Direct visualization of void nucleation and pore growth using ultra high-speed X-ray phase contrast imaging

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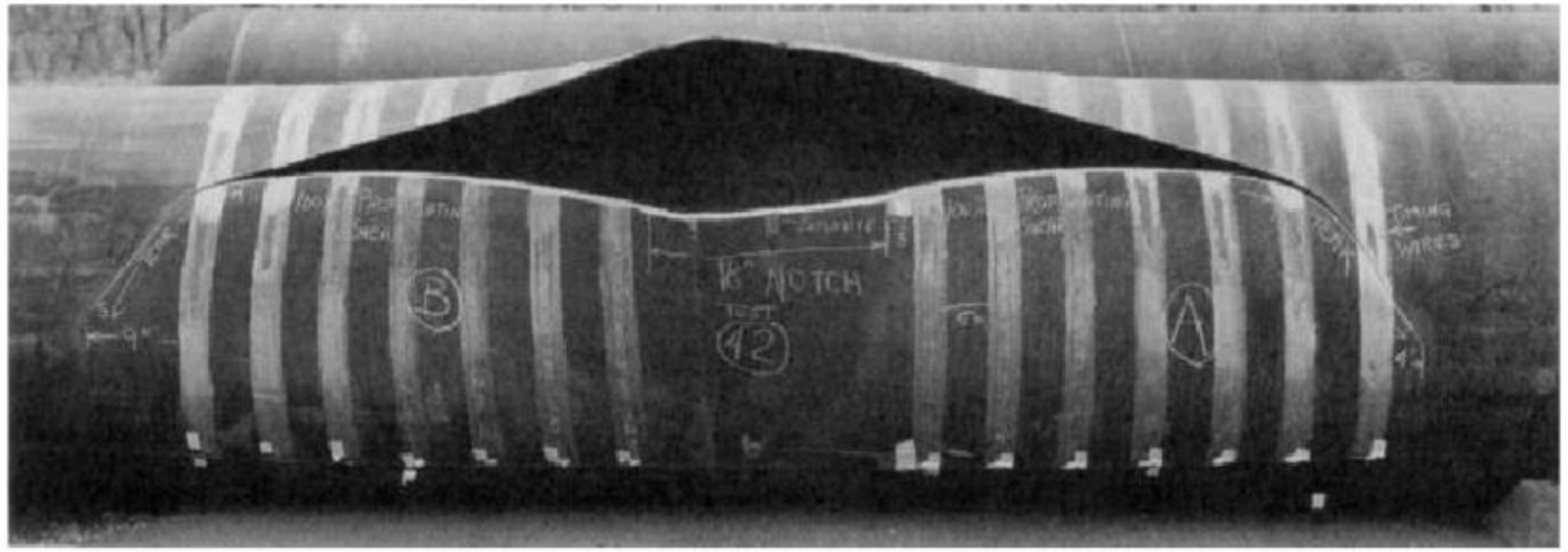
What happens in a metal under combined tension/shear?

Ductile failure occurs at high and low strain rates. Metals typically change their properties depending on strain rate. However, for high strain rate, the problem is not as well understood as for low strain rate.

Examples of ductile fracture:

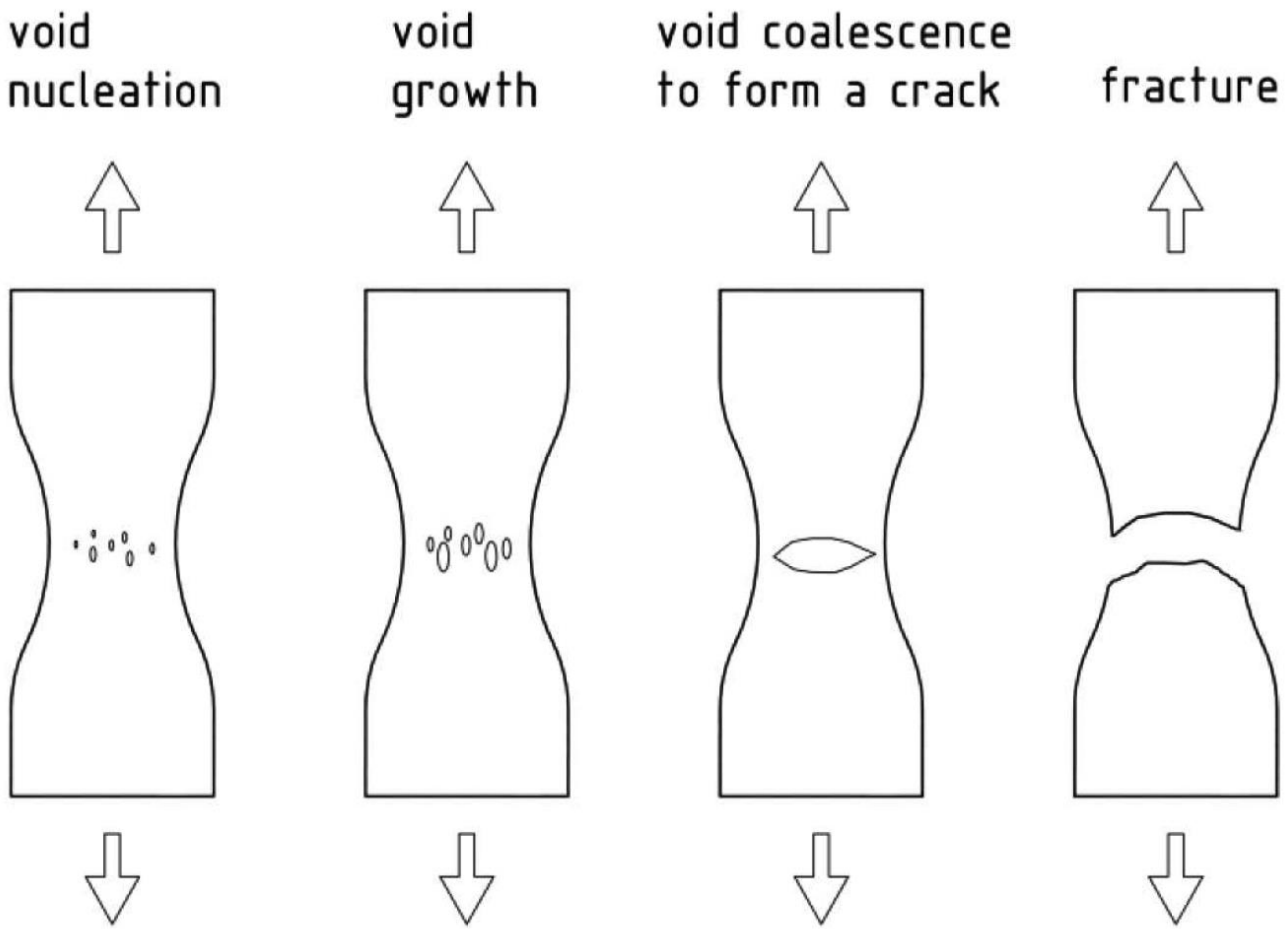
a) **failure of X60 grade line pipe,**
b) **Ductile damage after collision of USS Fitzgerald and containership**



(a)

(b)

What happens in a metal under combined tension/shear?



A.L. Gurson, *Continuum Theory of Ductile Rupture by Void Nucleation and Growth*, J. Eng. Mater. Technol. **99**, 2-15 (1977)

Is it possible to experimentally quantify the void nucleation and growth rate ?

✓ Interrupted CT scans
State of the art

? Real-time X-ray imaging
Continuous measurement, *in-situ*, during experiment

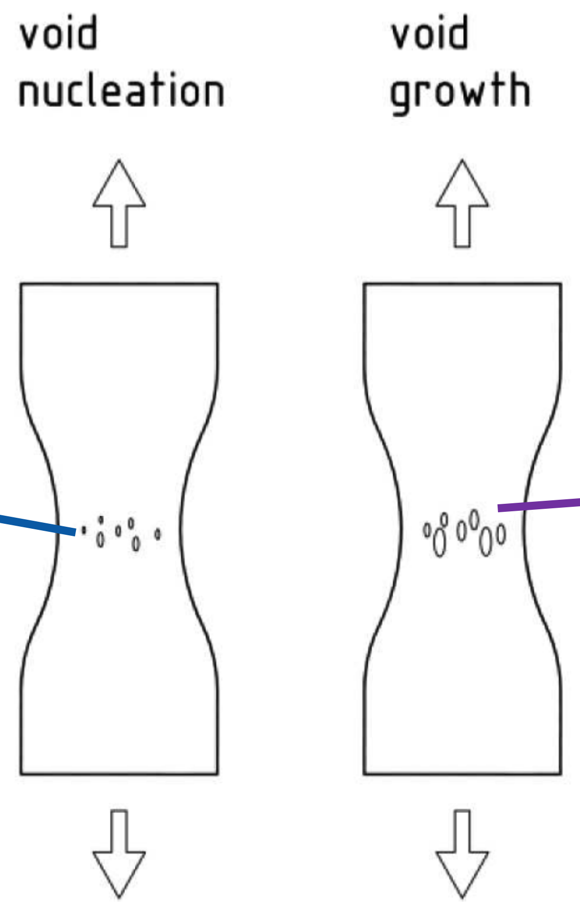
theoretical model background

<u>void nucleation</u>

Landron et al [1] number of voids:

$$N \sim \frac{\varepsilon}{\varepsilon_0}\, e^{\frac{\varepsilon}{\varepsilon_0}} + N_0$$

- ε is plastic strain
- ε_0 and N_0 are material parameters



<u>void growth</u>

once a pore has been nucleated Rice-Tracey (1969) model predicts the growth of pore radius R with the strain ε as

$$\frac{\mathrm{d}R}{\mathrm{d}\varepsilon} = \alpha\, e^{\frac{3}{2}T}\, \mathrm{d}\varepsilon$$

- T is the stress triaxiality
- $\alpha = 0.427\, T^{1/4}$

<u>Combined effect</u>

Damage D ~ sum of pores × pore size.

Assuming all pores are nucleated at the same time and grow to the same size:

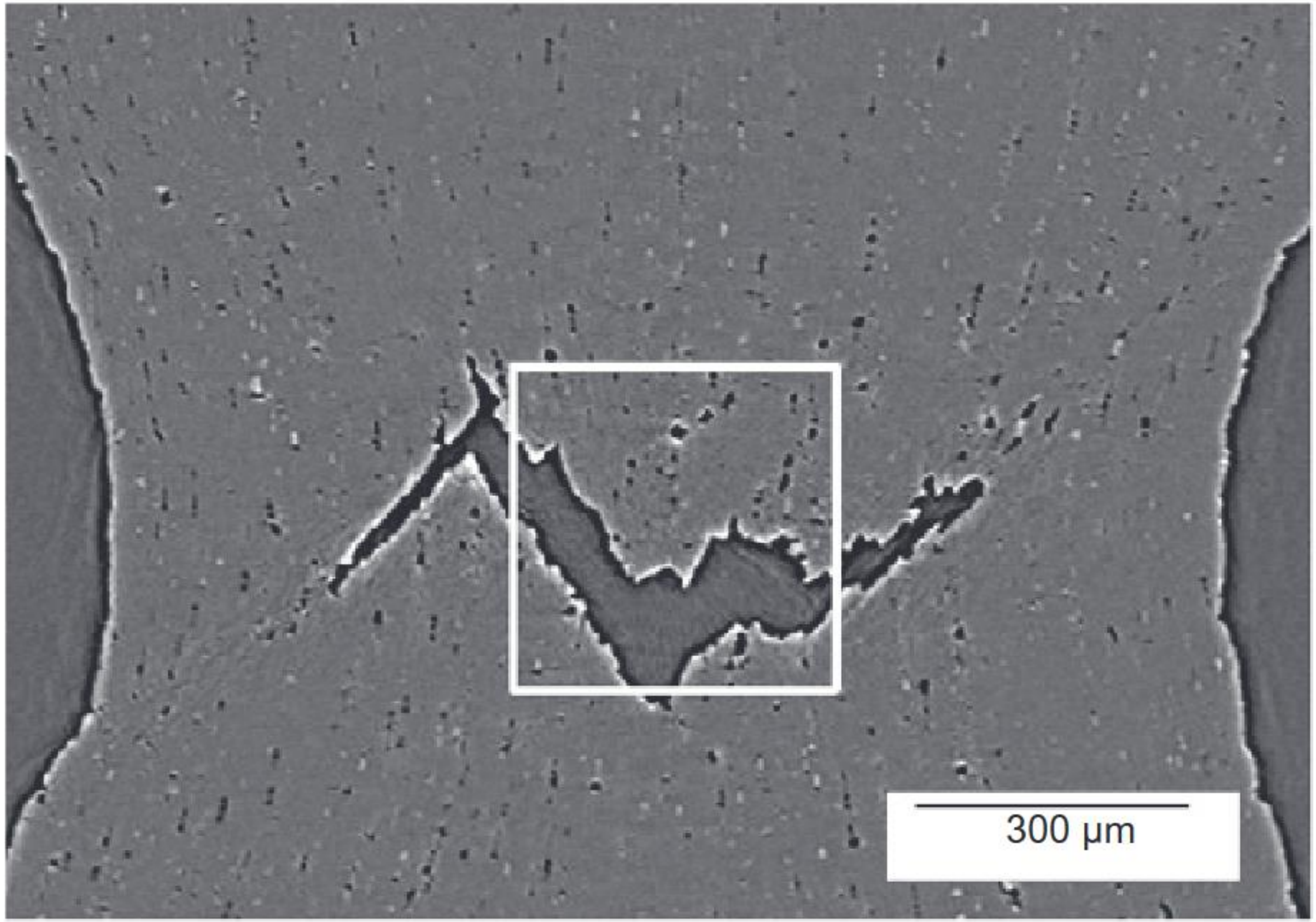
$$D(\varepsilon) \sim [\varepsilon e^{C\varepsilon} + 1] \times \left[\varepsilon^3 e^{\frac{3}{2}T}\right]$$

State of the art – interrupted / slow CT scans

Very nice work conducted
at ESRF ID15 back in 2010 by
Eric Maire *et al*.

A specimen is elongated very slowly
(strain rate 10-5 /s)

CT scans are taken either
- interrupted, in discrete stages
- Continuously



taken from:
Eric Maire, Suxia Zhou, Jerome Adrien, Marco Dimichiel, Damage quantification in aluminium alloys using in situ tensile tests in X-ray tomography, *Engineering Fracture Mechanics 78(15), 20*11, pp. 2679-2690

Hypothesis

Outset

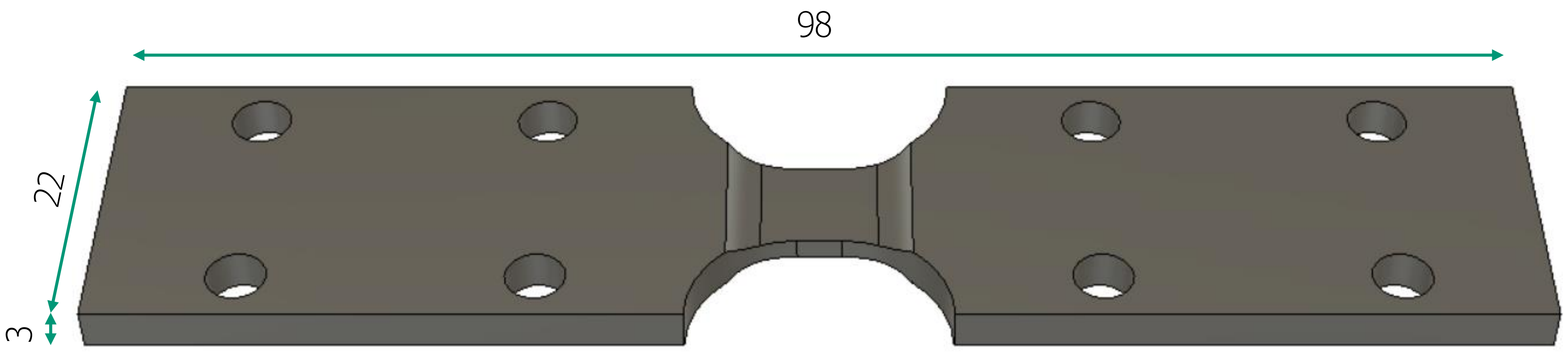
- The ductile failure mechanism is known to be strain rate sensitive. It is emipirically established that the loading rate affects the failure strain.
- There are theories which yield a pore growth rate depending on the speed of loading, e.g. Gurson's 1977 model.
- However, the kinetics of pore growth, i.e., the rate parameters ar not experimentally accessible. In practice, they are chosen such as to minimize the difference between simulation prediction and experimental observations.

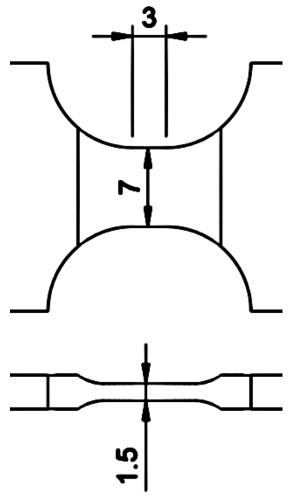
Hypothesis

By measuring the rate dependence of void growth using X-Ray imaging, we can directly obtain the kinetics, and thus have a physics-based model of damage and failure

Research question

How do we do this experimentally?



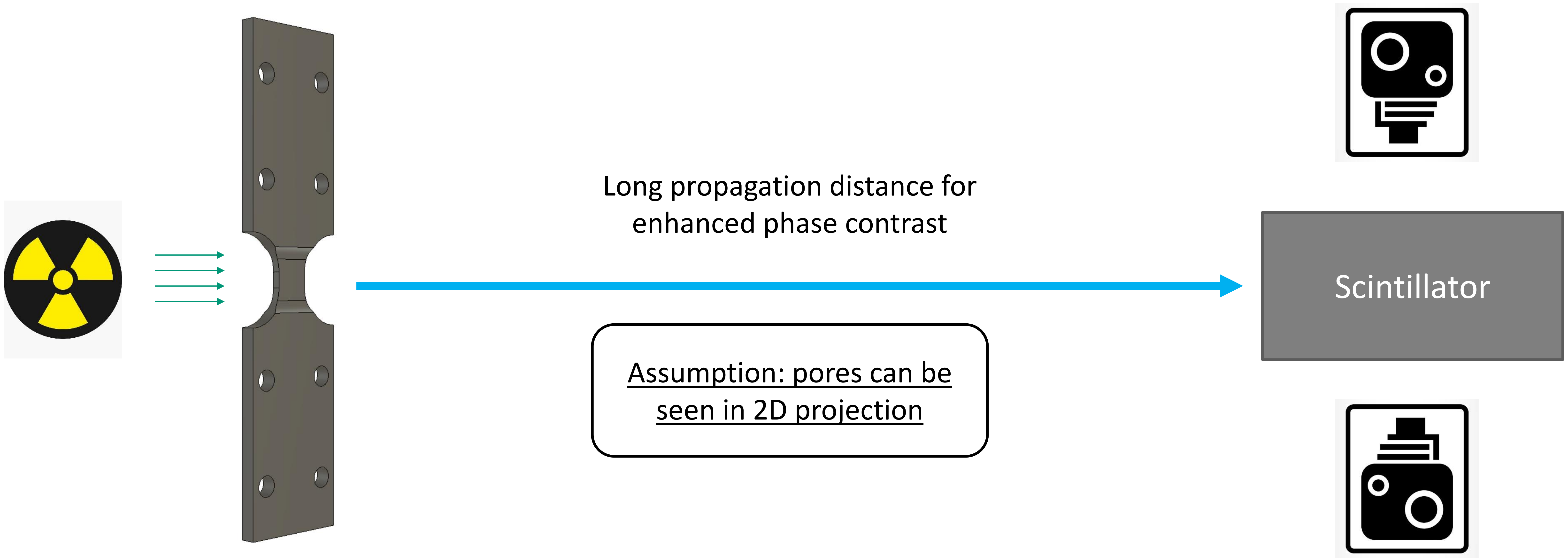


All dimensions are in mm.

Test specimen, from Scalmalloy® additively manufactured

- For the first test, a material without strain rate sensitivity of yield stress was chosen
- This is a 5000 series Al-Mg alloy, supplemented with Scandium
- Additively manufactured, so the defect density is high, for easier imaging

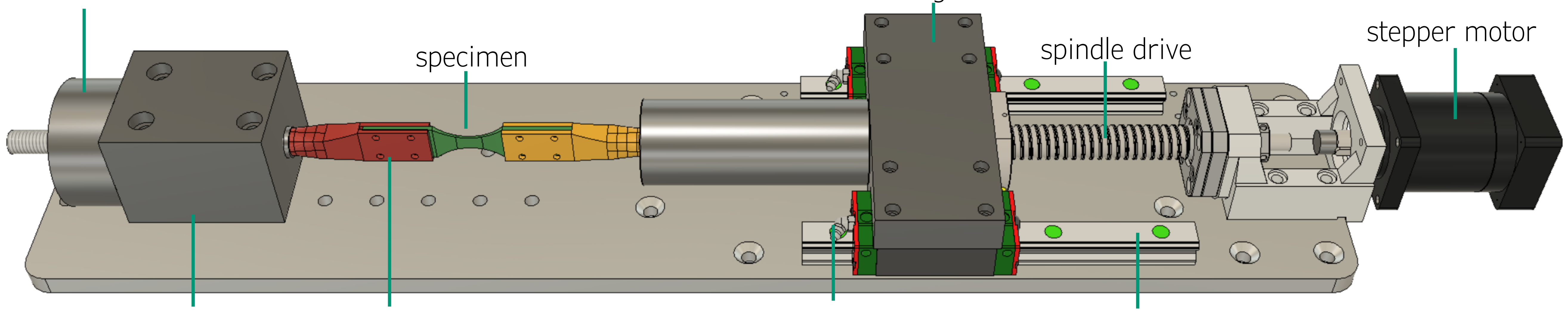
Imaging setup



Universal testing machine for slow tests $\dot{\varepsilon} \approx 10^{-2}\ /s$
-- or --
Split-Hopkinson Tension bar For dynamic tests at $\dot{\varepsilon} \approx 10^{-2}\ /s$

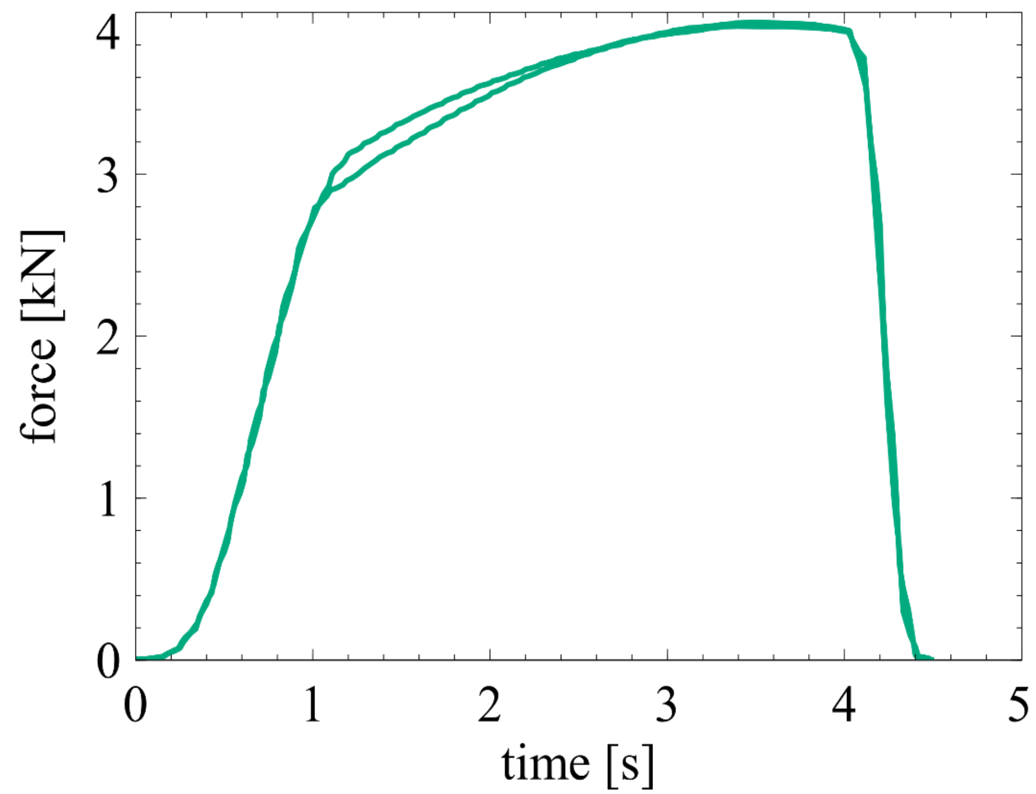
Single Photron SAZ @ 10 kHz
-- or --
2 x Shimadzu HPV, interlaced, around 5 MHz

Custom device @ID19: slow universal testing machine

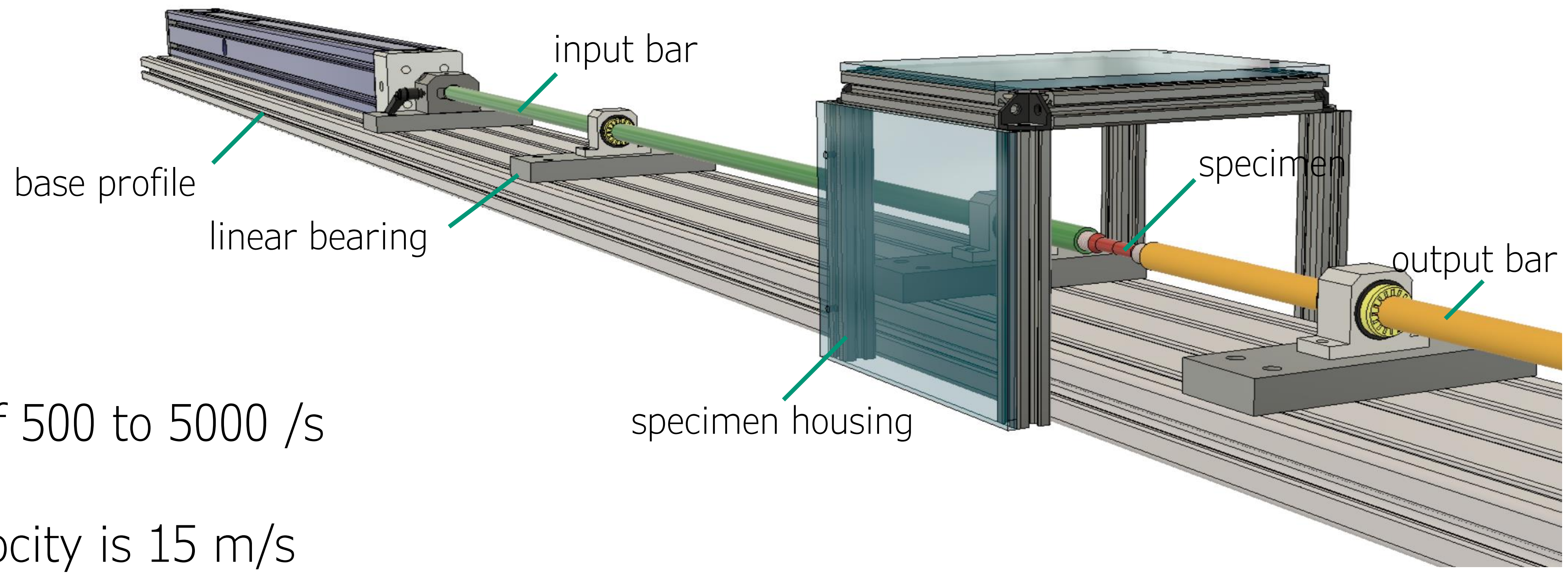


Universal Testing Machine

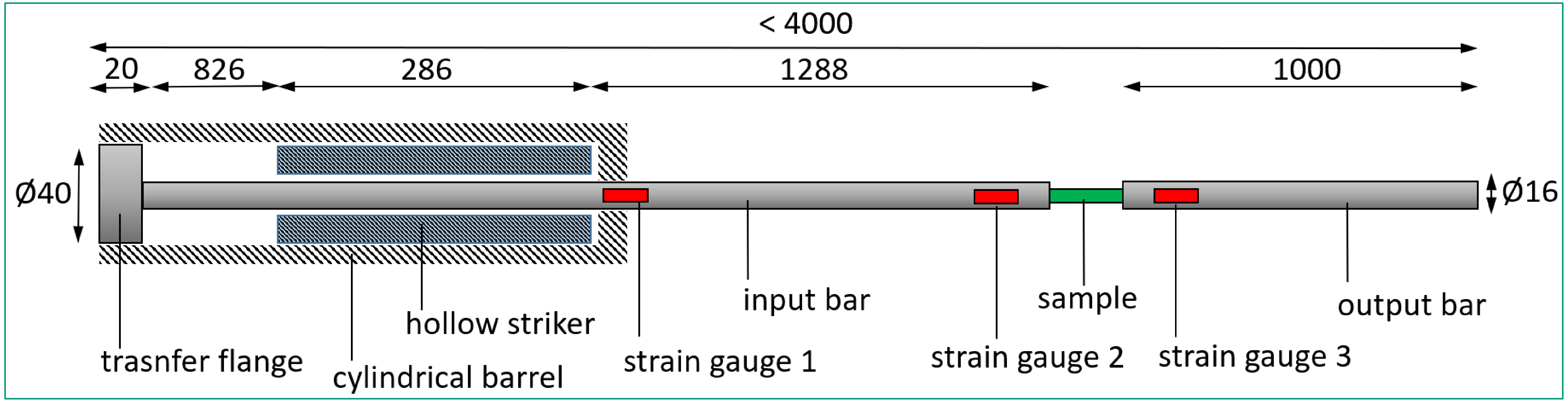
- Strain rates of 10^{-3} to 1 /s
- Maximum load of 10 kN

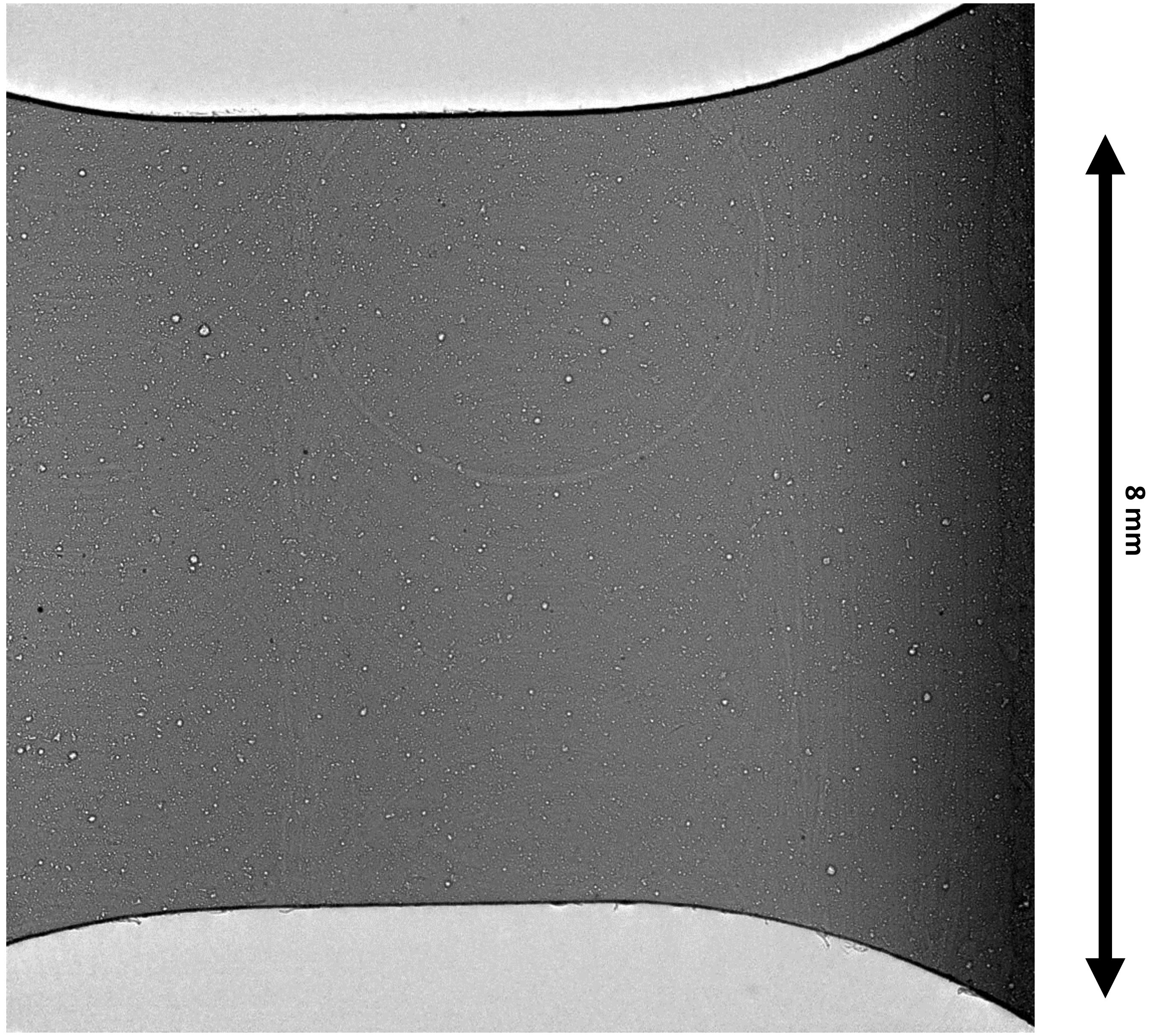


Custom device @ID19: split Hopkinson Tension Bar

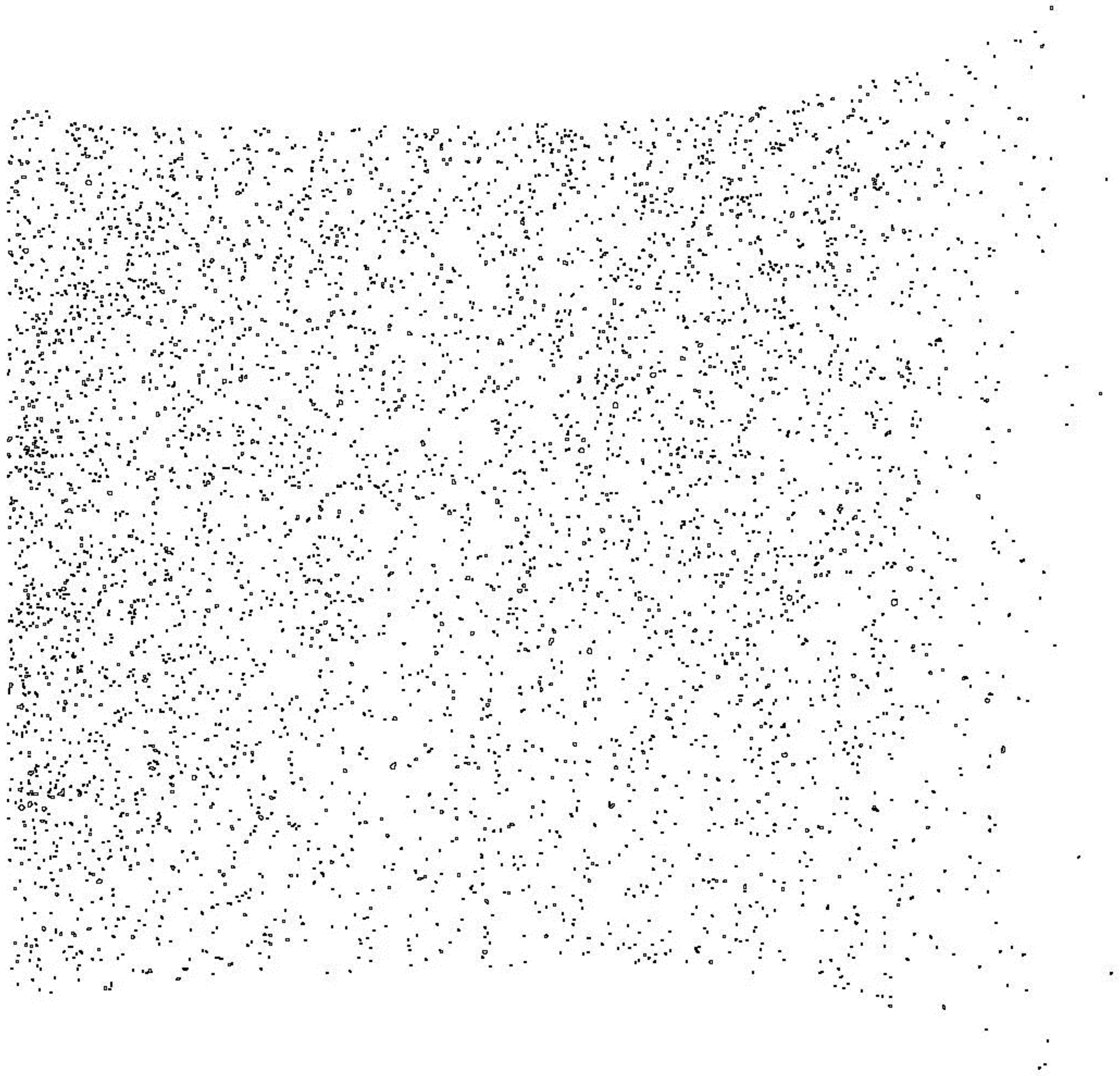


- typical Strain rates of 500 to 5000 /s
- Maximum striker velocity is 15 m/s
- Pulse duration: 0.45 ms



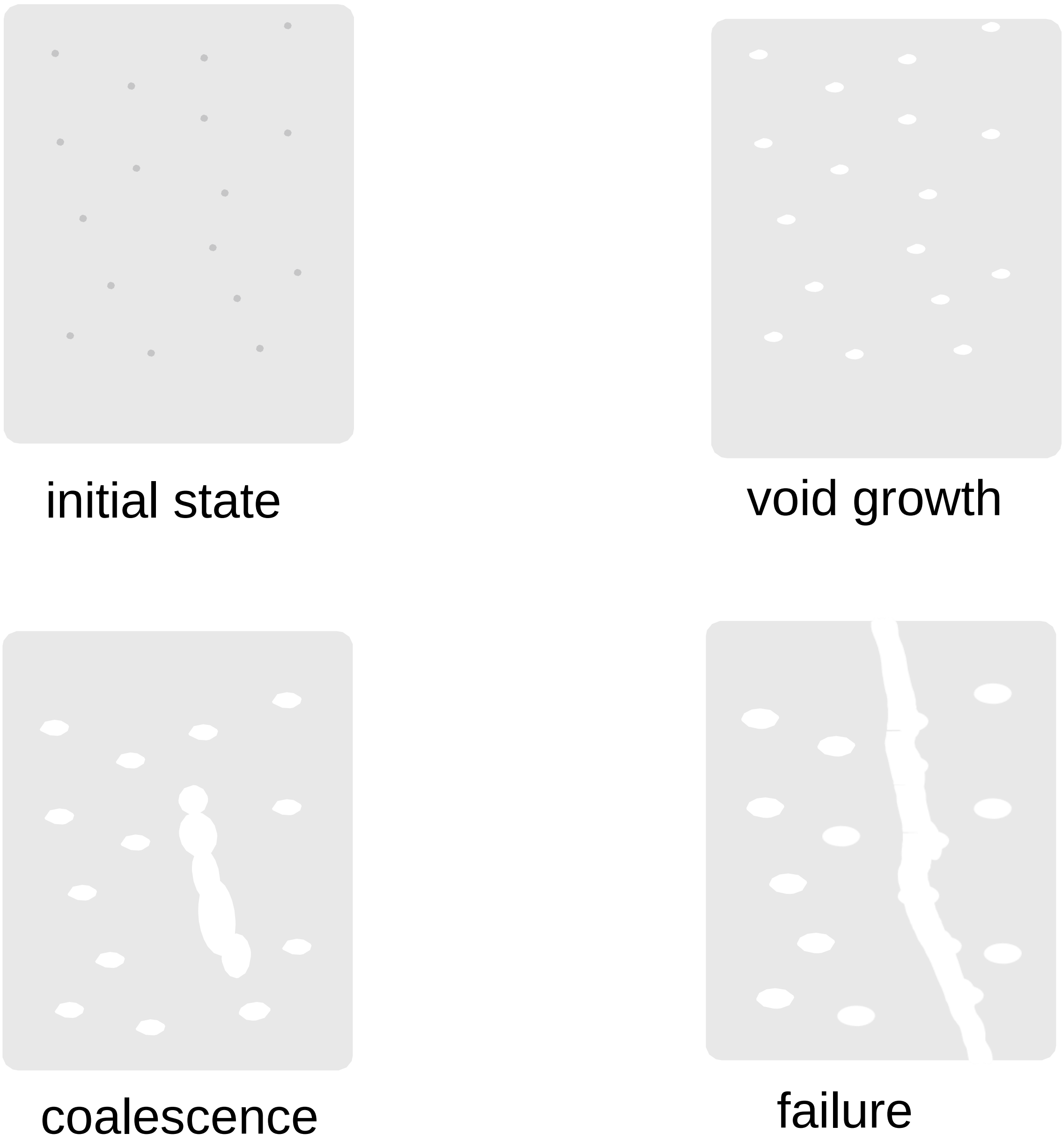


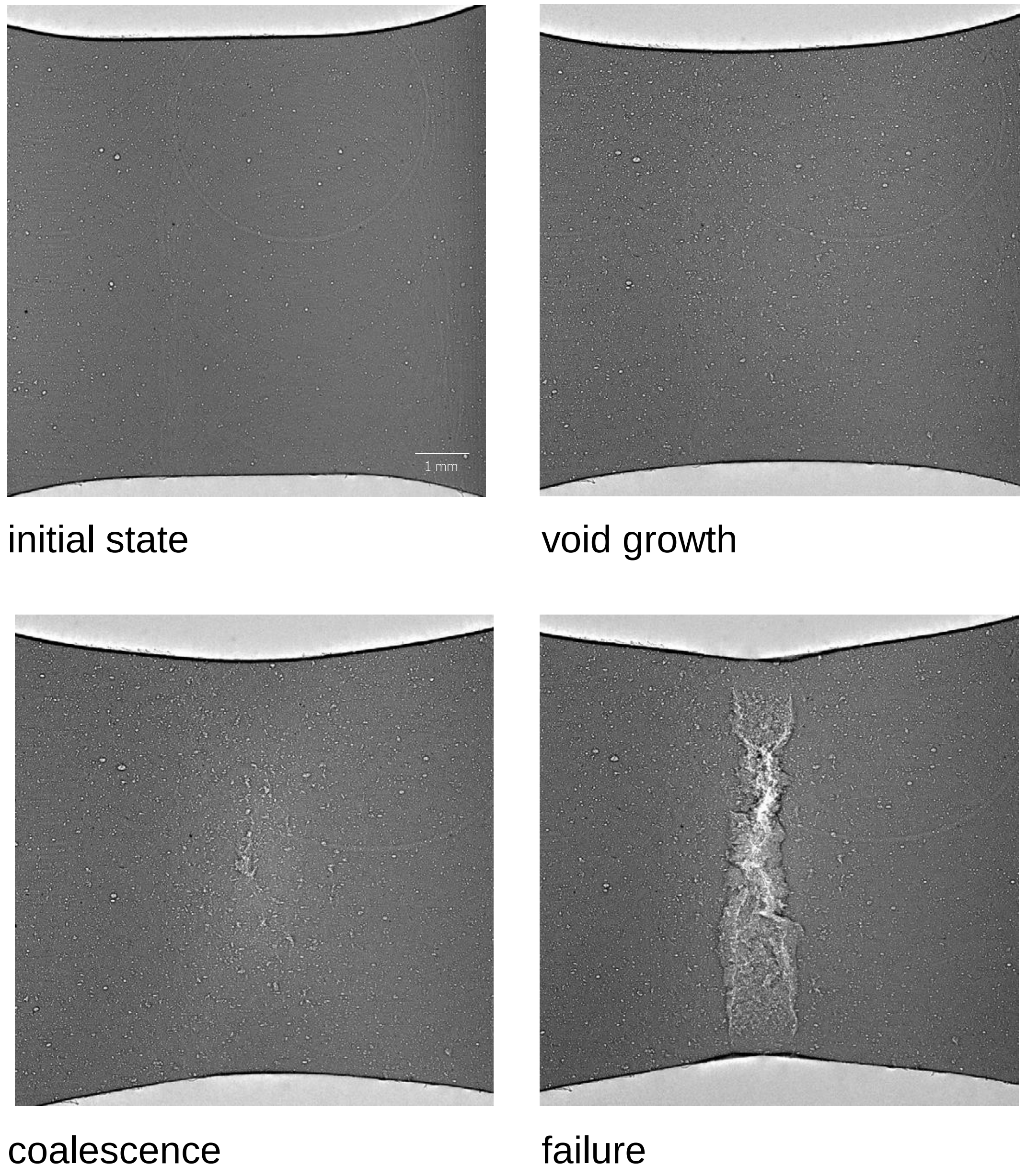
X-ray video



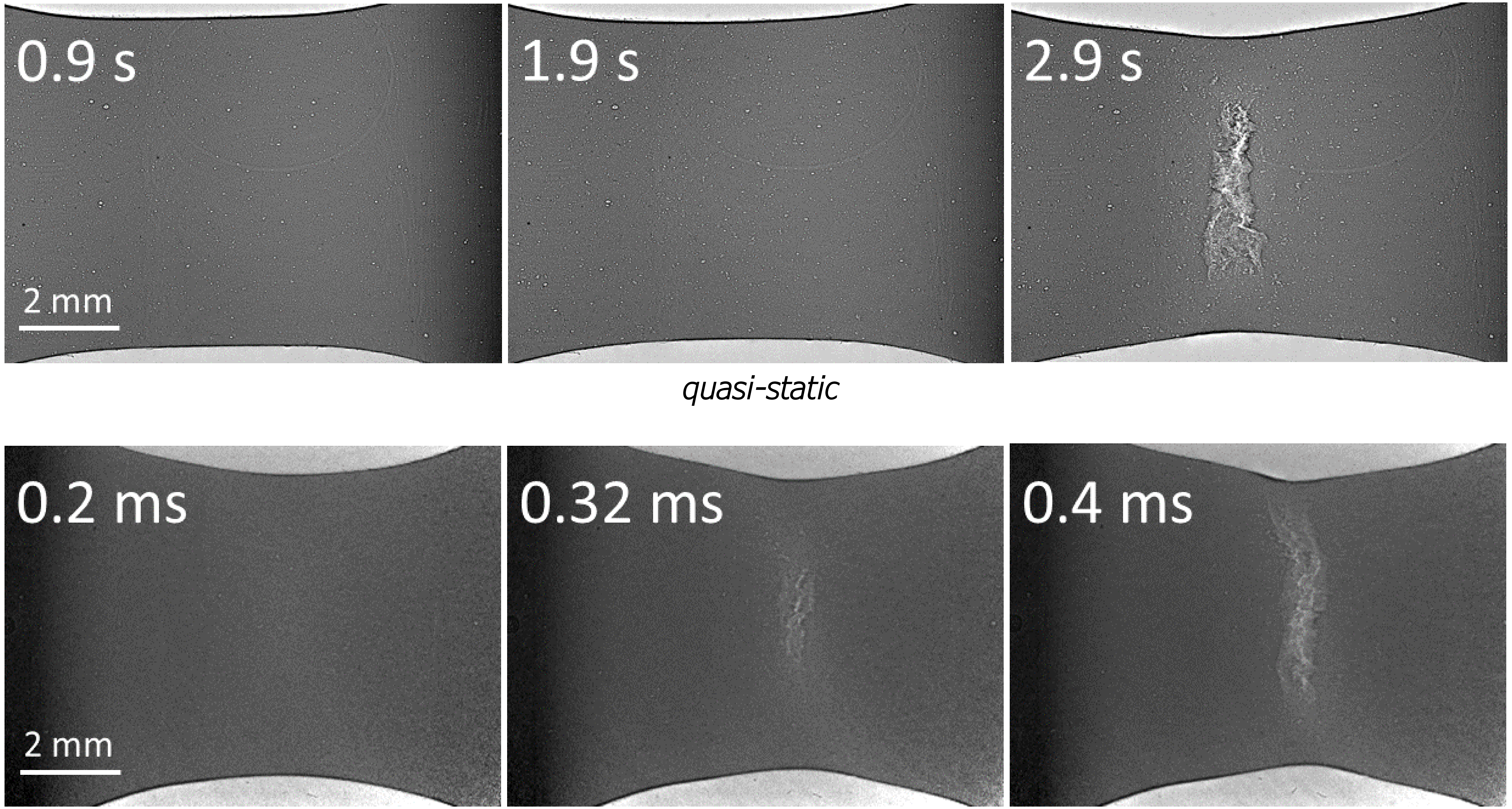
Algorithm counts defects

ductile failure – X-ray based proof of assumed mechanism?





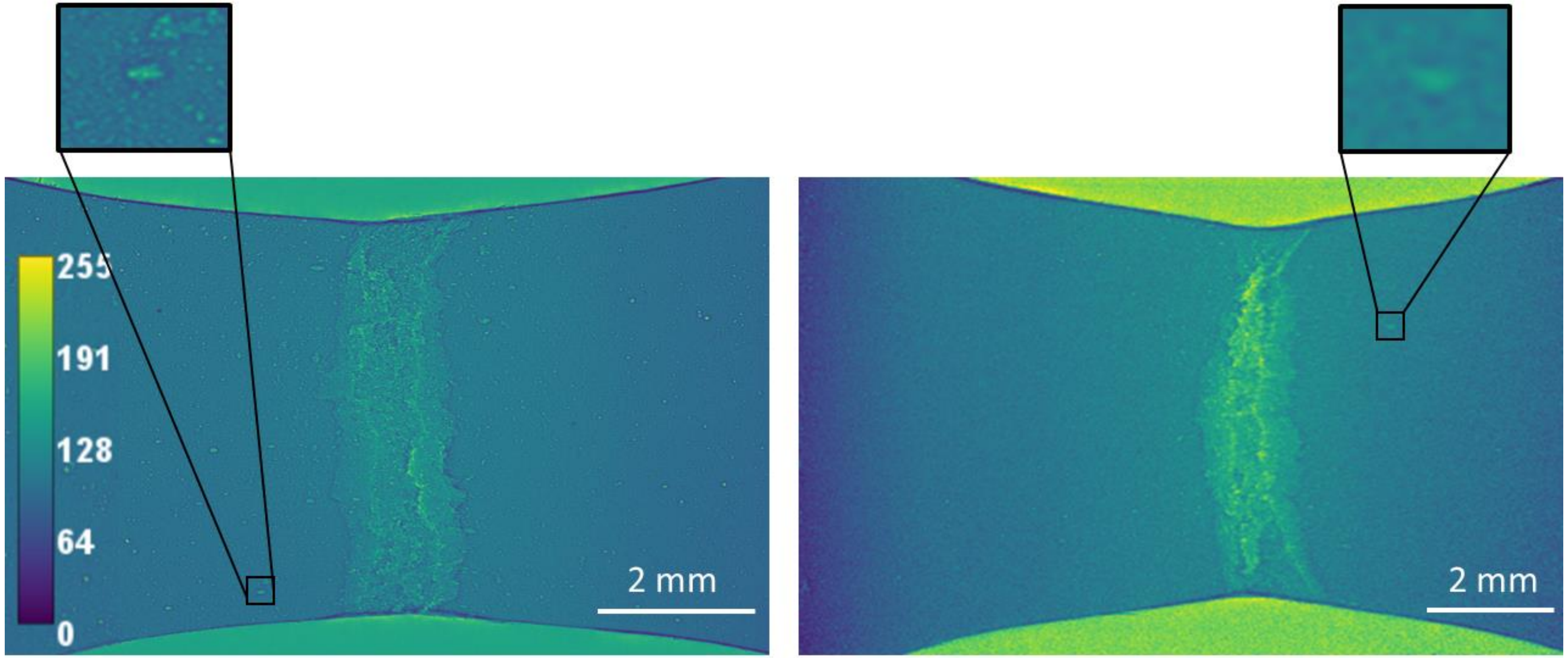
Results



quasi-static

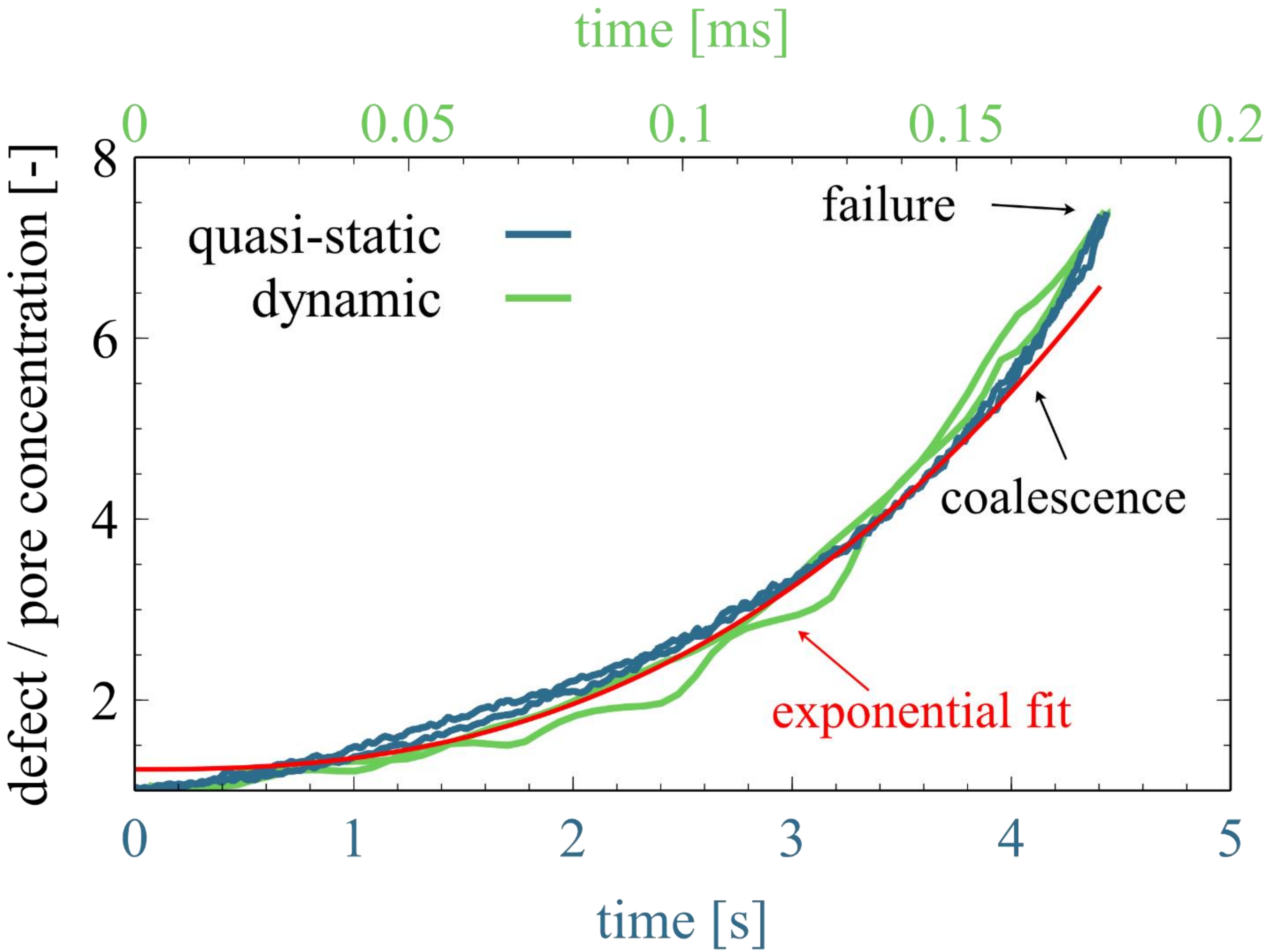
dynamic

Results, quasi-static vs. dynamic



quasi-static *dynamic*

Results


time [ms]
0
0.05
0.1
0.15
0.2
8
6
4
2
defect / pore concentration [-]
quasi-static
dynamic
failure
coalescence
exponential fit
0
1
2
3
4
5
time [s]

Summary

- Phase contrast X-ray imaging allows to visualize internal defects / pores
- The number of pores and their size can be counted using image analysis algorithms
- The total void volume exhibits exponential growth, both:
  - as a function of time
  - as a function of plastic strain
- The exponential character agrees with theoretical models of pore growth

- → We do not see a difference between slow and fast loading, as expected for the currently chosen alloy, which is not sensitive to strain-rate.
- Experiment seems feasible

Outlook

- New beamtime session in May
- Will consider strain-rate dependent materials: 316L, Ti6Al4V, 6061-T6 (AlMgSiCu)
- Will consider different states of stress triaxiality.