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Impact of machine stiffness and heat treatments on crack propagation instabilities in an Al-Mg-Si alloy

T. Petit, C. Ritter, Jacques Besson, Thilo F. Morgeneyer

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22ND EUROPEAN
CONFERENCE ON FRACTURE

LOADING AND ENVIRONMENT
EFFECTS ON STRUCTURAL INTEGRITY



DE LA RECHERCHE À L'INDUSTRIE



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

T. PETIT

C. RITTER, J. BESSON, T. F. MORGENEYER



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BELGRADE | TUESDAY, AUGUST 28TH 2018

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*LOADING AND ENVIRONMENT
EFFECTS ON STRUCTURAL INTEGRITY*



DE LA RECHERCHE À L'INDUSTRIE

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DEFINITION

EXPERIMENTAL INVESTIGATIONS

INSTABILITY CRITERIA

BELGRADE | TUESDAY, AUGUST 28TH 2018

DEFINITION →

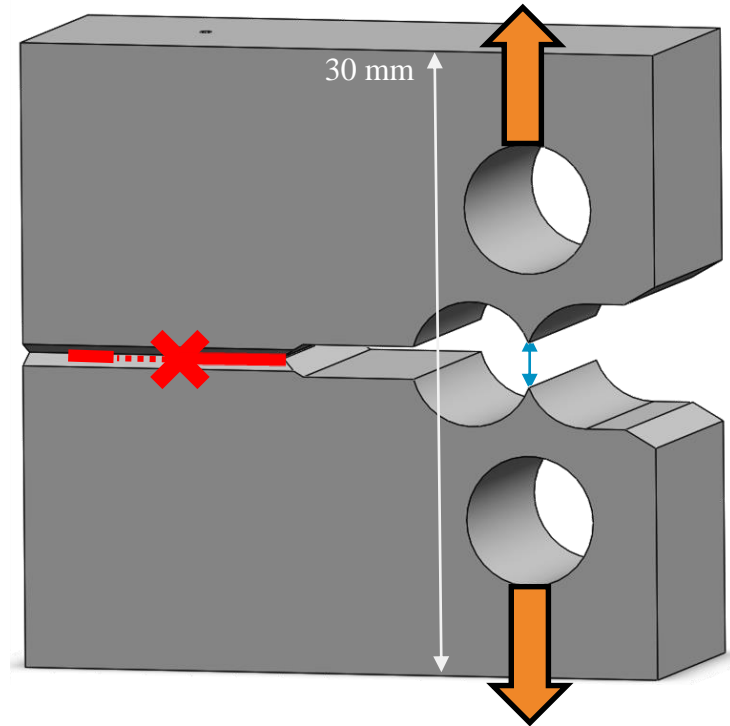
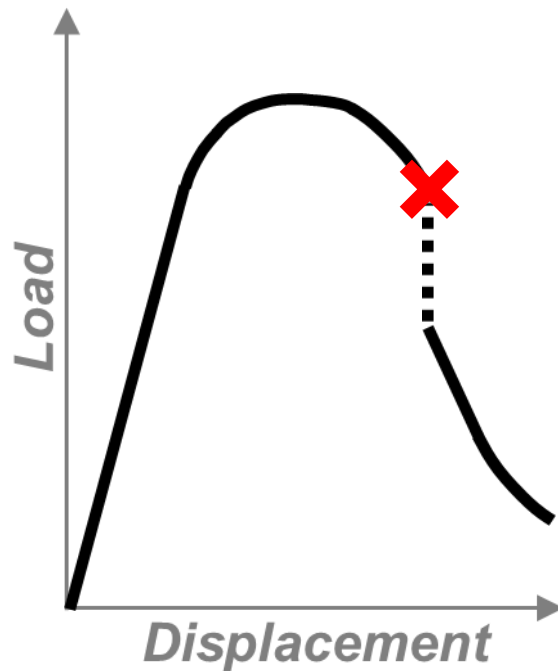
EXPERIMENTAL INVESTIGATIONS

- Mechanical properties
- Fracture mechanisms
- Machine stiffness

INSTABILITY CRITERIA

⇒ Fracture toughness tests

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



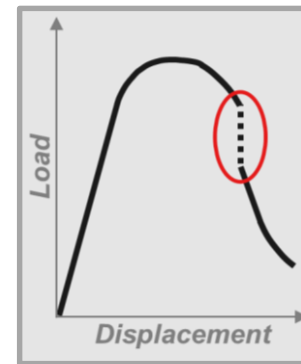
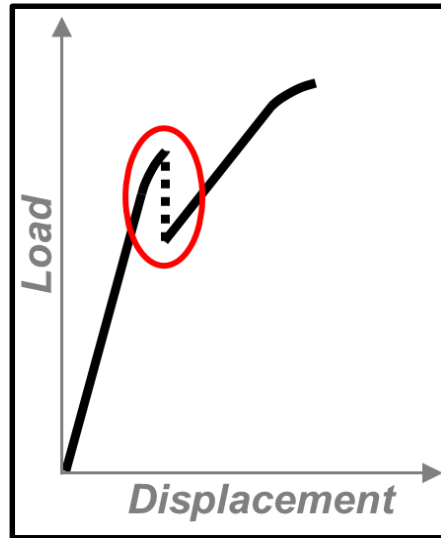
DEFINITION →

EXPERIMENTAL
INVESTIGATIONS

→ Mechanical properties
→ Fracture mechanisms
→ Machine stiffness

INSTABILITY
CRITERIA

- ⇒ 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

DEFINITION →

EXPERIMENTAL INVESTIGATIONS

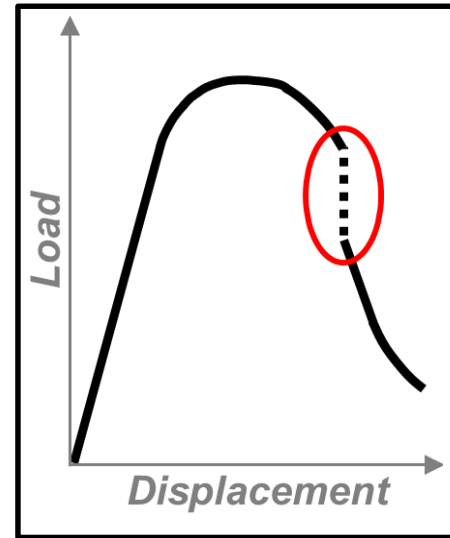
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INSTABILITY CRITERIA

- ⇒ 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?

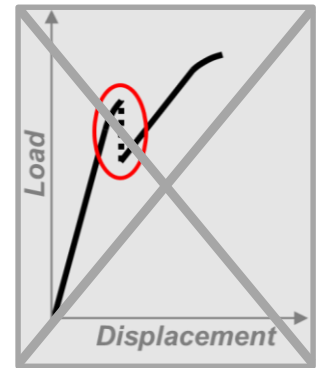
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EXPERIMENTAL INVESTIGATIONS

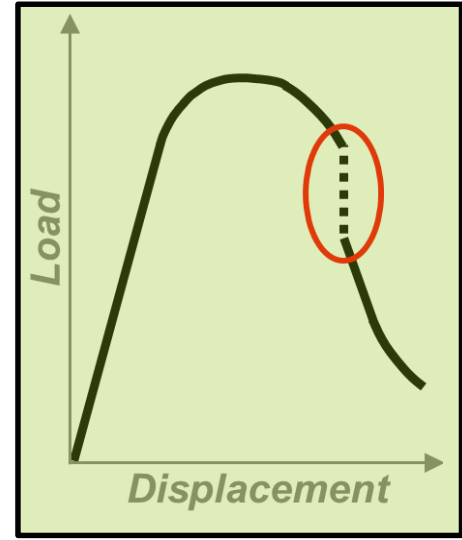
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- Fracture mechanisms
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→ **INSTABILITY CRITERIA**

- ⇒ 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
Machine stiffness

Aluminium Al-Mg-Si (6061)
Crack growth toughness



DEFINITION →

EXPERIMENTAL INVESTIGATIONS

- Mechanical properties
- Fracture mechanisms
- Machine stiffness

→ INSTABILITY CRITERIA

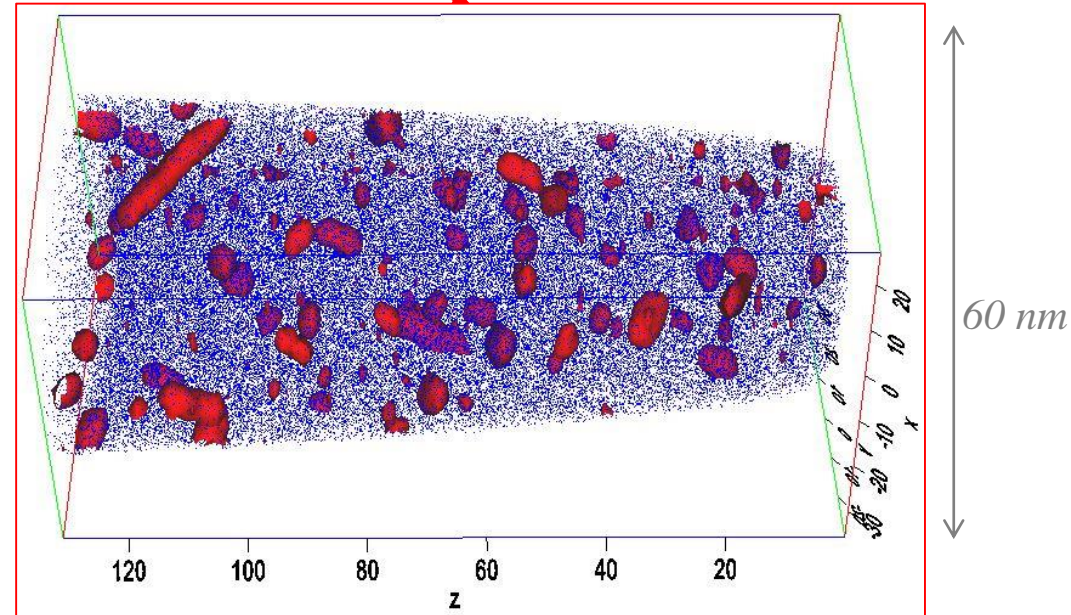
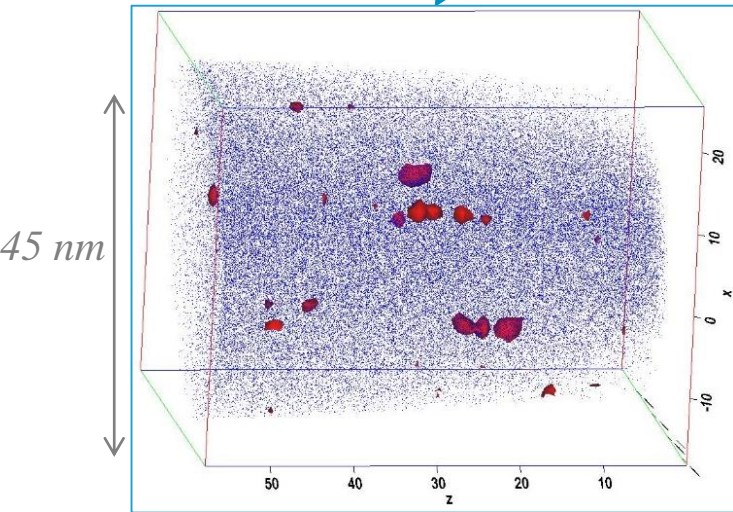
→ Aluminium 6061-T6

→ Age-hardened alloy →

Aging time (h)			
4	8	12	16

→ 4 metallurgical states

→ Atom Probe Tomography:



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



DEFINITION →

EXPERIMENTAL INVESTIGATIONS

- Mechanical properties
- Fracture mechanisms
- Machine stiffness

INSTABILITY CRITERIA

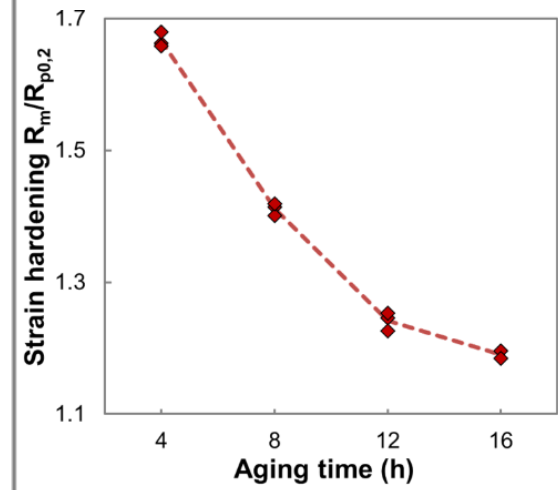
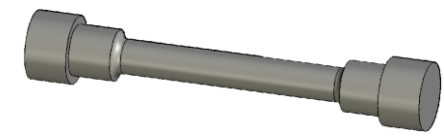
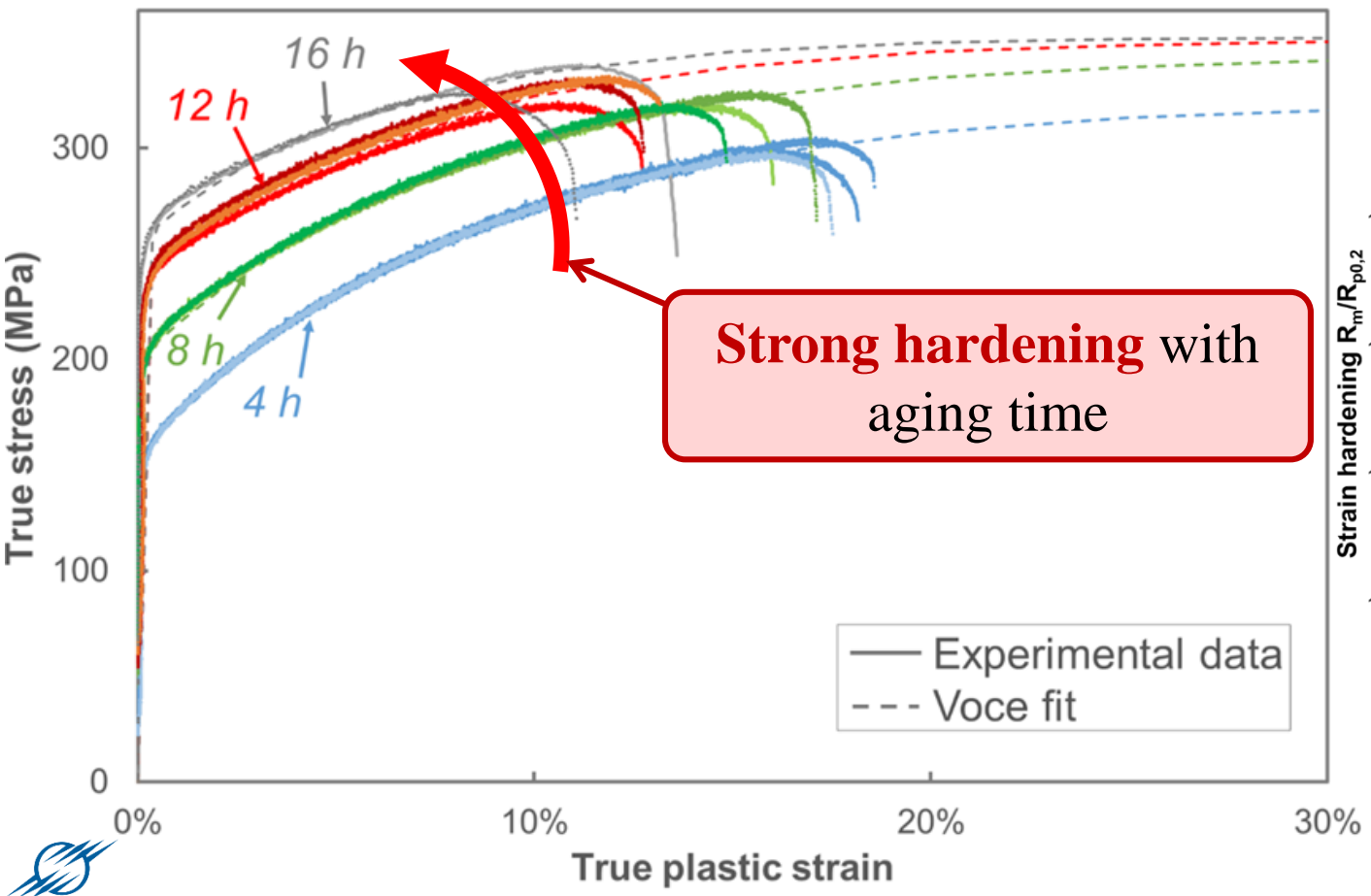
→ Aluminium 6061-T6

→ Age-hardened alloy →

Aging time (h)			
4	8	12	16

→ 4 metallurgical states

→ Tensile tests:





DEFINITION →

EXPERIMENTAL INVESTIGATIONS

- Mechanical properties
- Fracture mechanisms
- Machine stiffness

INSTABILITY CRITERIA

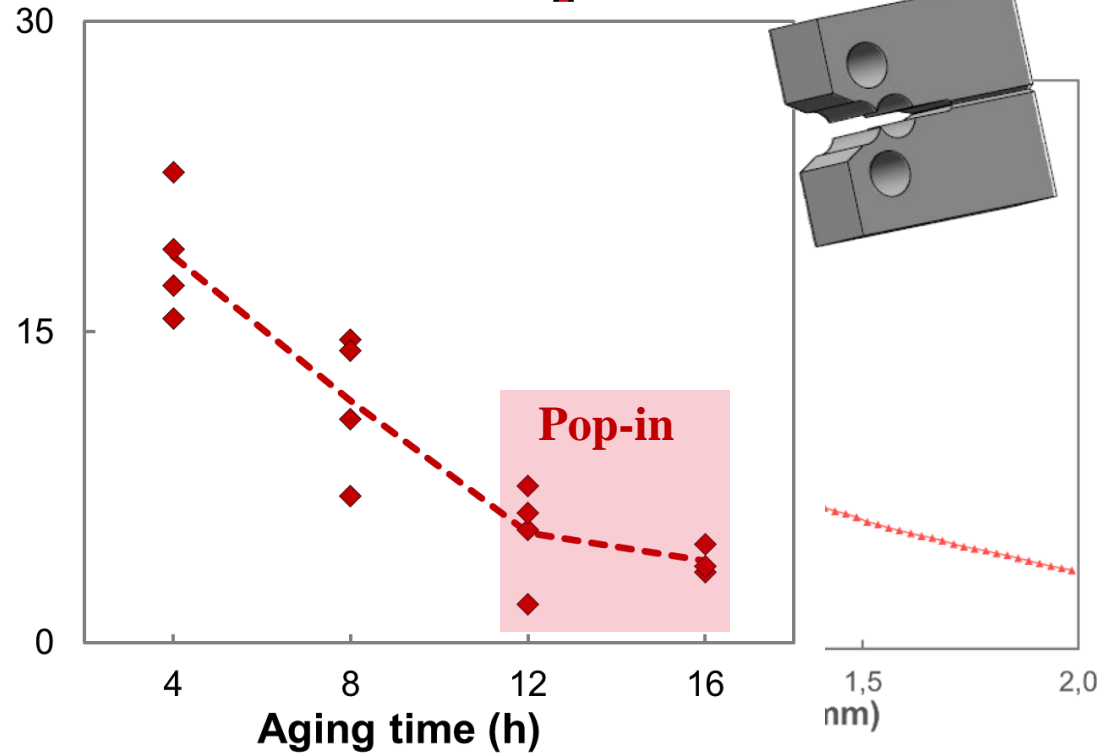
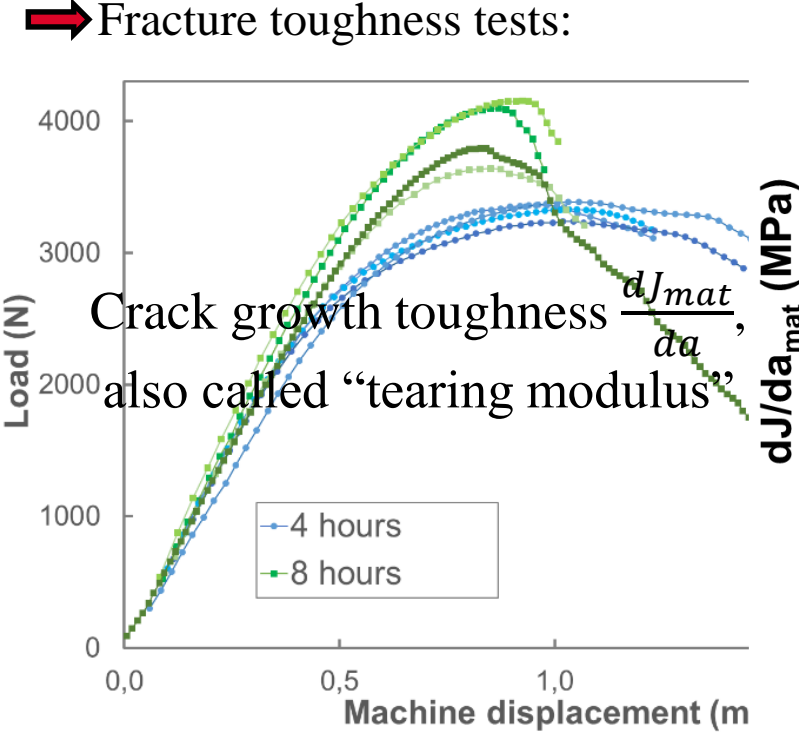
→ Aluminium 6061-T6

→ Age-hardened alloy →

Aging time (h)			
4	8	12	16

→ 4 metallurgical states

→ Fracture toughness tests:



→ **Pop-in appearance** after 12 and 16 h of aging time

→ **Decrease in tearing modulus**

DEFINITION →

EXPERIMENTAL INVESTIGATIONS

- Mechanical properties
- Fracture mechanisms
- Machine stiffness

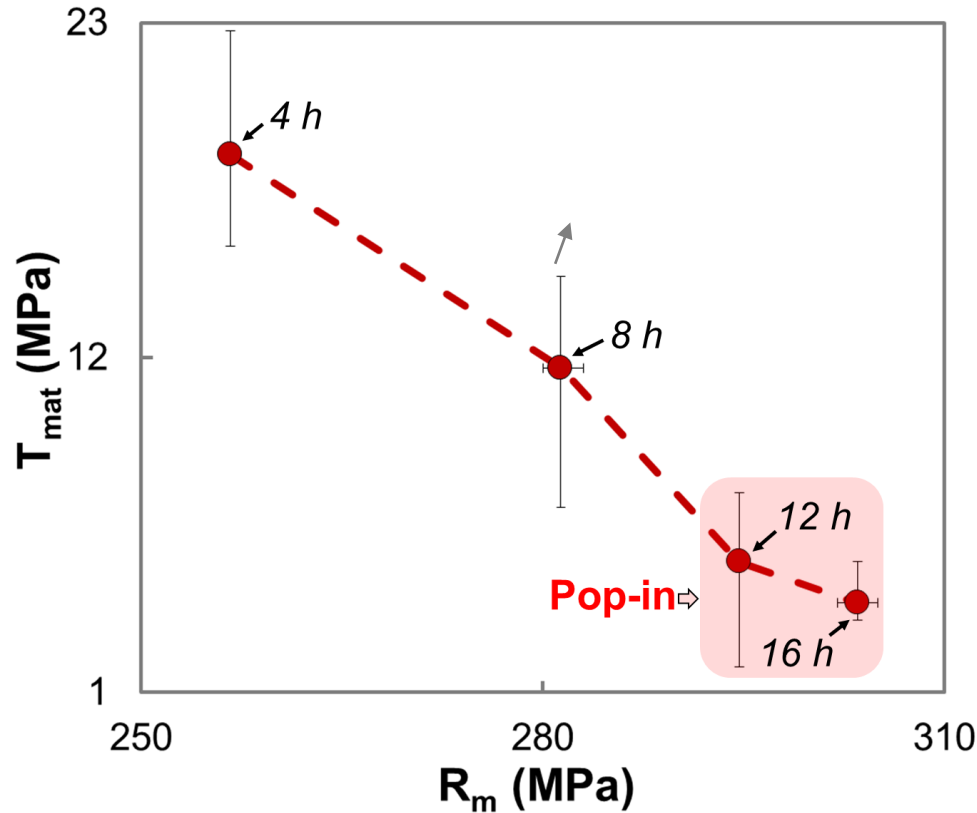
INSTABILITY CRITERIA

→ Aluminium 6061-T6

→ Age-hardened alloy →

Aging time (h)			
4	8	12	16

→ 4 metallurgical states



→ Link between :

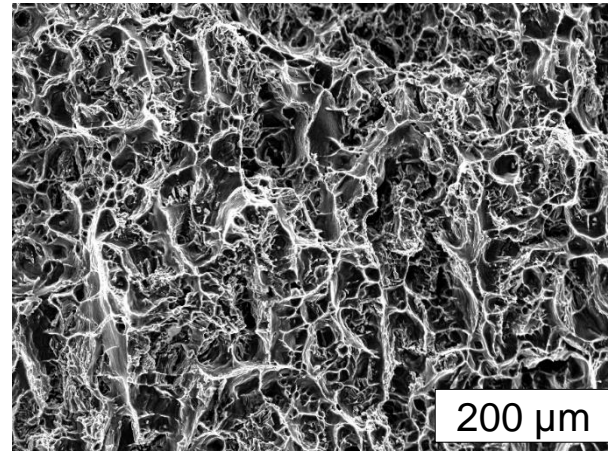
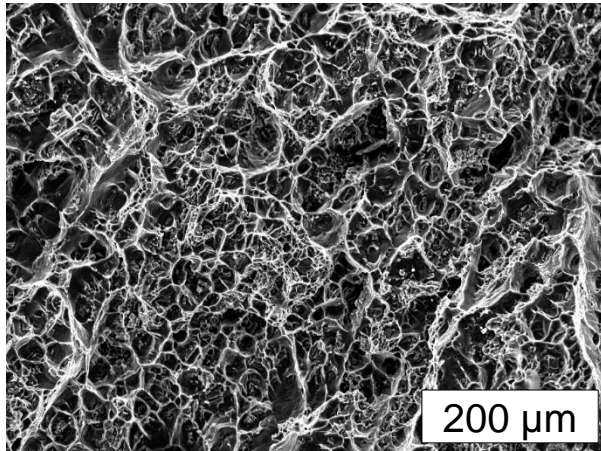
Low **strain hardening** ability | High **strength** → low **tearing modulus** → **pop-in**

→ Fractography after fracture toughness tests:

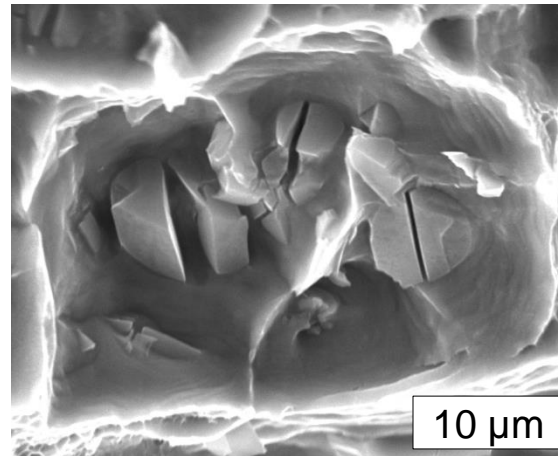
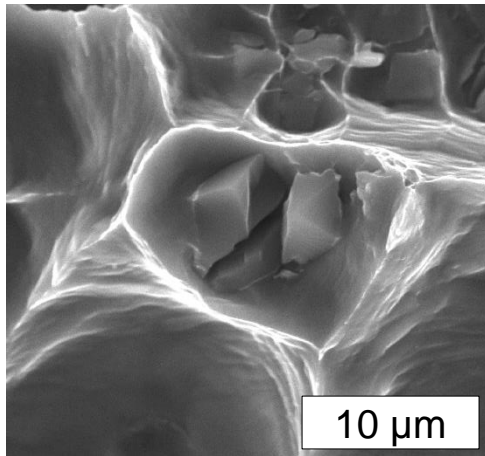
No pop-in (aging: 4 h)

With pop-in (aging: 12 h)

Scanning electron microscope



- 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

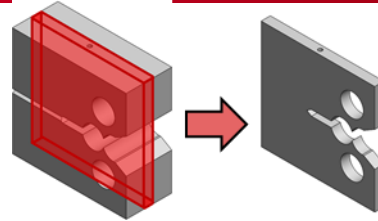
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EXPERIMENTAL INVESTIGATIONS

- Mechanical properties
- Fracture mechanisms
- Machine stiffness

INSTABILITY CRITERIA

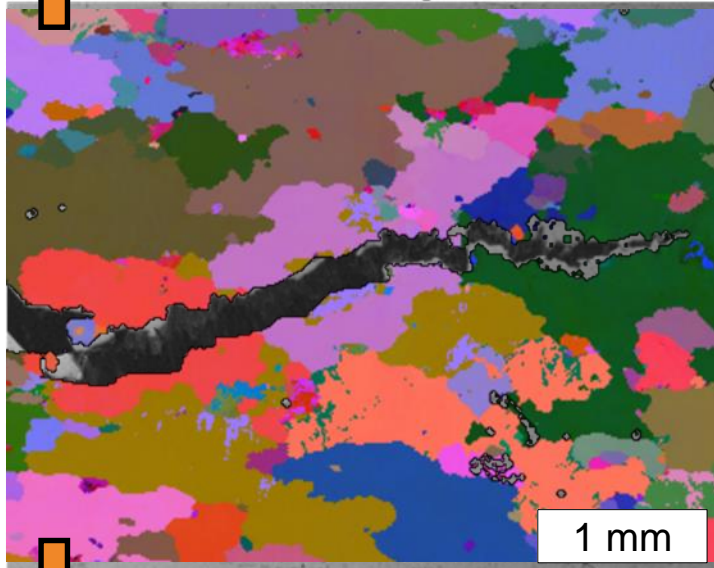
→ Fracture mechanisms for an interrupted test:



Scanning electron microscope

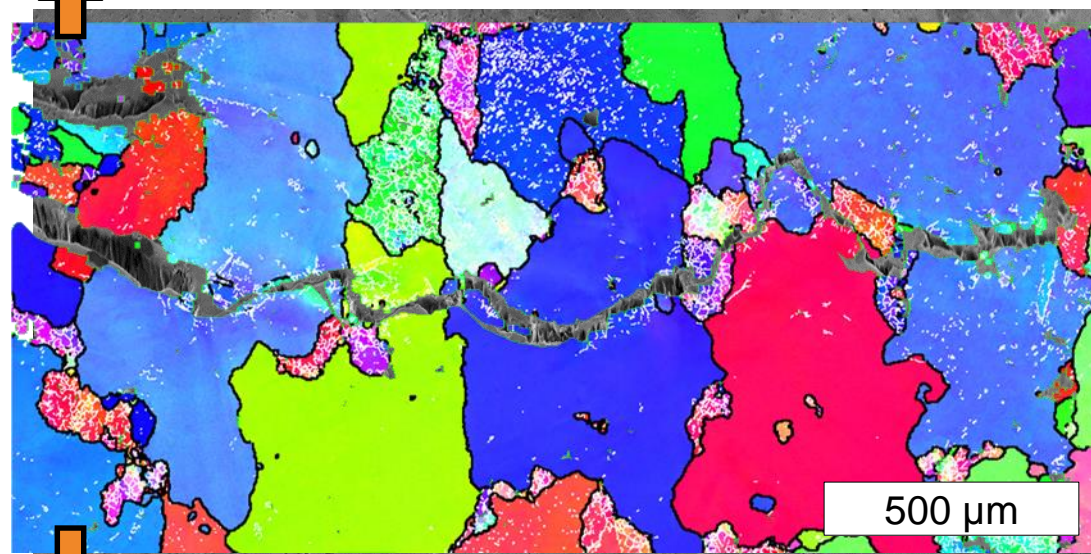
+
EBSD

8 hours



Crack propagation

16 hours



Crack propagation

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

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

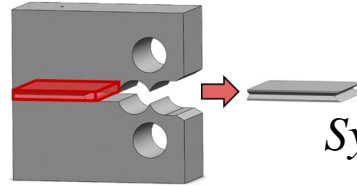
DEFINITION →

EXPERIMENTAL INVESTIGATIONS

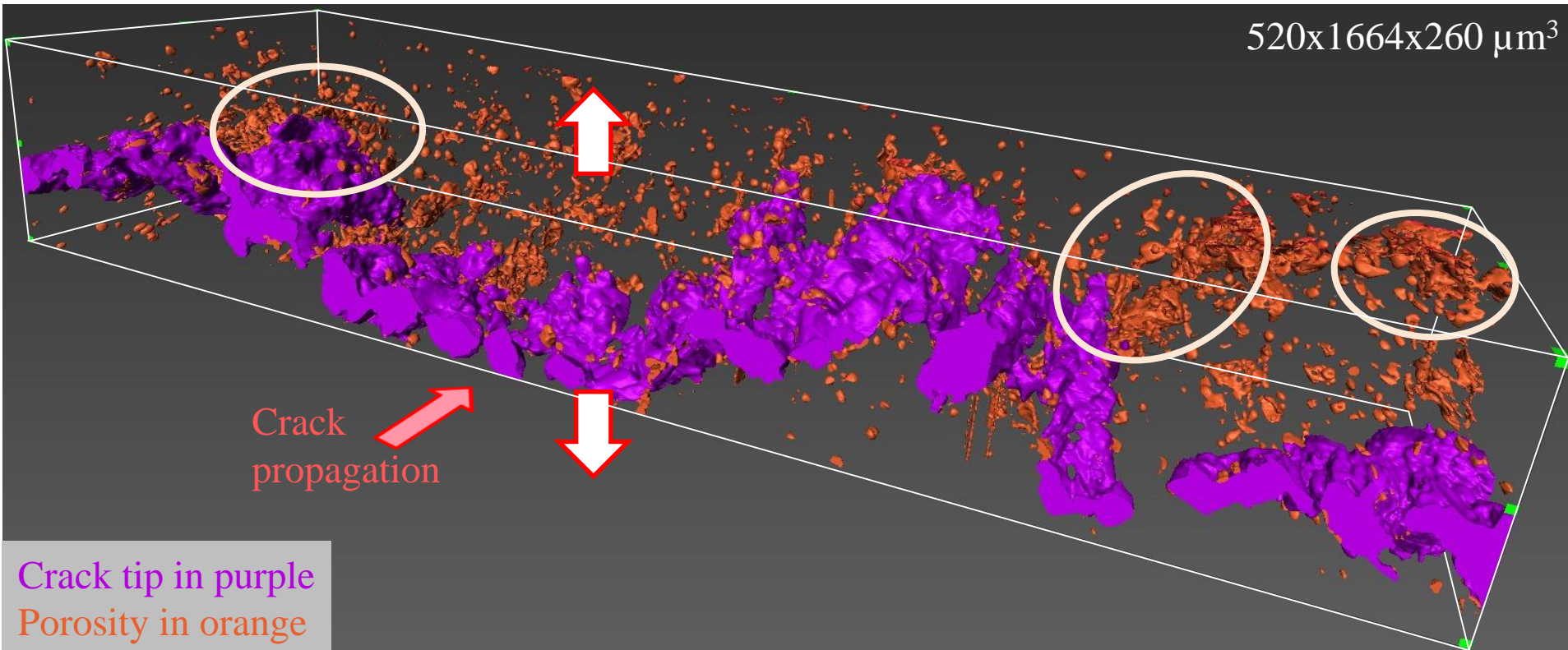
- Mechanical properties
- Fracture mechanisms
- Machine stiffness

INSTABILITY CRITERIA

→ Fracture mechanisms for an interrupted test:



Tomography:
Synchrotron X-laminography (ESRF, France)



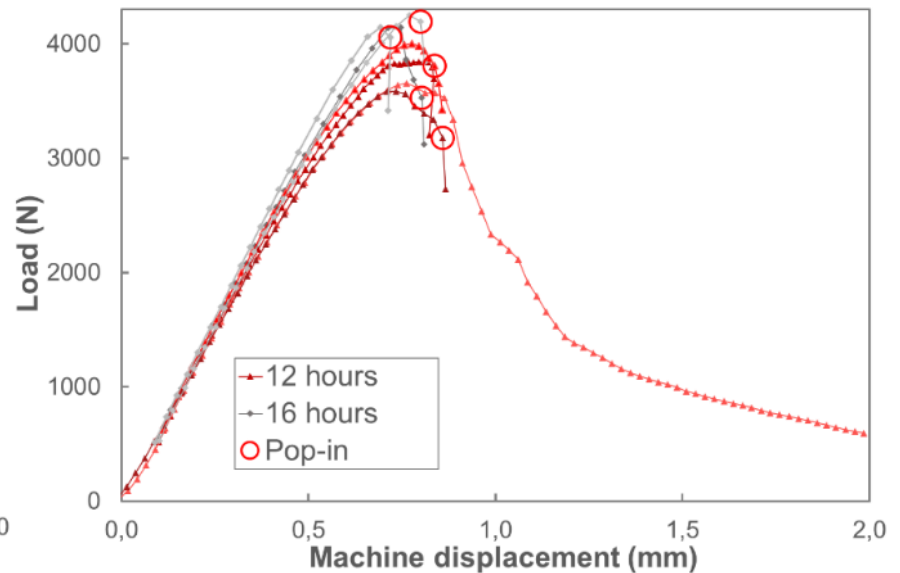
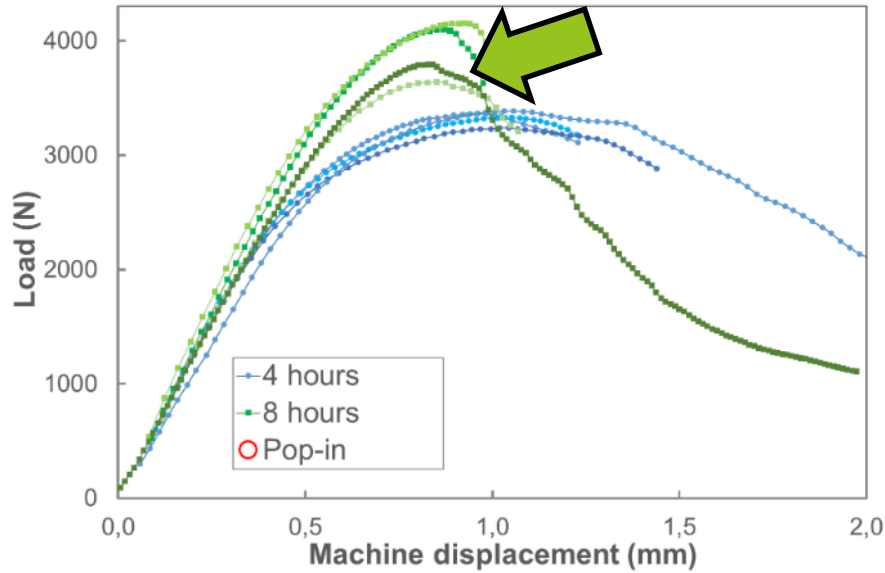
- **Ductile failure**, very rough crack surface
- Heterogeneous presence of large **clusters of porosity** at the crack tip
- **No difference in zone with and without pop-in**

DEFINITION →

EXPERIMENTAL INVESTIGATIONS

- Mechanical properties
- Fracture mechanisms
- Machine stiffness

INSTABILITY CRITERIA



- 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 ?

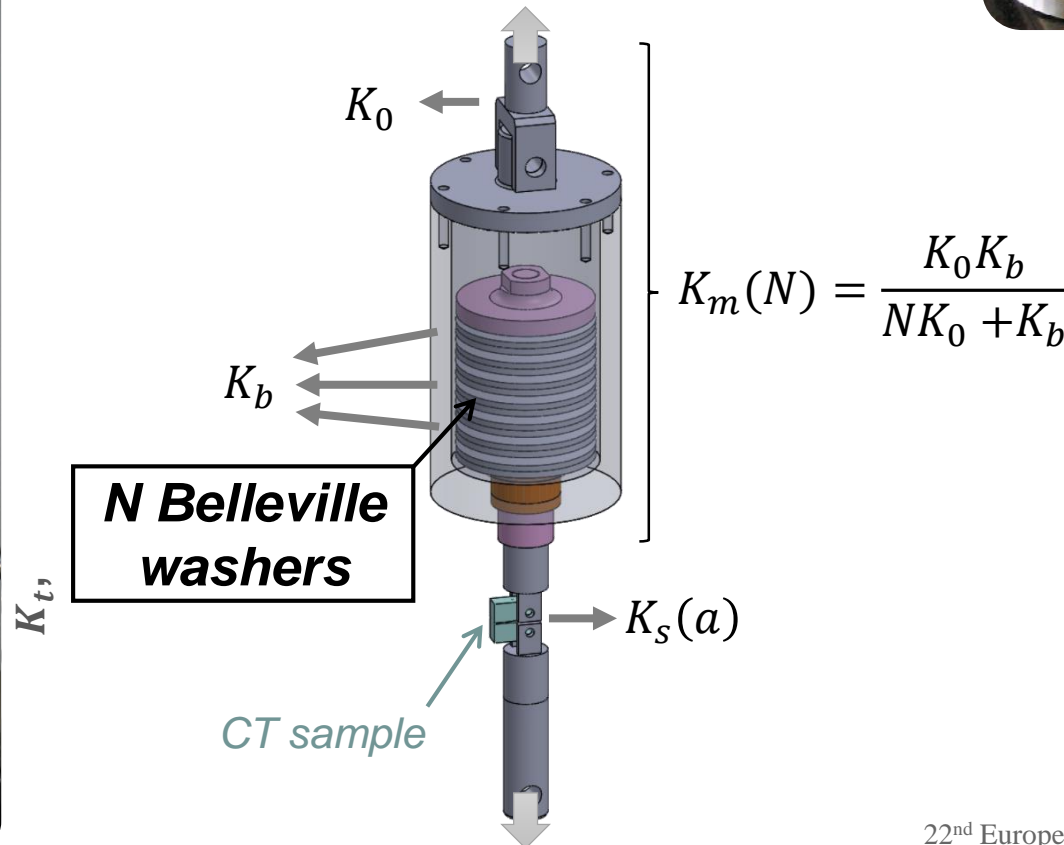
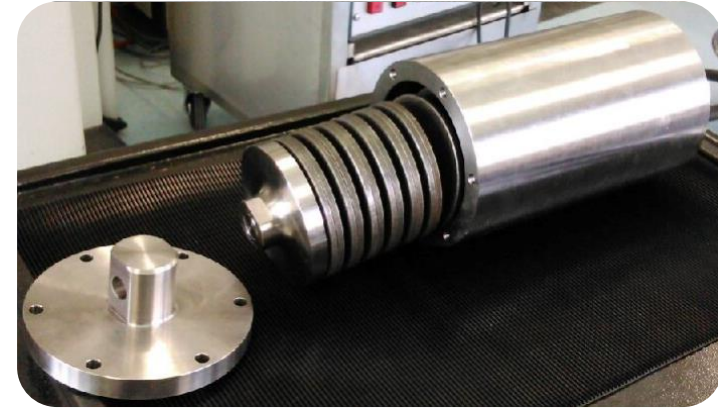
DEFINITION →

EXPERIMENTAL
INVESTIGATIONS

- Mechanical properties
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INSTABILITY
CRITERIA

- Design of an dedicated assembly (titanium alloy)
- Use of **belleville washers**, to increase the compliance



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

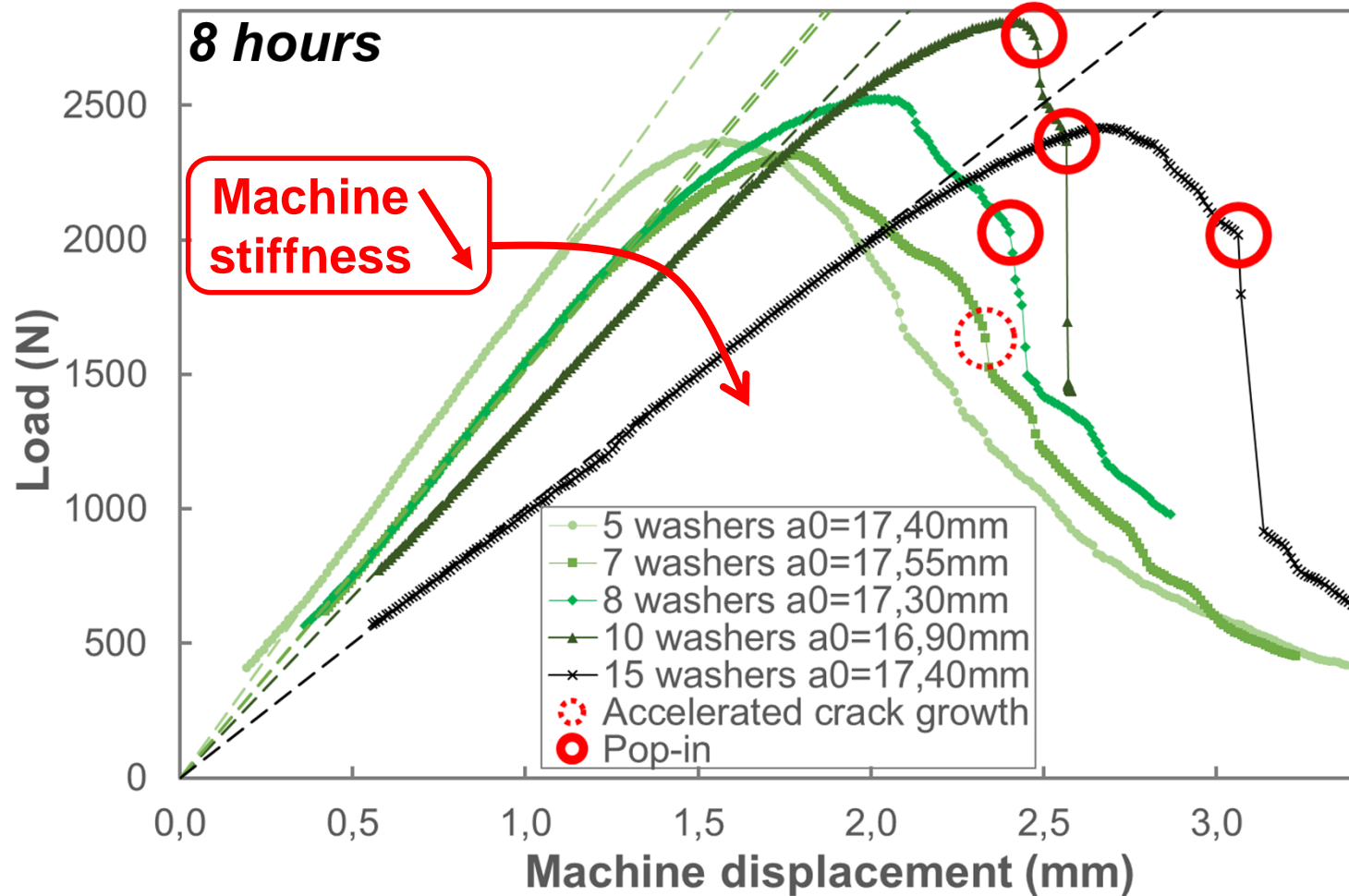
DEFINITION →

EXPERIMENTAL INVESTIGATIONS

→ Mechanical properties
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→ Machine stiffness

INSTABILITY CRITERIA

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



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

DEFINITION →

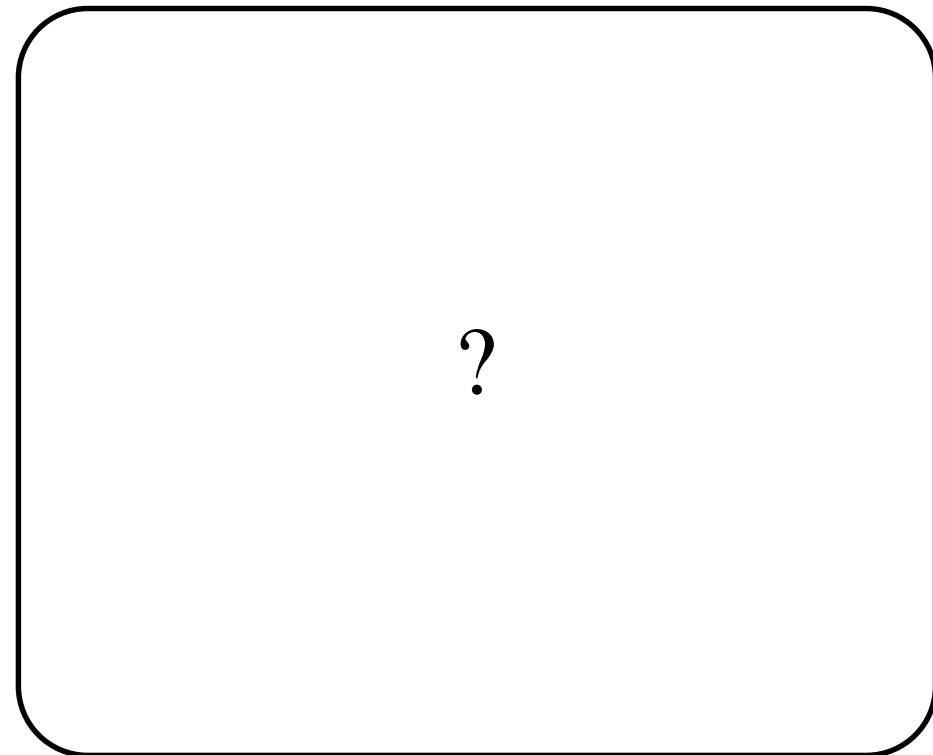
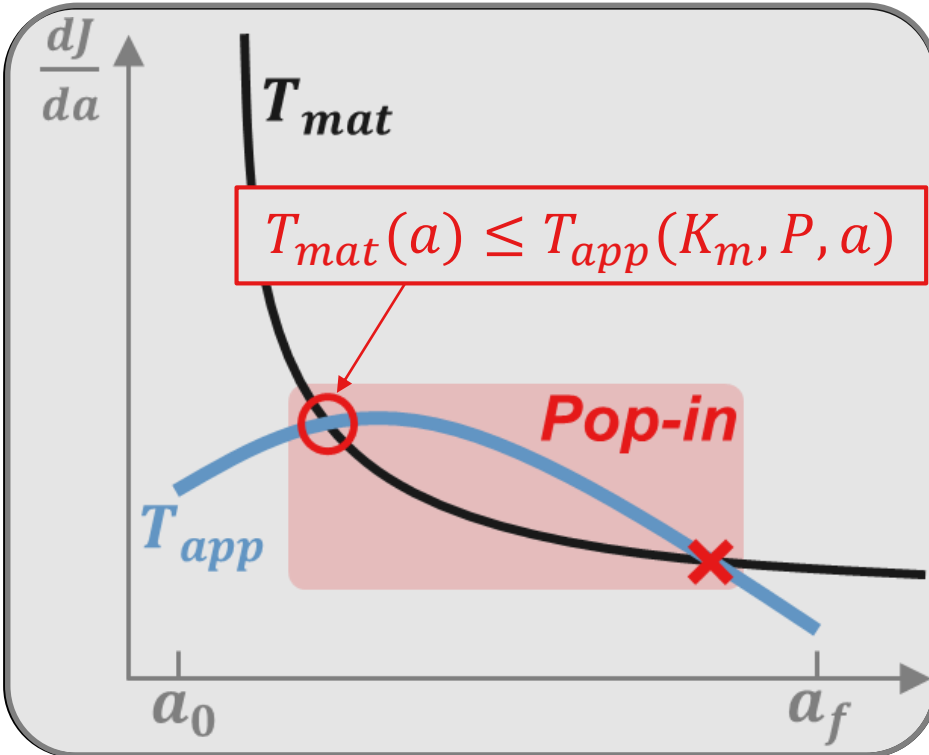
EXPERIMENTAL INVESTIGATIONS

- Mechanical properties
- Fracture mechanisms
- Machine stiffness

INSTABILITY CRITERIA

J-integral approach

Load-displacement approach



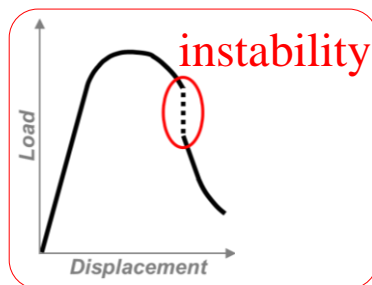
DEFINITION →

EXPERIMENTAL INVESTIGATIONS

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→ INSTABILITY CRITERIA

→ Load-displacement approach ?



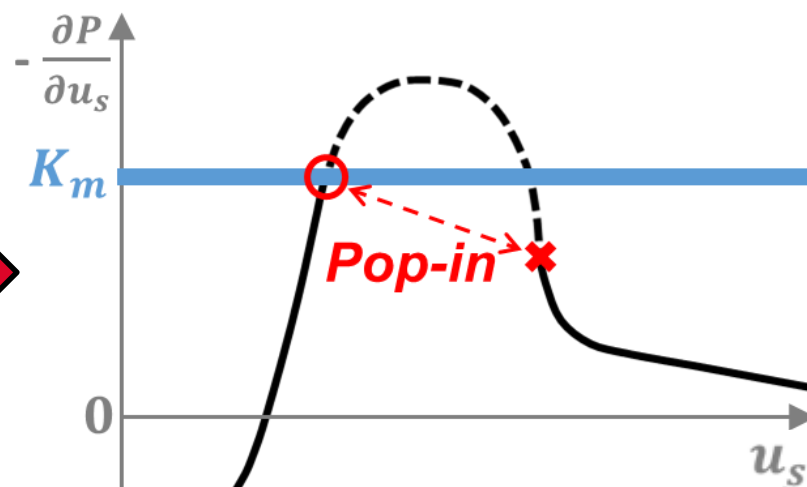
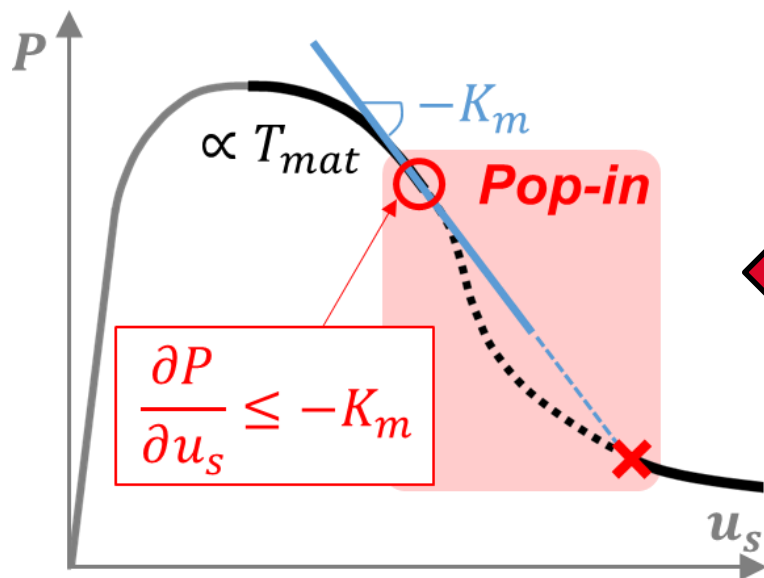
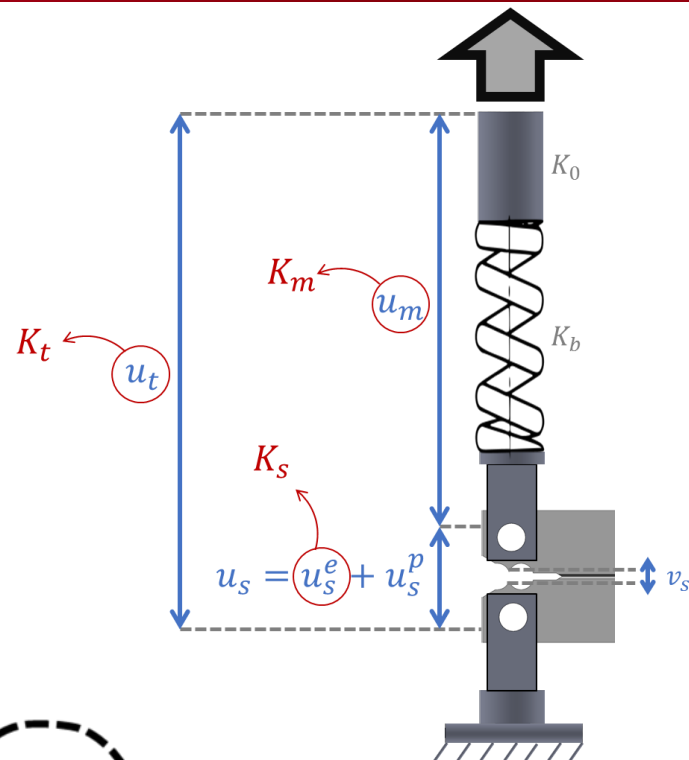
$$u_t = u_m + u_s$$

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

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

Material

Loading



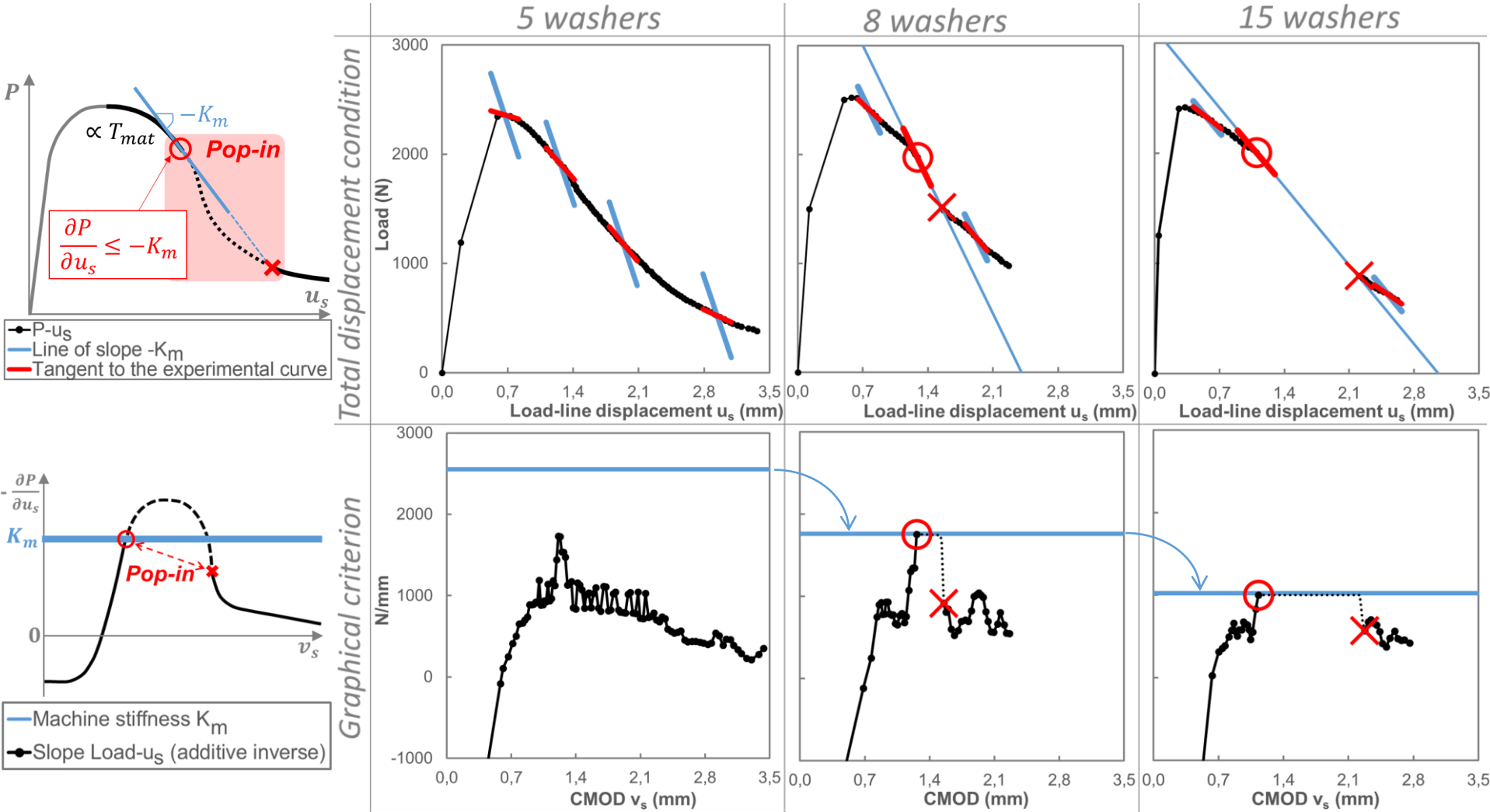
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INSTABILITY CRITERIA

→ Load-displacement approach ?



DEFINITION →

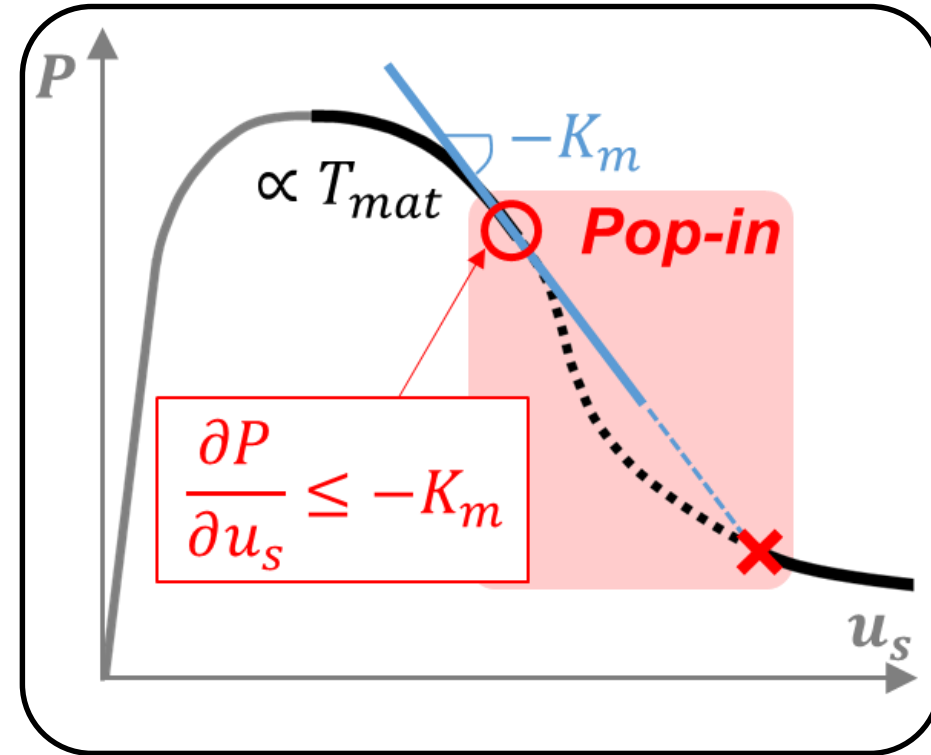
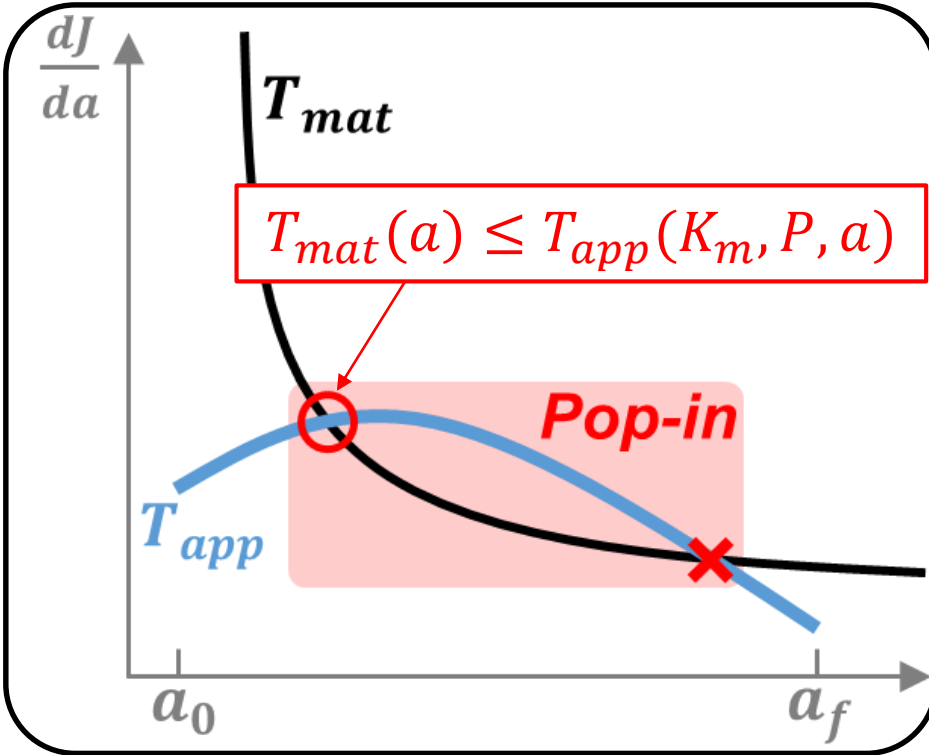
EXPERIMENTAL INVESTIGATIONS

- Mechanical properties
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INSTABILITY CRITERIA

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

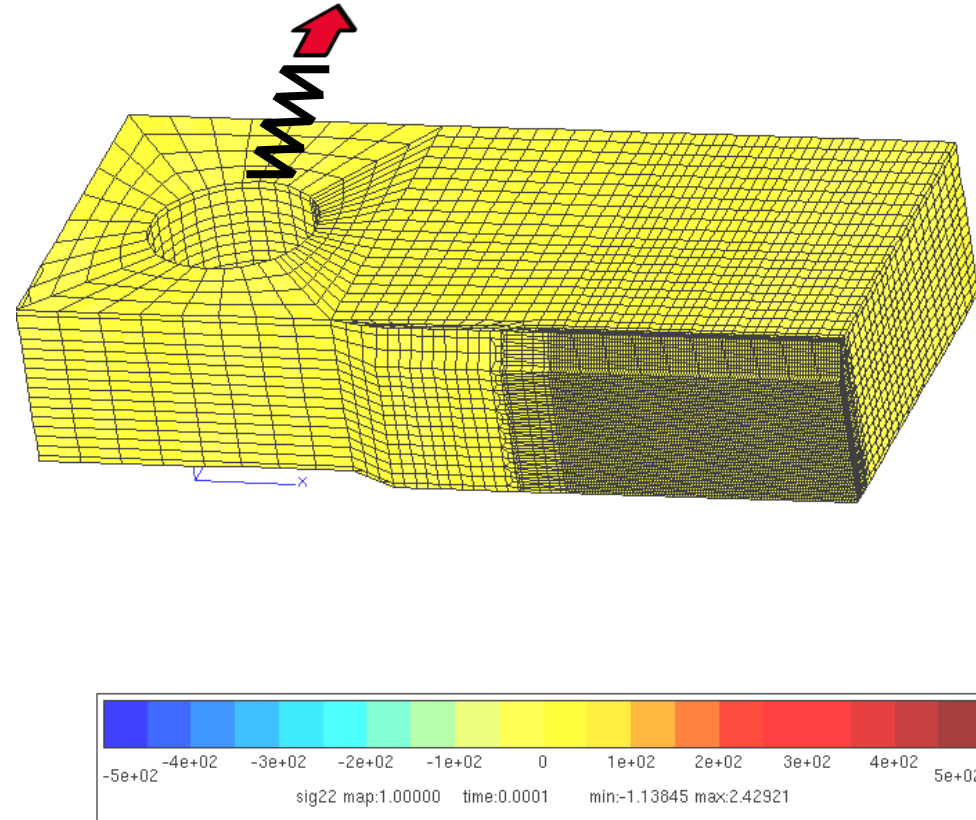
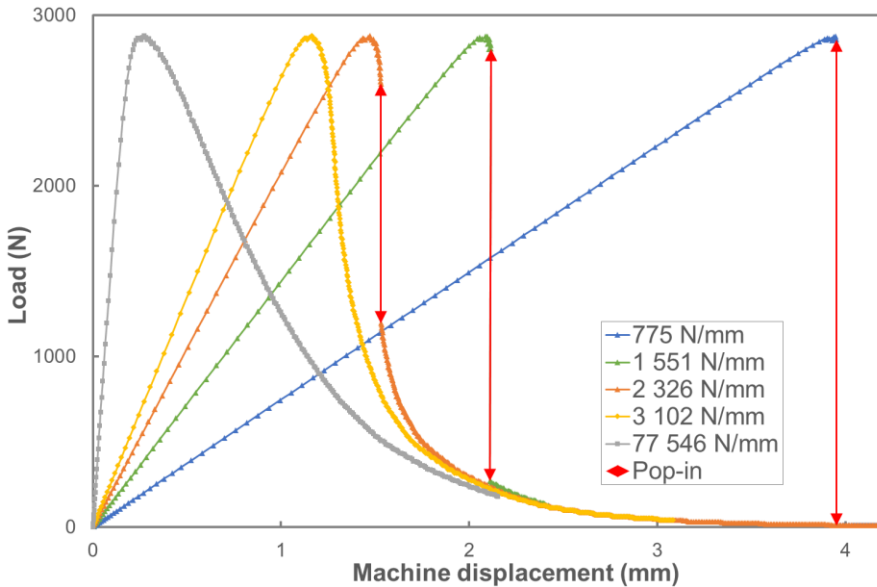
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INSTABILITY CRITERIA

- 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)
L. Helfen (ANKA / ESRF)
C. Varenne (Mines Paristech)



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