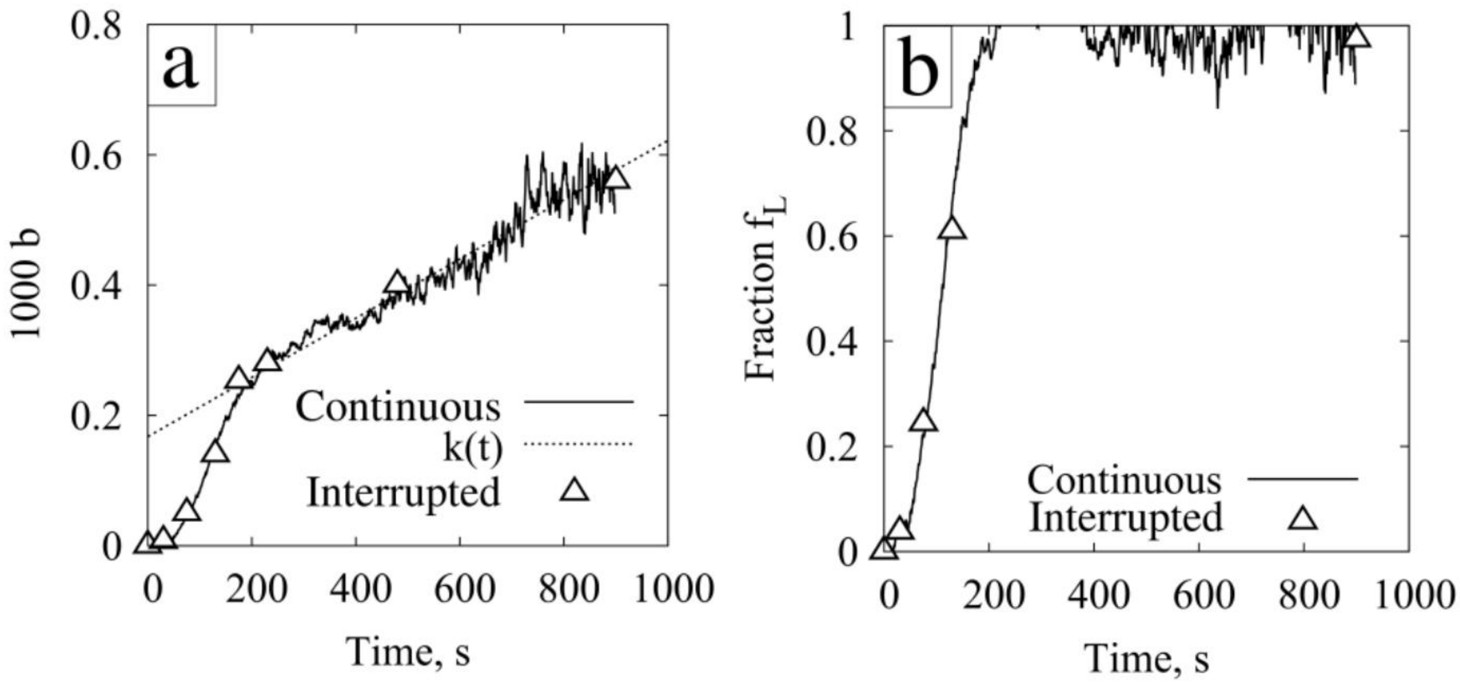


- ✓ Confirm the influence of size distribution on the measurement of grain size with LUMet

Did we get closer to our goal ?

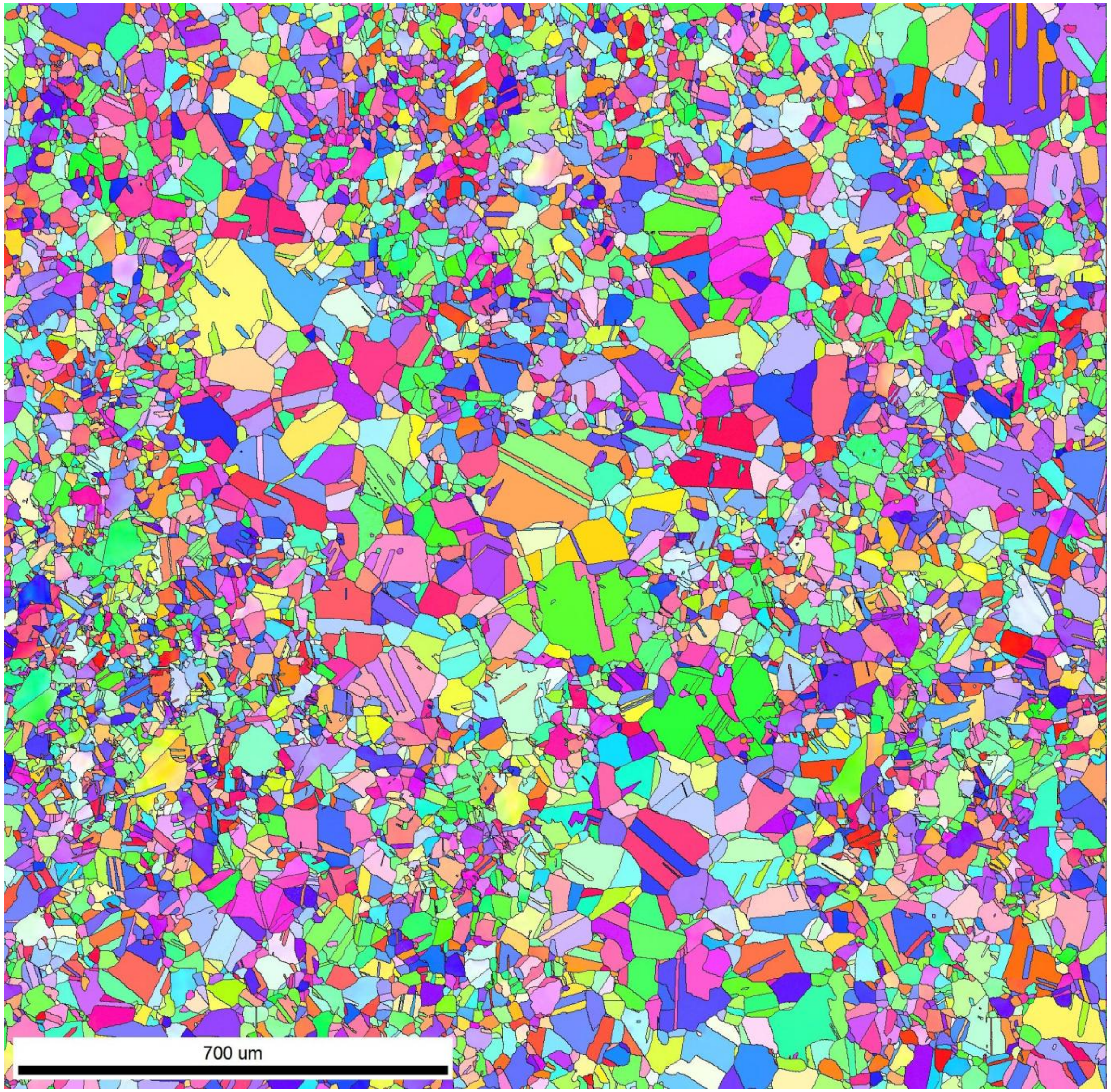
- ✓ Time necessary to dissolve all the precipitates and reach a homogeneous grain size structure.
- ✓ Fraction of large grains as a function of time

$$f_L = 1{,}000.\,b(t)/k(t)$$



EBSD on interrupted sample

- ✓ Better statistic on grain area
- ✓ Build criterion for the evaluation of size of cluster
- ✓ Fraction of large grains as a function of time



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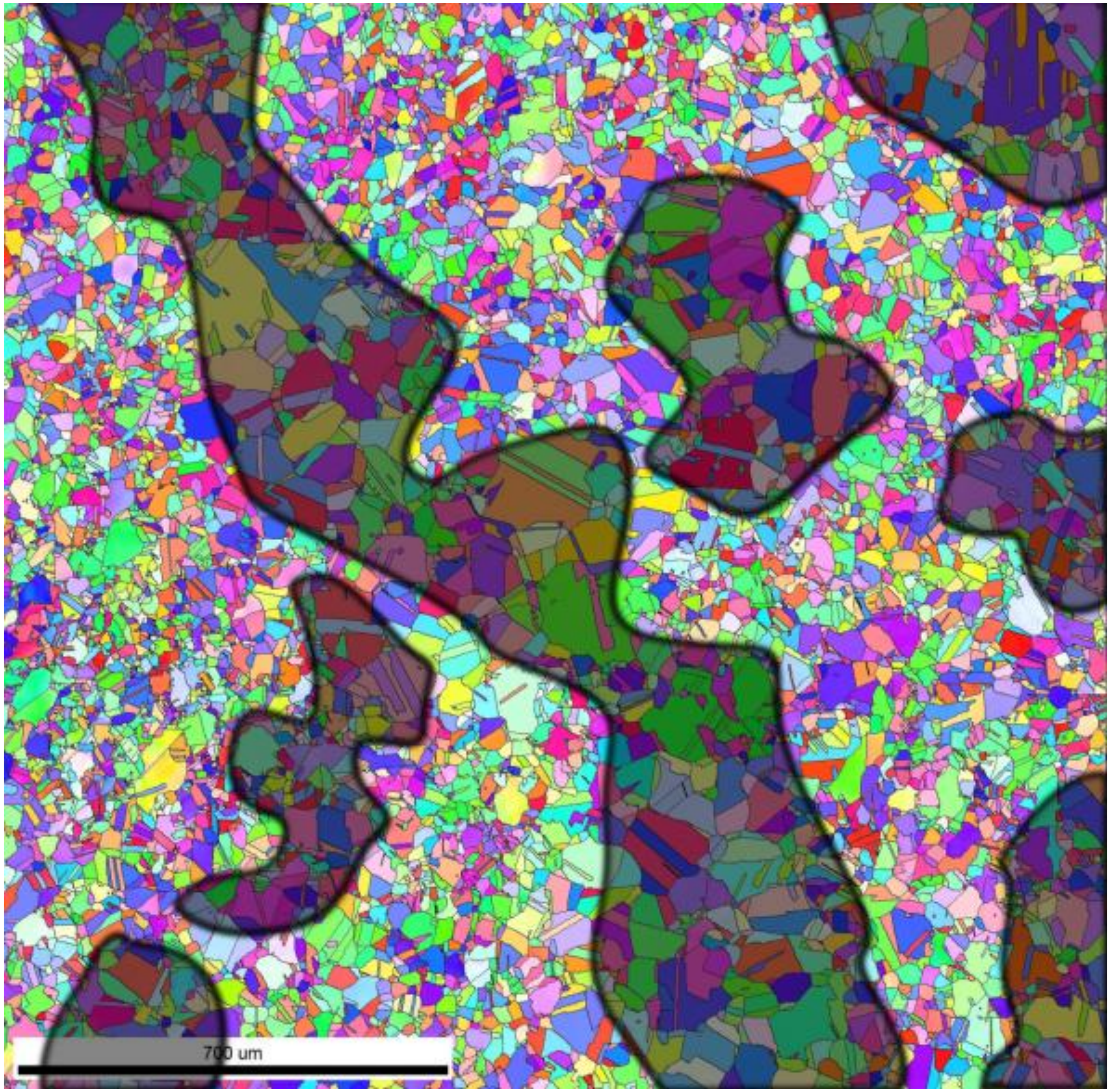

Conclusions

- ✓ Grain growth influenced by the heterogeneous dissolution of the delta phase
- ✓ Mean grain size not a sufficient parameter to construct the ultrasound calibration
- ✓ LUMet measurement may be capable of indicating the end of period of “abnormal” grain growth
- ✓ Can rapidly give important indication on the time required for annealing prior to forging.