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DE LA RECHERCHE À L'INDUSTRIE

22ND EUROPEAN CONFERENCE ON FRACTURE

LOADING AND ENVIRONMENT EFFECTS ON STRUCTURAL INTEGRITY

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IMPACT OF MACHINE STIFFNESS AND HEAT TREATMENTS ON CRACK PROPAGATION INSTABILITIES IN AN AL-MG-SI ALLOY

T. PETIT

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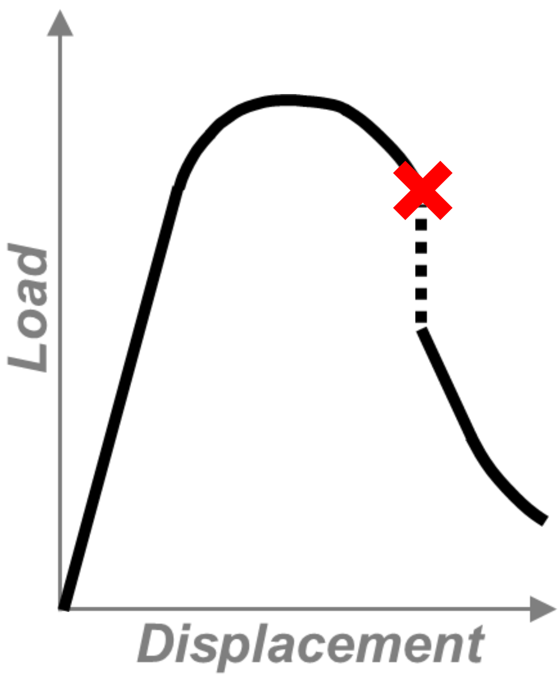
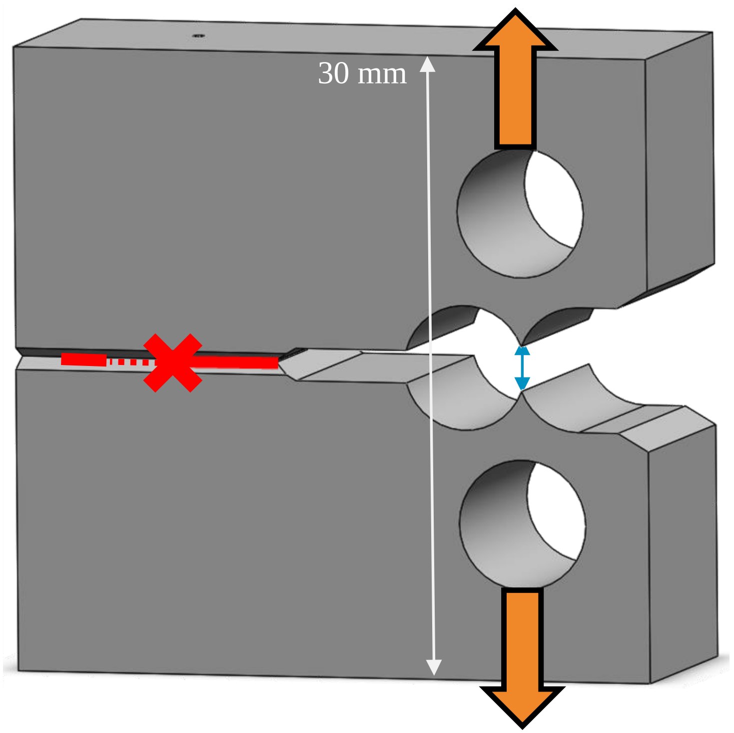
DEFINITION

EXPERIMENTAL INVESTIGATIONS

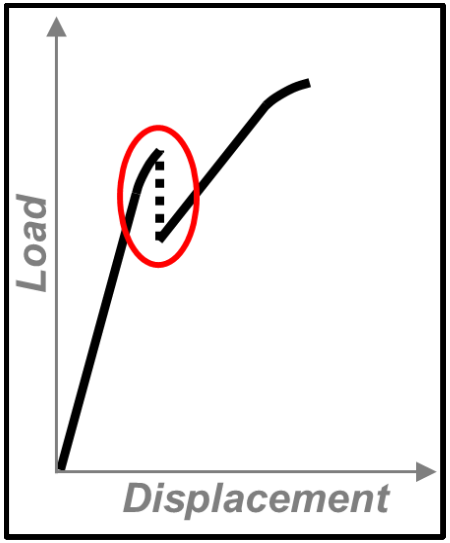
INSTABILITY CRITERIA

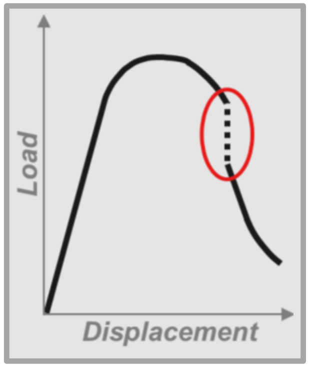
- Fracture toughness tests
- "**Pop-in**" = **local instability** leading to **rapid but limited crack propagation** associated with a sudden decrease in load





- Fracture toughness tests
- "**Pop-in**" = **local instability** leading to **rapid but limited crack propagation** associated with a sudden decrease in load
- Little studied in the literature. 2 types :





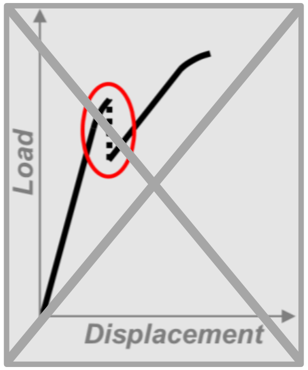
- Microstructural origin
  Before max load
  Typical for brittle fracture

➡ First pop-in type: "Cleavage" instability

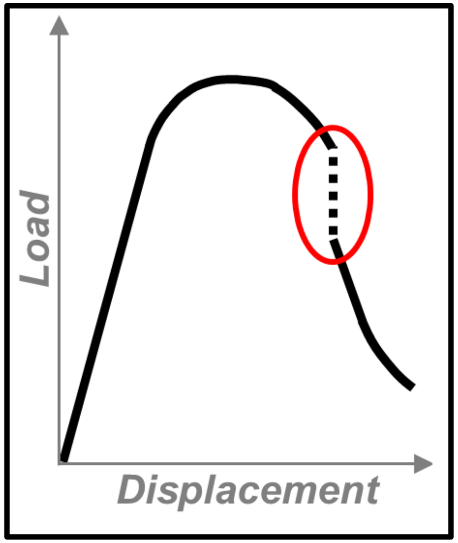
➡ Fracture toughness tests

➡ "**Pop-in**" = **local instability** leading to **rapid but limited crack propagation** associated with a sudden decrease in load

➡ Little studied in the literature. 2 types :



"cleavage" instability



Paris, Tada, Zahoor, Ernst, 1979
Paris, Tada, Ernst, Zahoor, 1979
Hutchinson, Paris, 1979
Zahoor, Paris, 1981
Zahoor, 1982

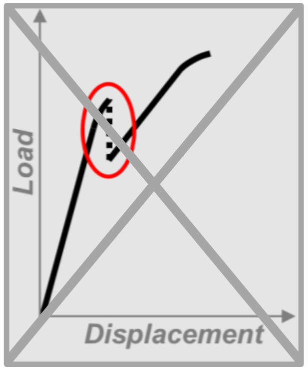
➡ Mechanical origin
After max load
Typical for ductile fracture

➡ Second pop-in type:
"Tearing" mechanism

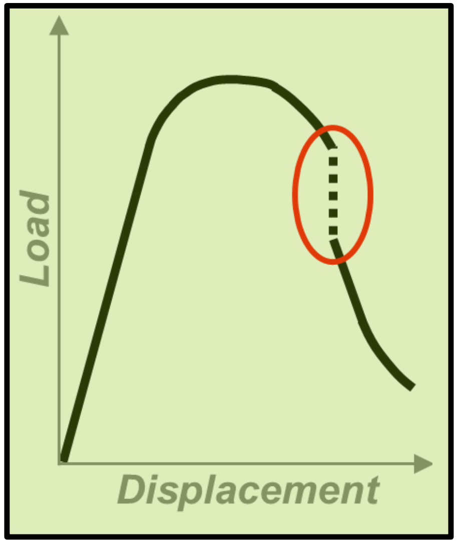
Origin ?

Interaction between elastic energy and tearing modulus?

- Fracture toughness tests
- "**Pop-in**" = **local instability** leading to **rapid but limited crack propagation** associated with a sudden decrease in load
- Little studied in the literature. 2 types :



"cleavage" instability



"tearing" mechanism

System		Aluminium Al-Mg-Si (6061)
Machine stiffness	⟷ POP-IN ?	Crack growth toughness

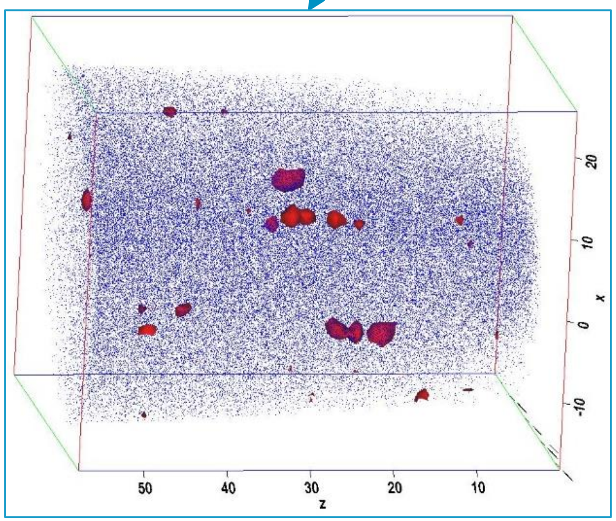
- Aluminium 6061-T6
- Age-hardened alloy →

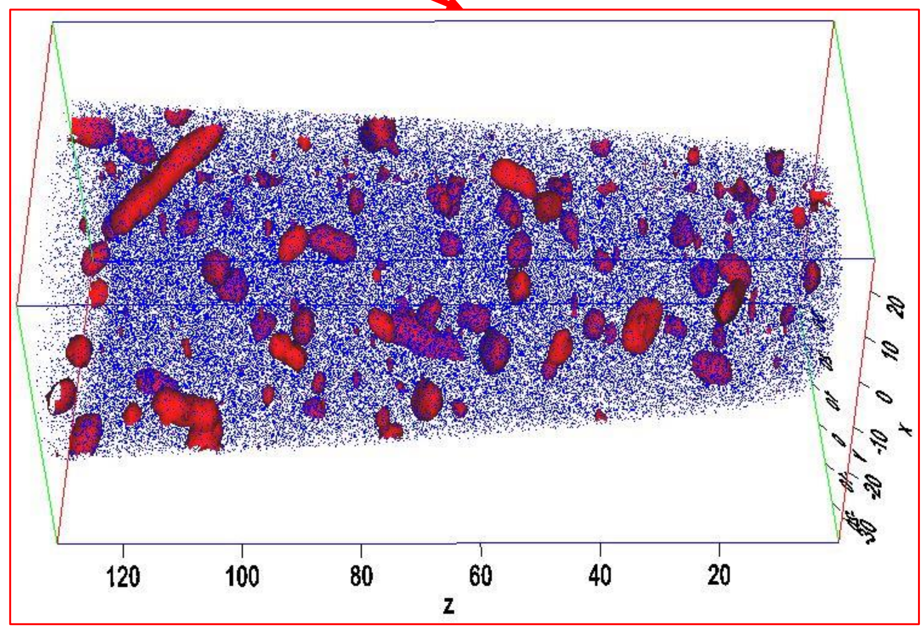
Aging time (h)			
4	8	12	16

→ 4 metallurgical states

- Atom Probe Tomography:

45 nm





60 nm

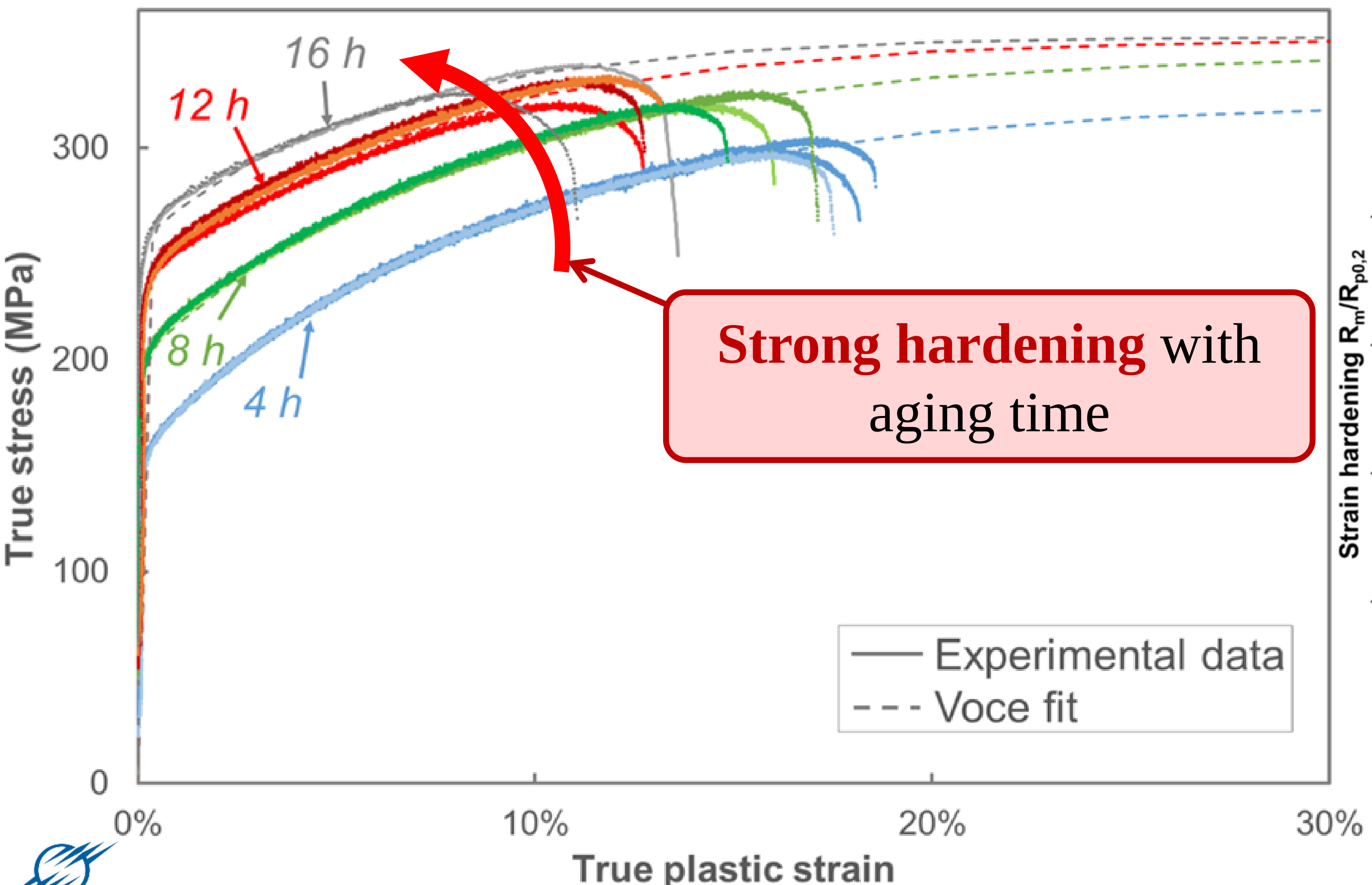
Hardening **nanoprecipitation increase in the size and density** with the aging time

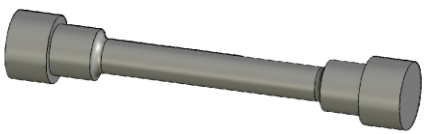
- Aluminium 6061-T6
- Age-hardened alloy →

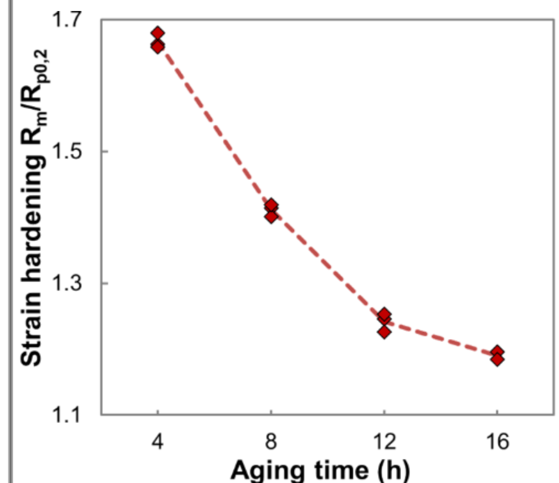
Aging time (h)			
4	8	12	16

→ 4 metallurgical states

- Tensile tests:





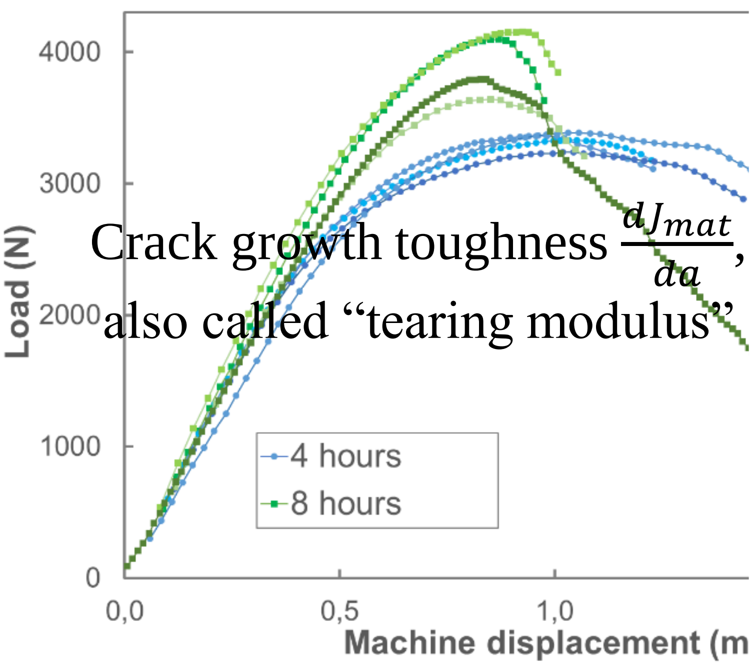


- Aluminium 6061-T6
- Age-hardened alloy →

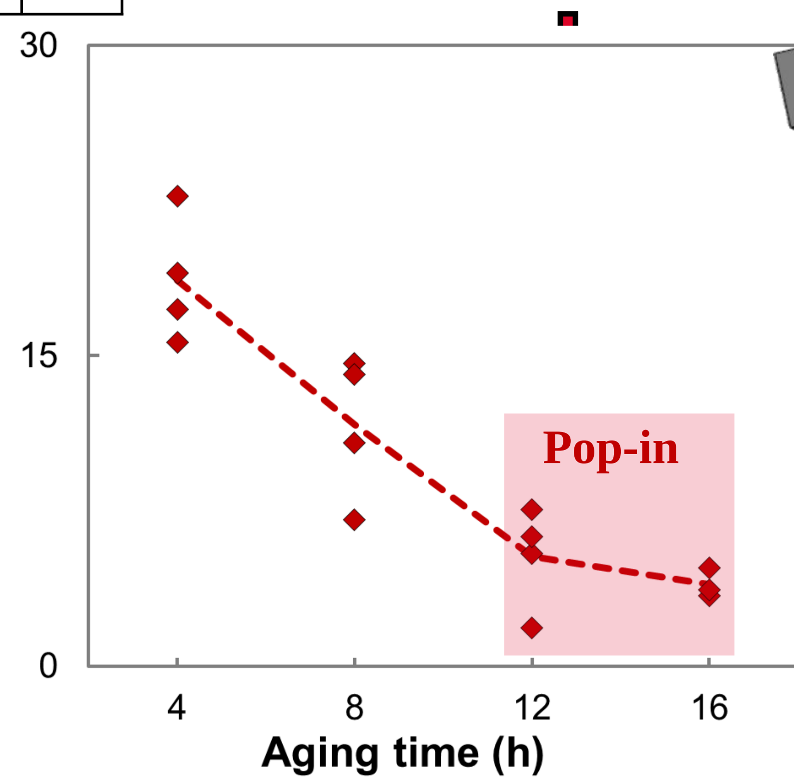
Aging time (h)			
4	8	12	16

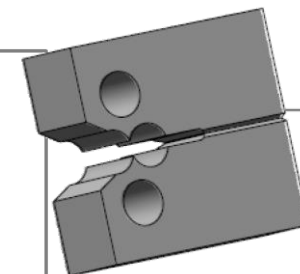
→ 4 metallurgical states

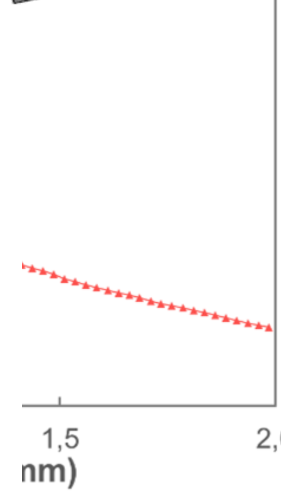
- Fracture toughness tests:



Crack growth toughness $\frac{dJ_{mat}}{da}$, also called "tearing modulus"







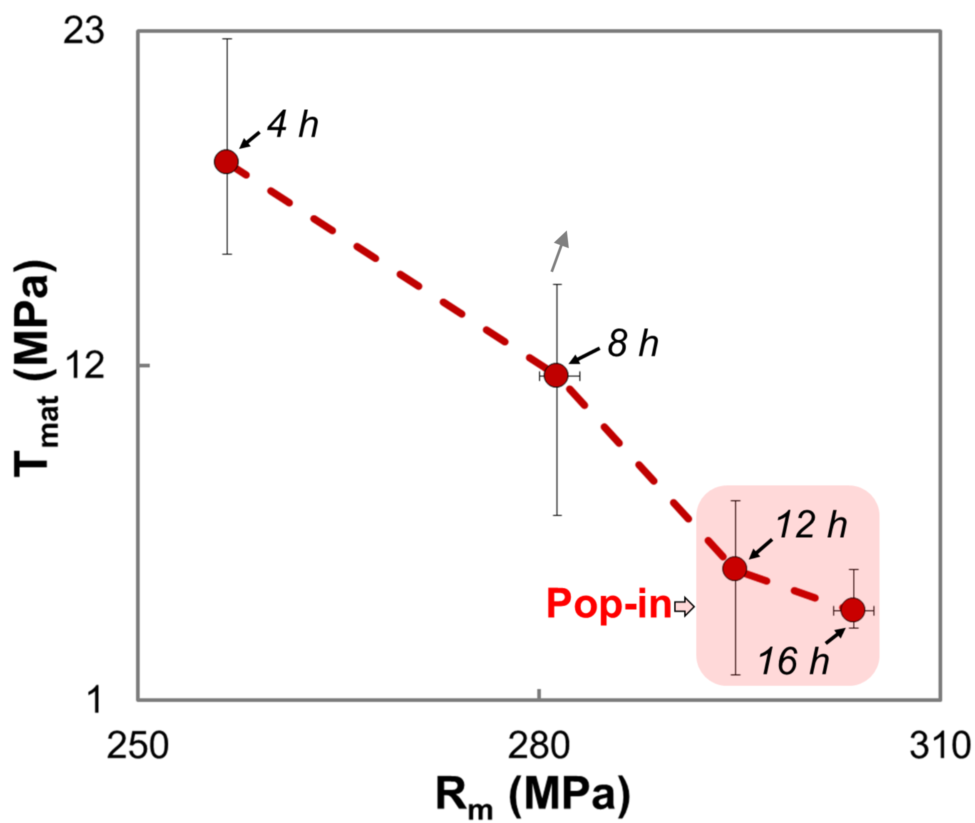
- **Pop-in appearance** after 12 and 16 h of aging time
- Decrease in **tearing modulus**

➡ Aluminium 6061-T6

➡ Age-hardened alloy →

Aging time (h)			
4	8	12	16

→ 4 metallurgical states



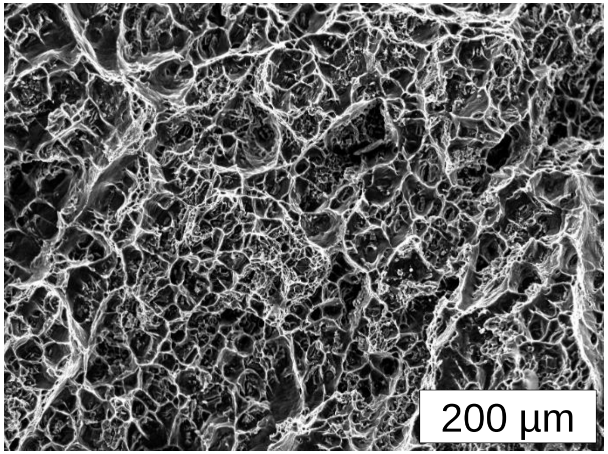
➡ Link between :

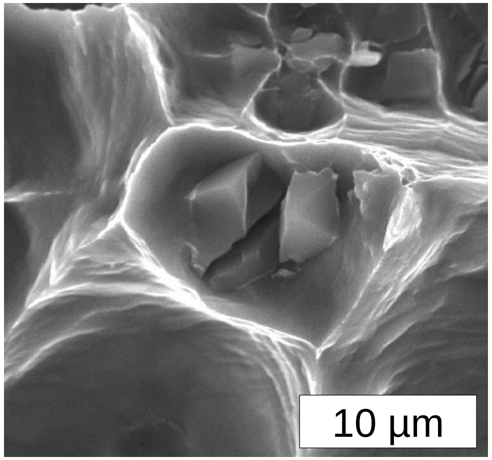
Low **strain hardening** ability
High **strength**
→ low **tearing modulus** → **pop-in**

➡ Fractography after fracture toughness tests:

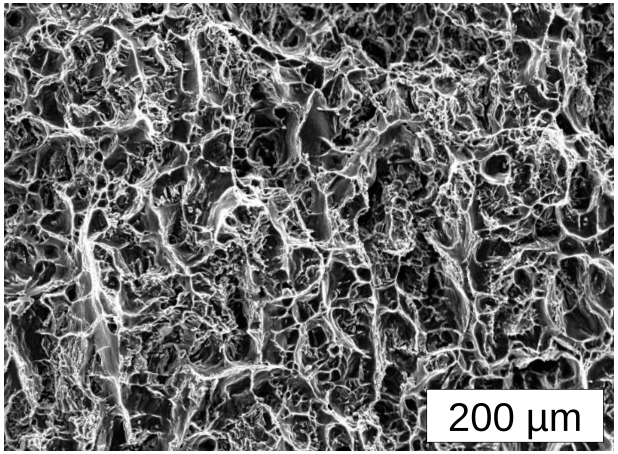
Scanning electron microscope

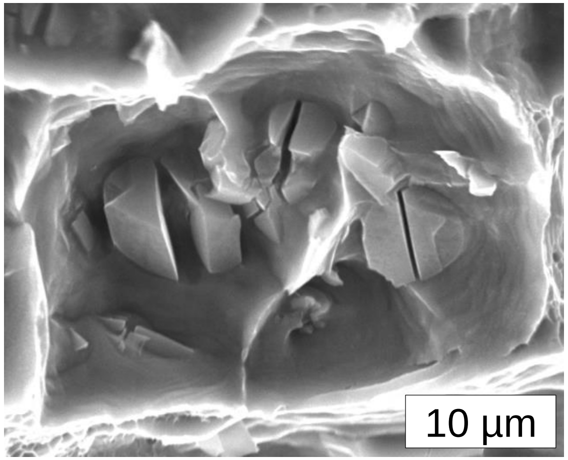
No pop-in *(aging: 4 h)*





With pop-in *(aging: 12 h)*

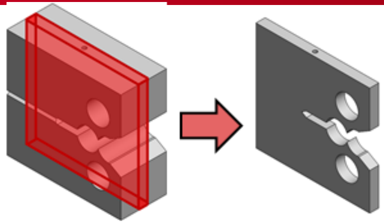




- **Ductile failure** micromechanisms
- Void growth to coalescence by **internal necking** (and void-sheeting) mechanisms
- Broken coarse **Mg_2Si** particles in dimples
- Nucleation controlled by **coarse precipitates** (Mg_2Si & IMF)

➡ **No difference in zone with and without pop-in**

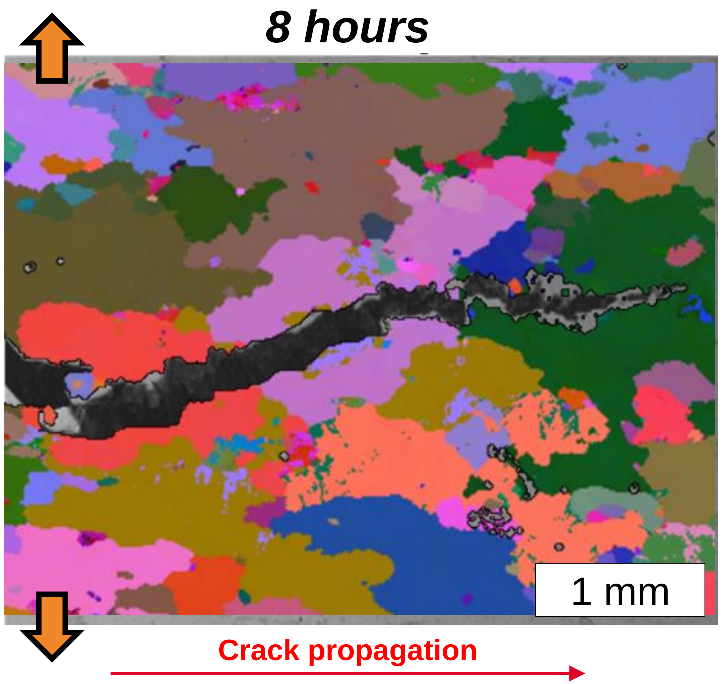
➡ Fracture mechanisms for an interrupted test:

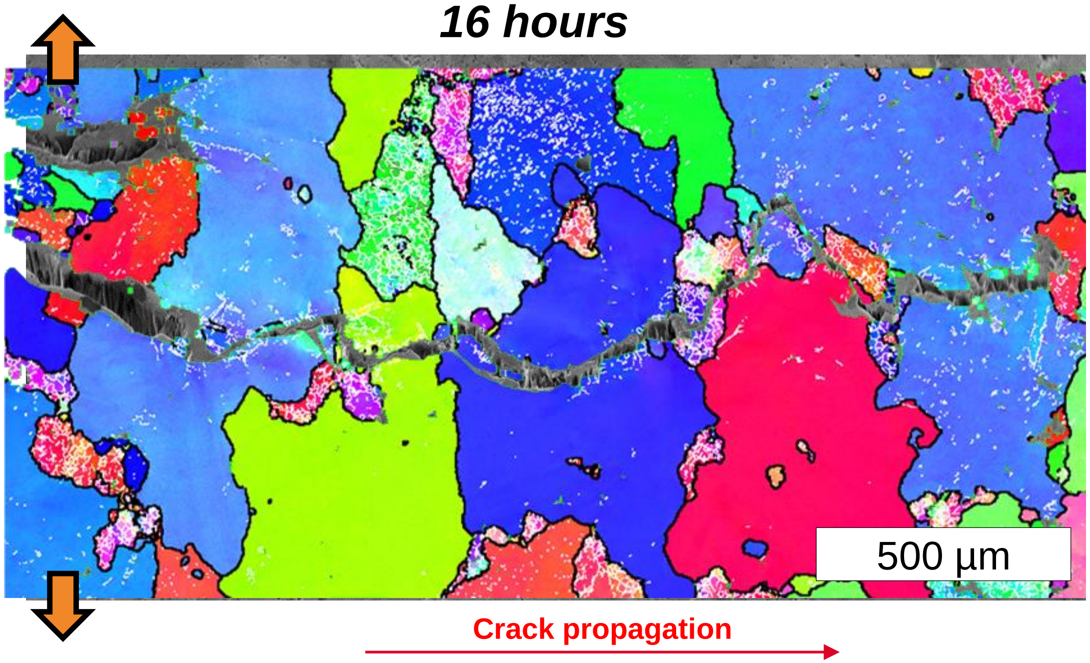


Scanning electron microscope

+

EBSD

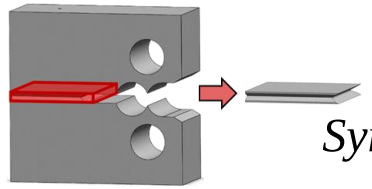




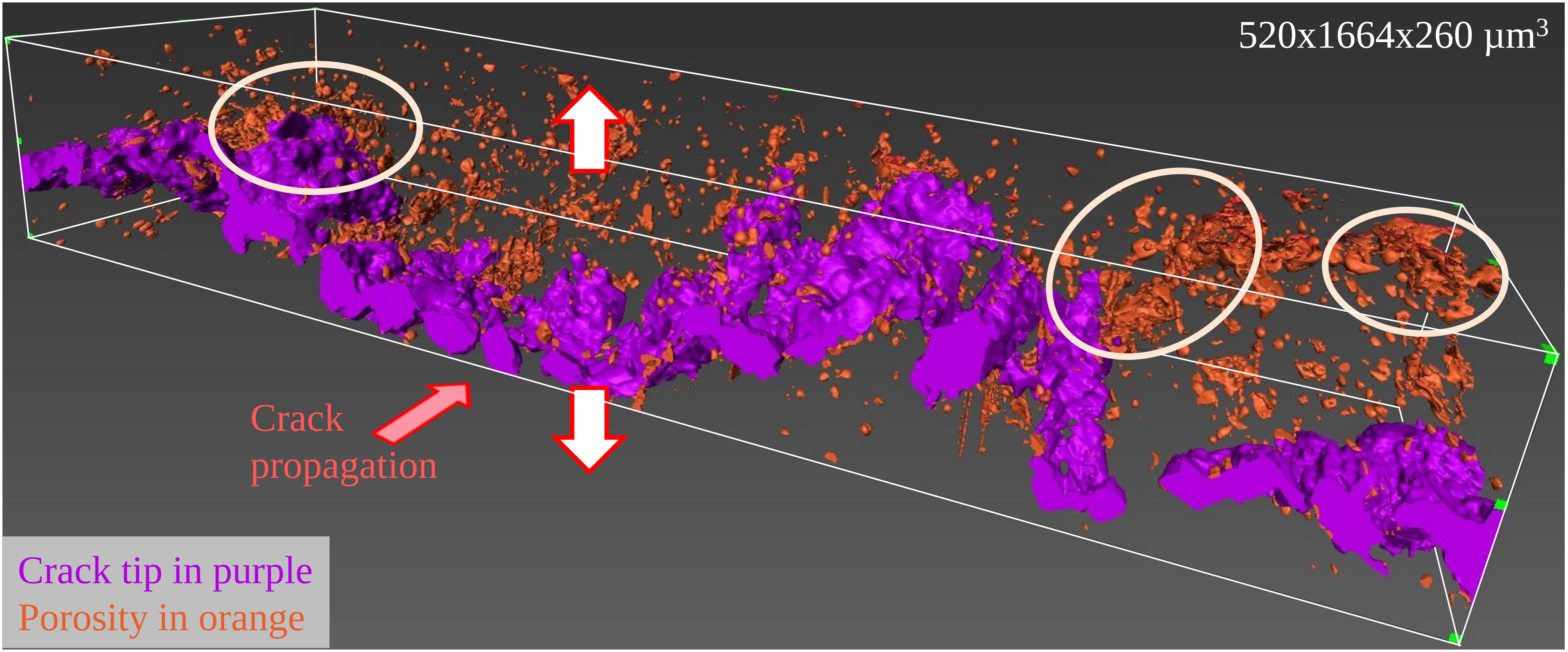
➡ No preferential localization of coarse particles → **transgranular fracture**

➡ **Intergranular** fracture only around the small grains

➡ Fracture mechanisms for an interrupted test:



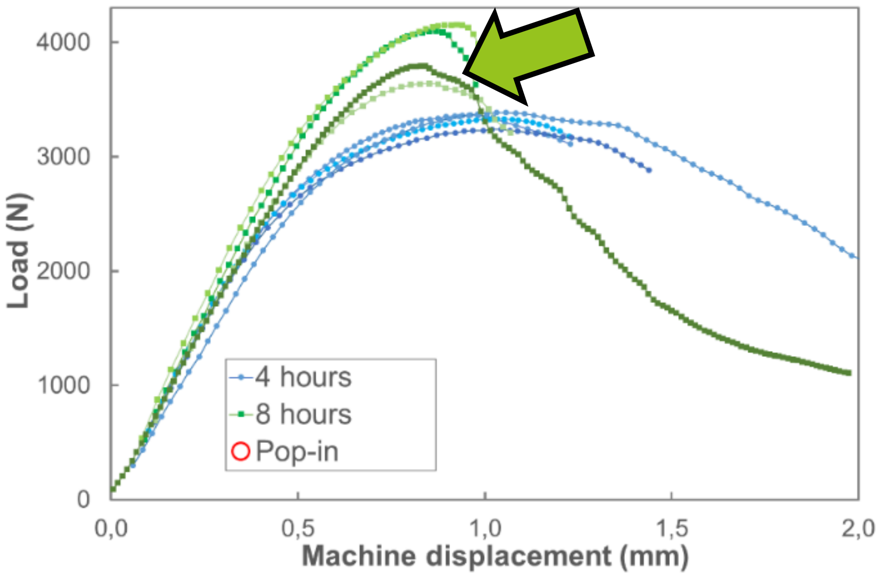
Tomography: Synchrotron X-laminography (ESRF, France)

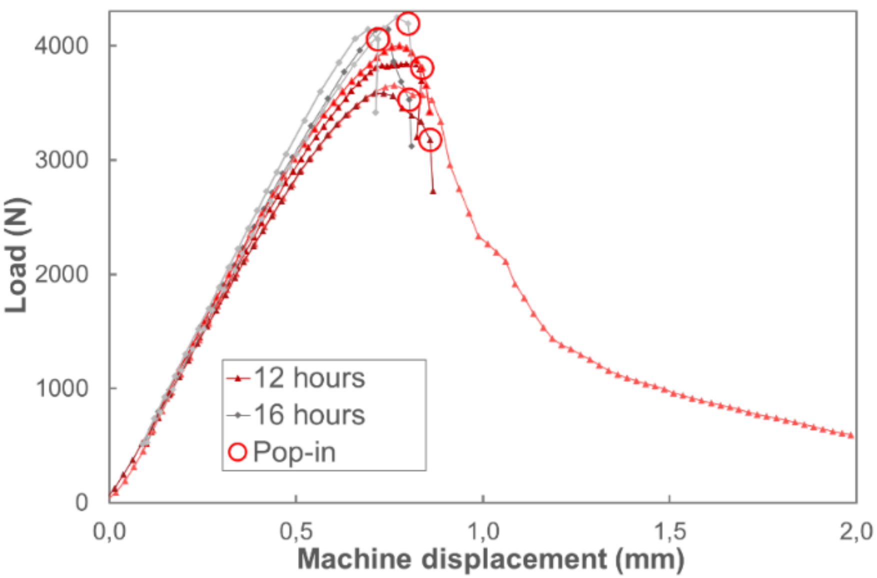


➡ **Ductile failure**, very rough crack surface

➡ Heterogeneous presence of large **clusters of porosity** at the crack tip

➡ **No difference in zone with and without pop-in**





- New tests after 8 h
- **No pop-in in previous tests**
- Try to **create pop-in** by **reducing the system stiffness**

Low **strain hardening** ability

↔

Low **tearing modulus**

↔

Pop-in

System

Machine stiffness

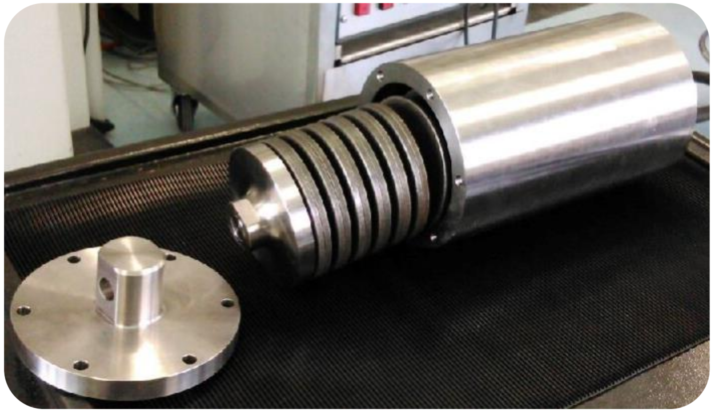
Aluminium Al-Mg-Si (6061)

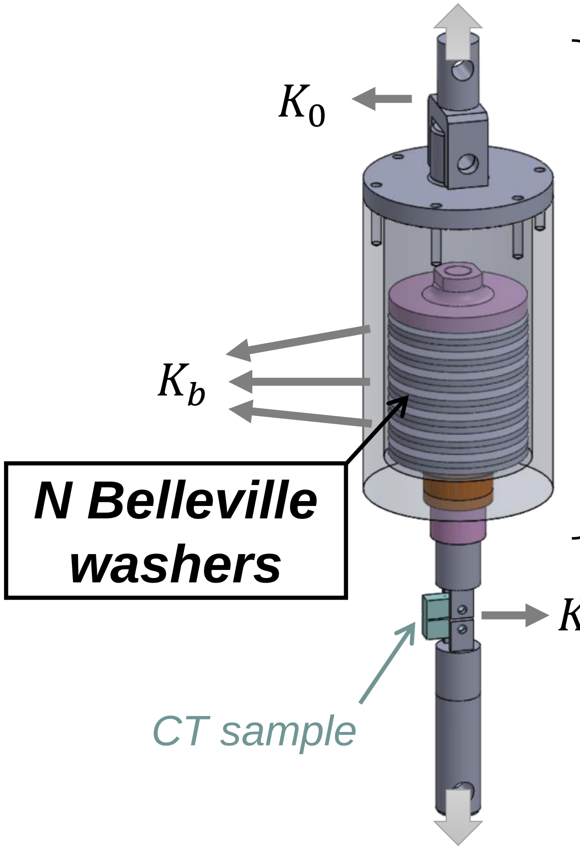
Crack growth toughness

POP-IN ?

➡ Design of an dedicated assembly (titanium alloy)

➡ Use of **belleville washers**, to increase the compliance



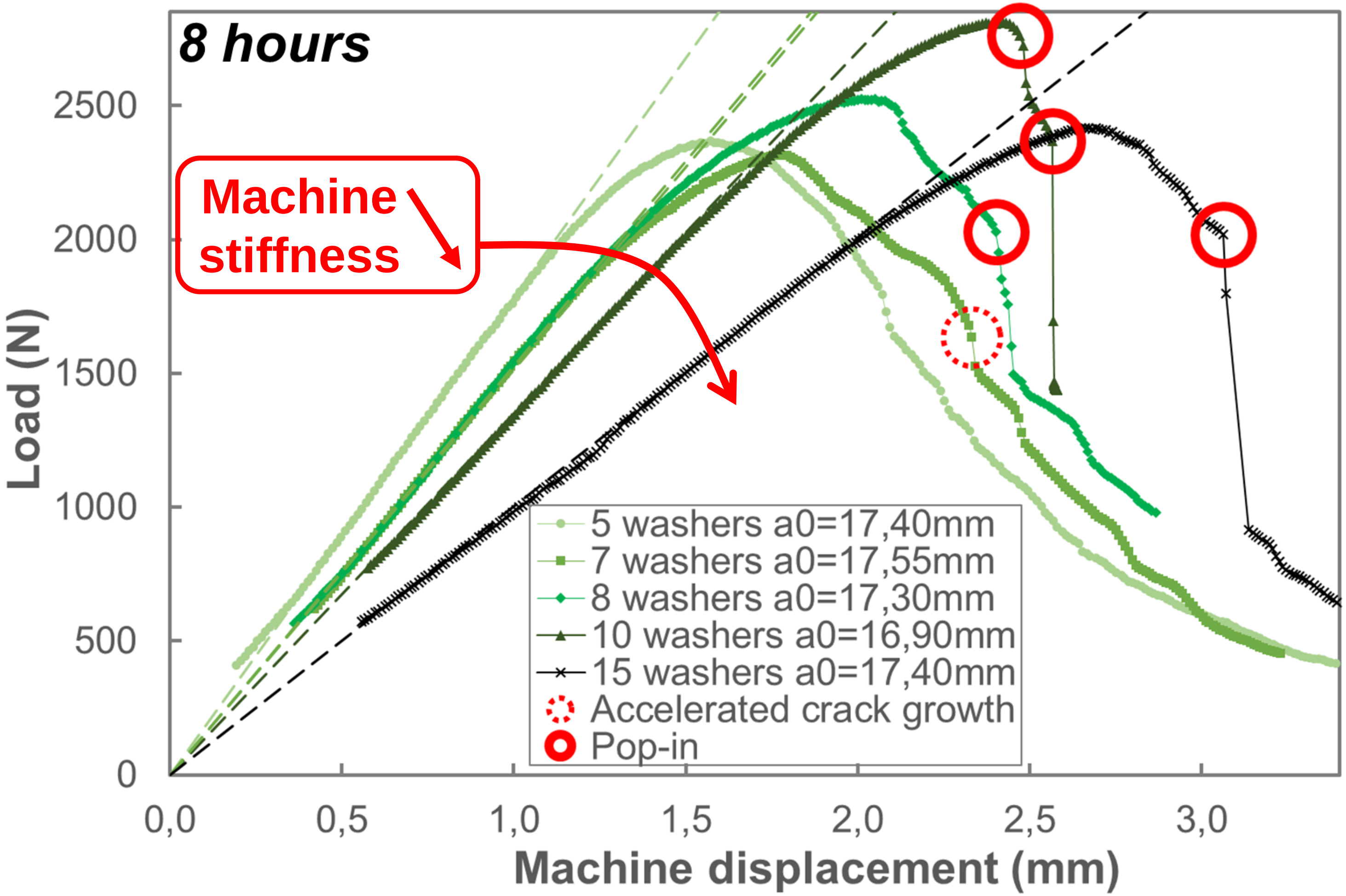


$K_{t},$

$$K_m(N) = \frac{K_0 K_b}{N K_0 + K_b}$$

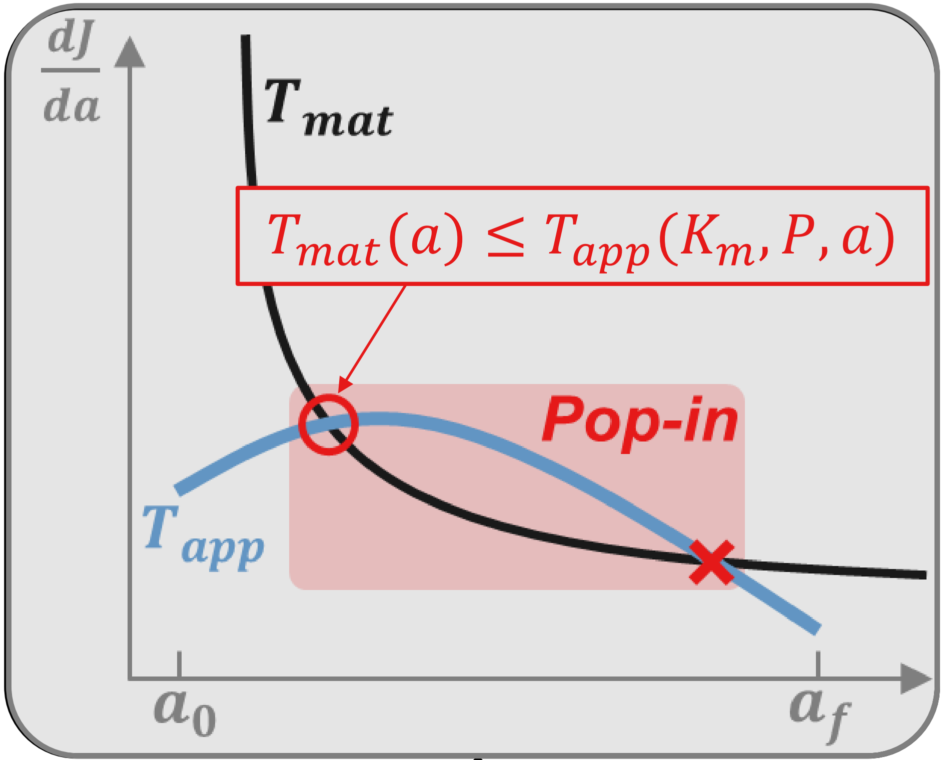
$$\boxed{K_t(N,a) = \frac{K_m(N) K_s(a)}{K_m(N) + K_s(a)}}$$

➡ 5 tests after 8 hours with **5, 7, 8, 10 and 15 washers**



Number of washers ↗ ➡ Stiffness ↘ ➡ Pop-in & amplitude ↗

J-integral approach



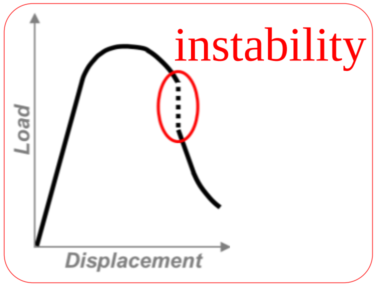
Load-displacement approach

?

Instability criteria ?

Number of washers ↗ ➡ Stiffness ↘ ➡ Pop-in & amplitude ↗

➡ *Load-displacement approach ?*



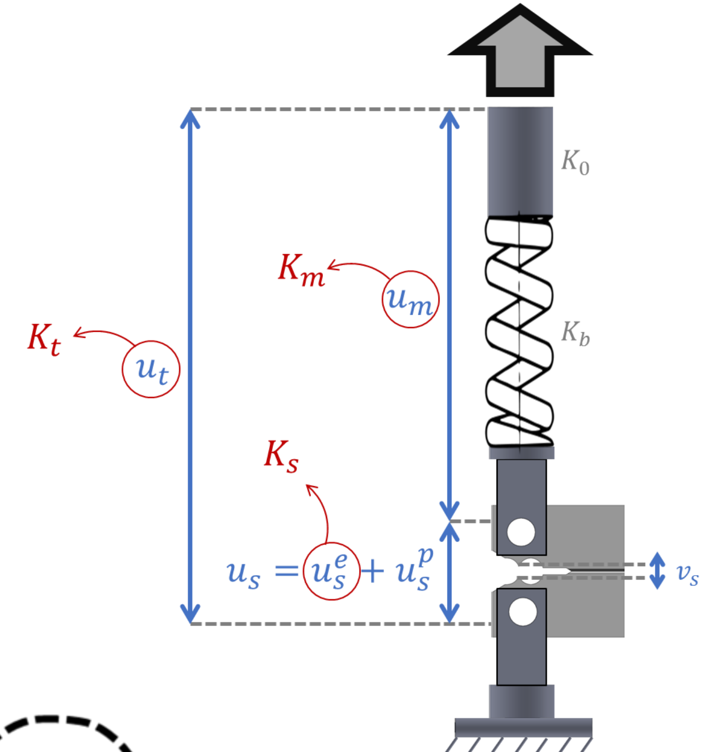
$$u_t = u_m + u_s$$

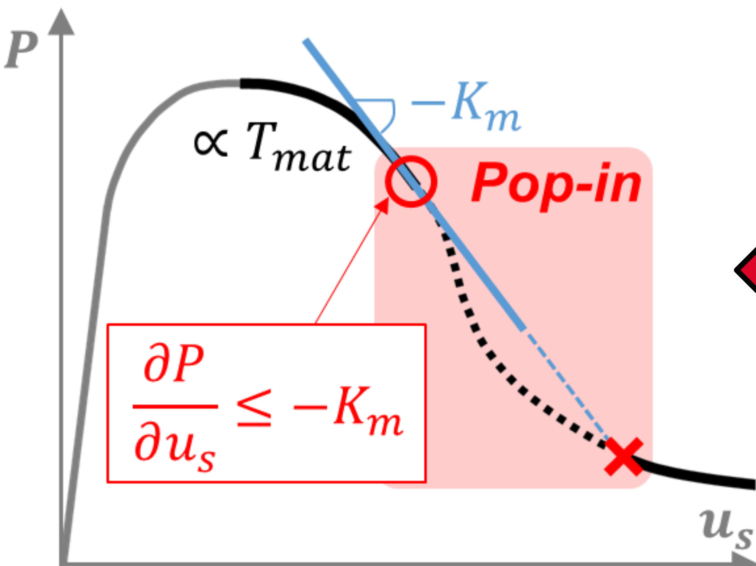
$$\delta u_t = 0 = \frac{\delta P}{K_m} + \partial u_s$$

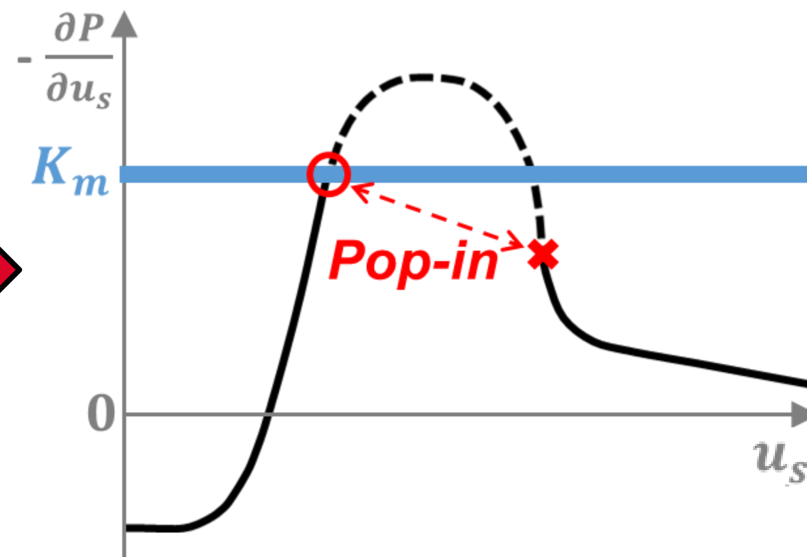
$$\boxed{\frac{dP}{du_s} \leq -K_m}$$

Material

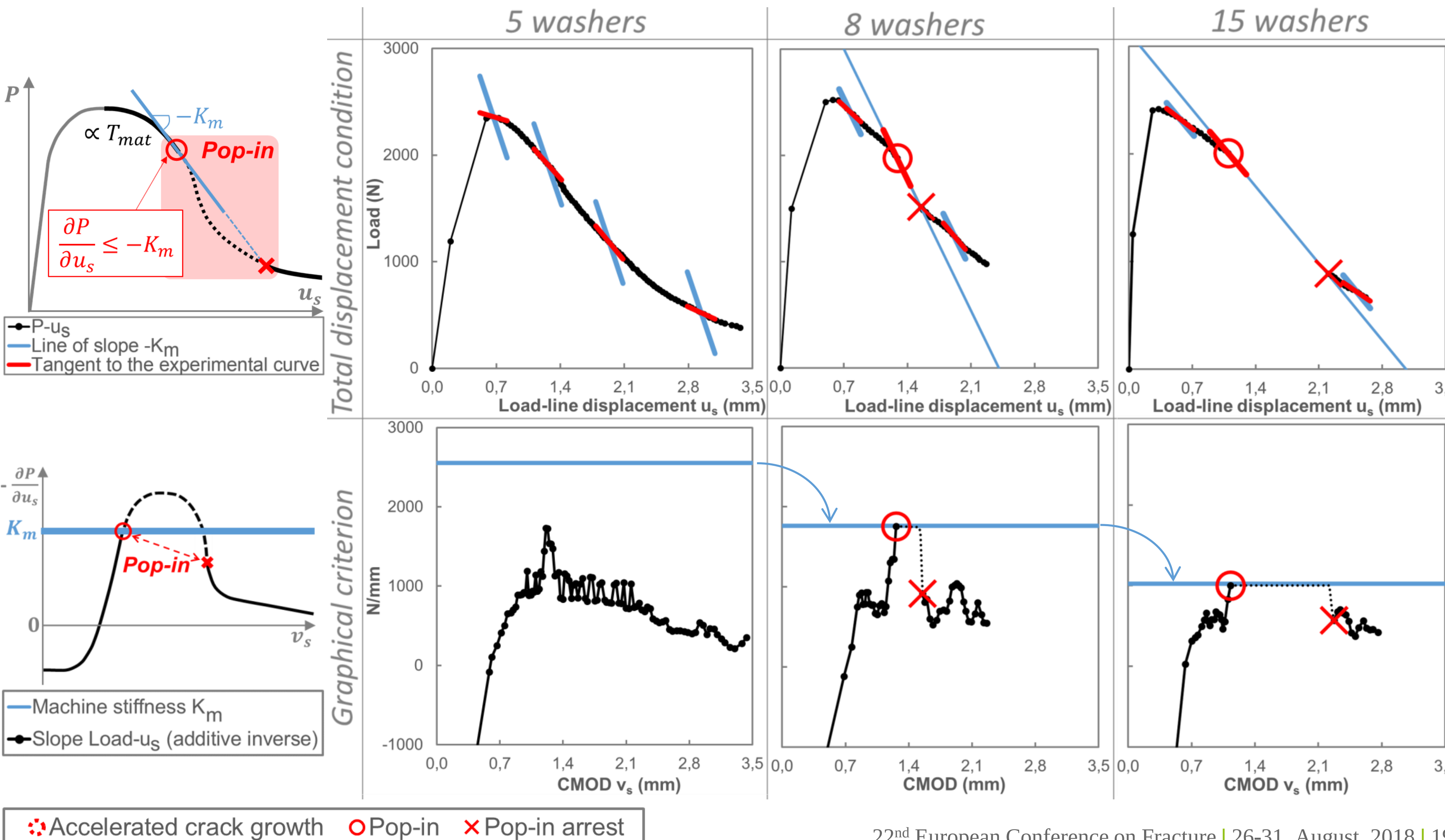
Loading



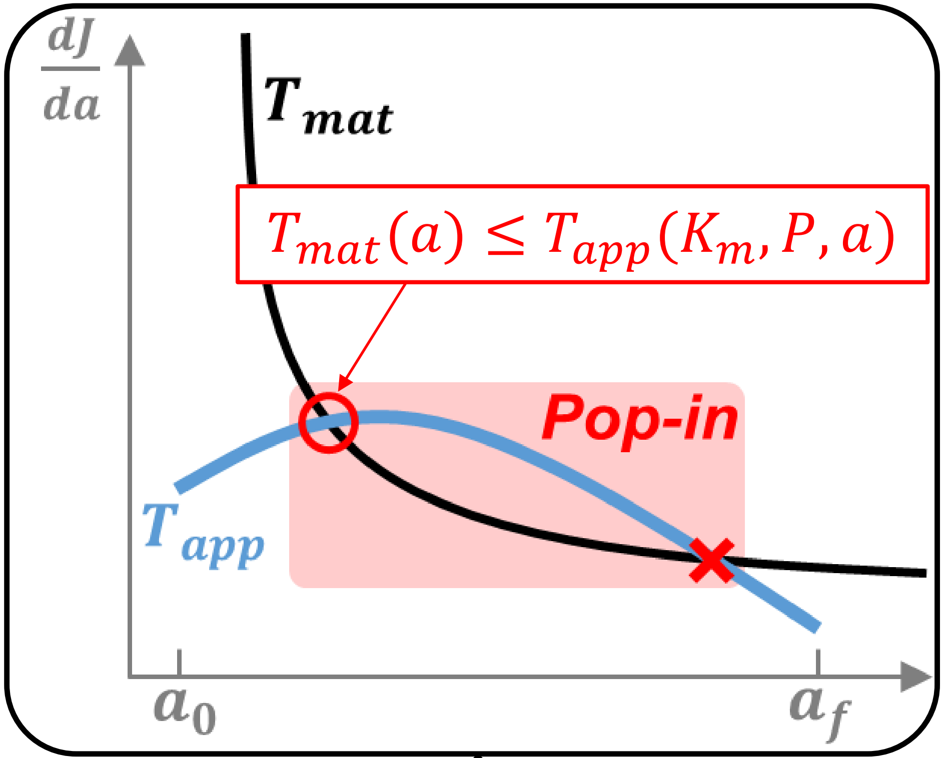




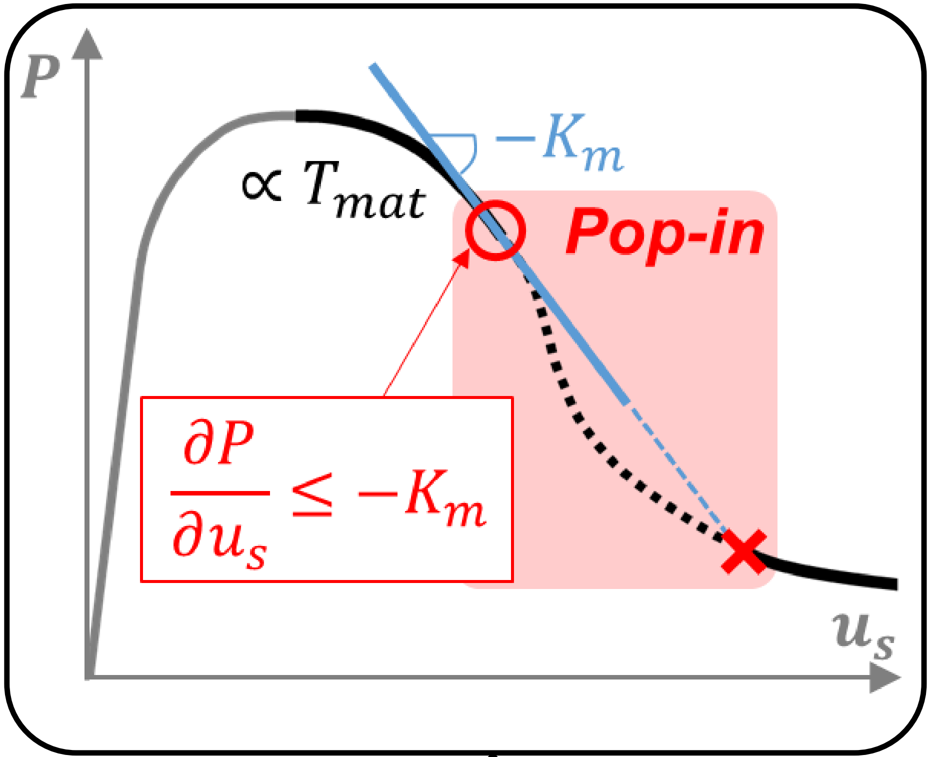
Load-displacement approach ?



J-integral approach



Load-displacement approach



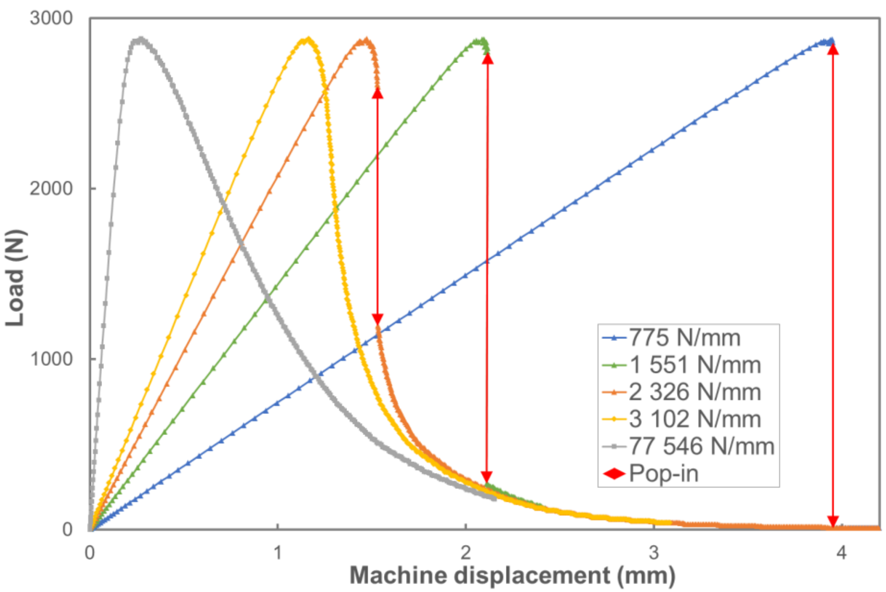
Instability criteria ?

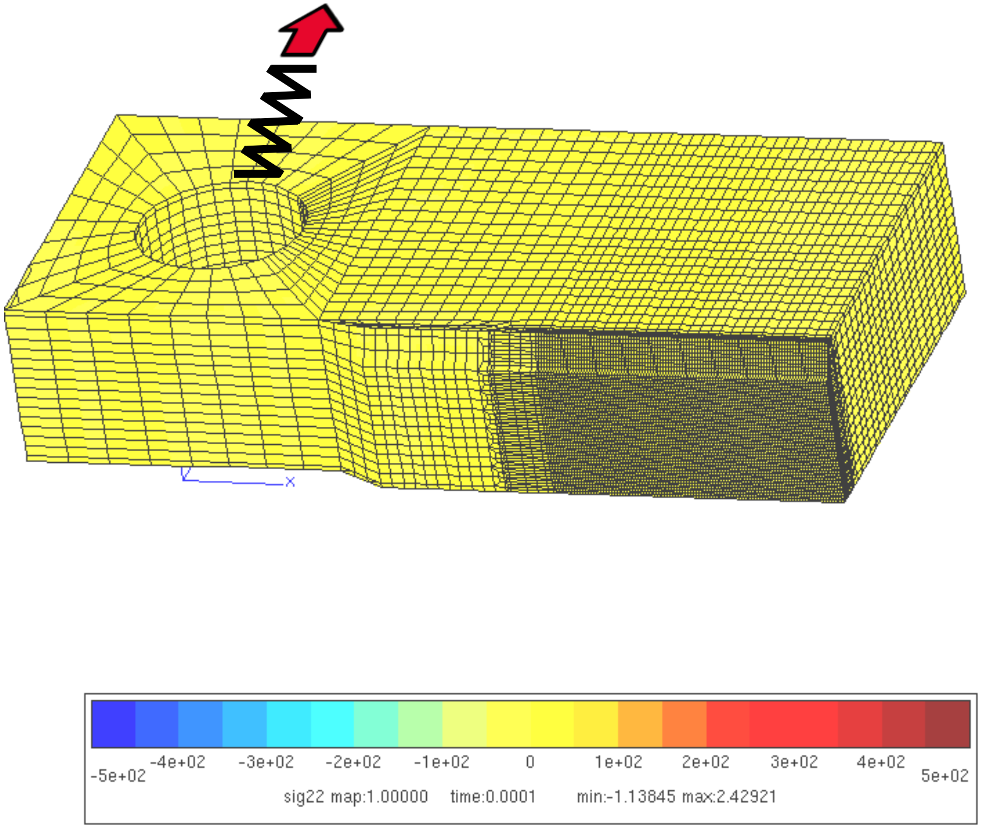
Number of washers ↗ ➡ Stiffness ↘ ➡ Pop-in & amplitude ↗

➡ Conclusions :

- Pop-ins studied are purely **mechanical** crack growth instabilities
- Result from the interaction of the **material behavior** (favored by a decrease of tearing modulus) and **imposed loading** (favored by a high compliance of the total system)
- **System stiffness** ⟺ **Crack growth toughness**
  POP-IN
- **2 instability criteria** ➡ **Excellent agreement** between the predictions of the criterion and the tests

- Finite-element simulation
- Gurson law (with strain- and stress-dependant nucleation)
- Arc-Length method (Riks, 1979)





➡ **Spring creates numerical pop-in**

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THANK YOU FOR YOUR ATTENTION!

Thanks to K. Colas, B. Kapusta, B. Tanguy (CEA)
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C. Varenne (Mines Paristech)

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