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

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# 16<sup>TH</sup> EUROPEAN MECHANICS OF MATERIALS CONFERENCE

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

**T. PETIT**

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



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DEFINITION

EXPERIMENTAL INVESTIGATIONS

INSTABILITY CRITERIA

NANTES | TUESDAY, MARCH 27<sup>TH</sup> 2018

DEFINITION →

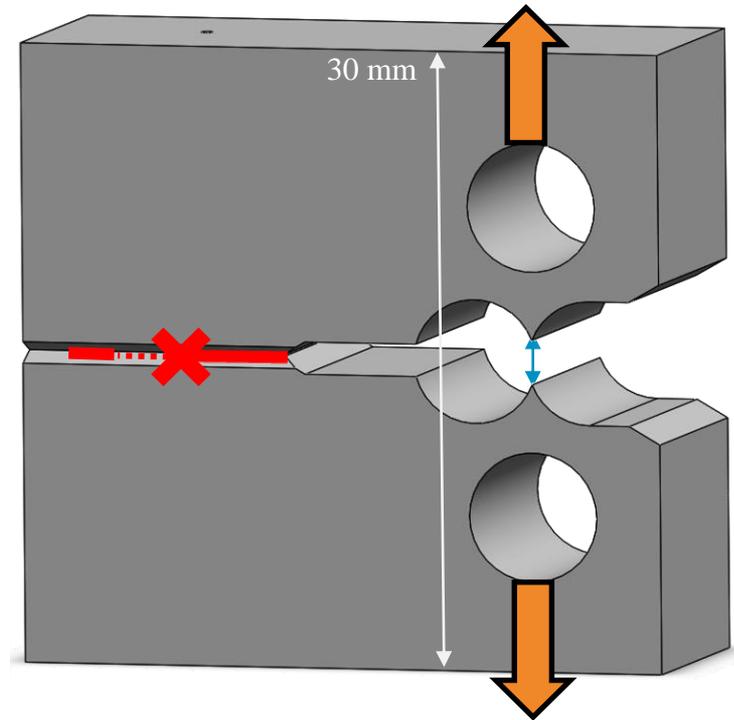
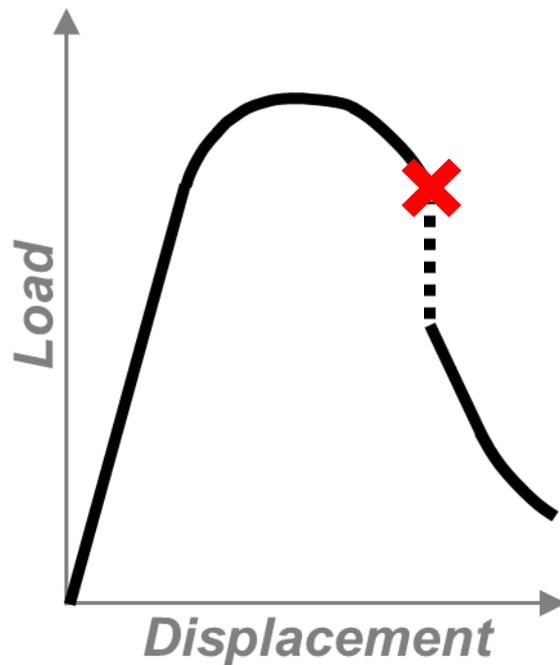
EXPERIMENTAL INVESTIGATIONS

- 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



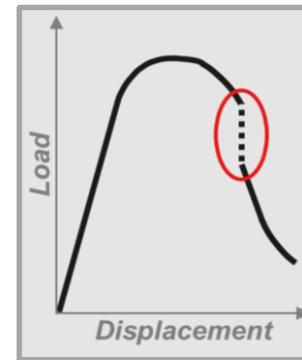
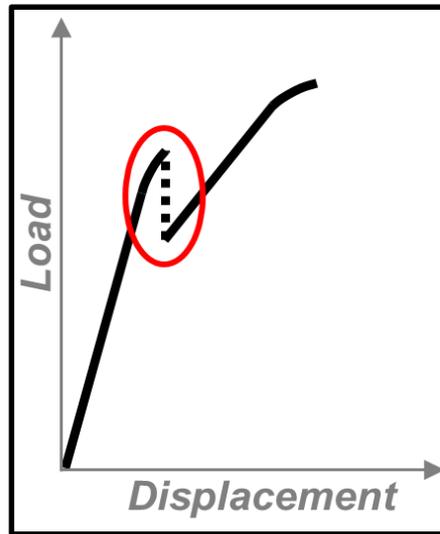
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CRITERIA

- 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 :

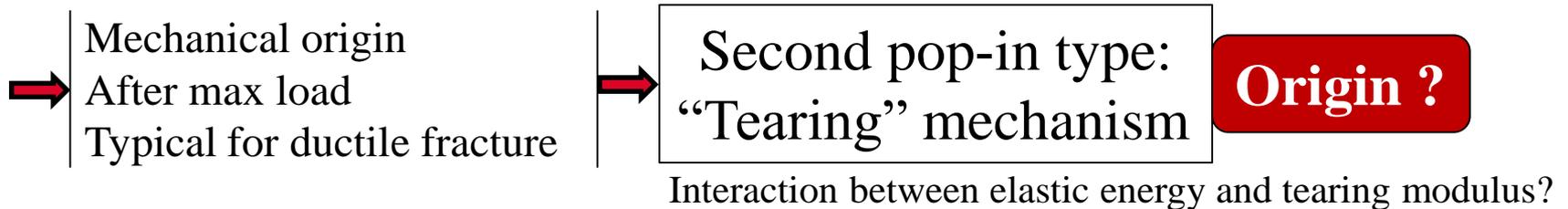
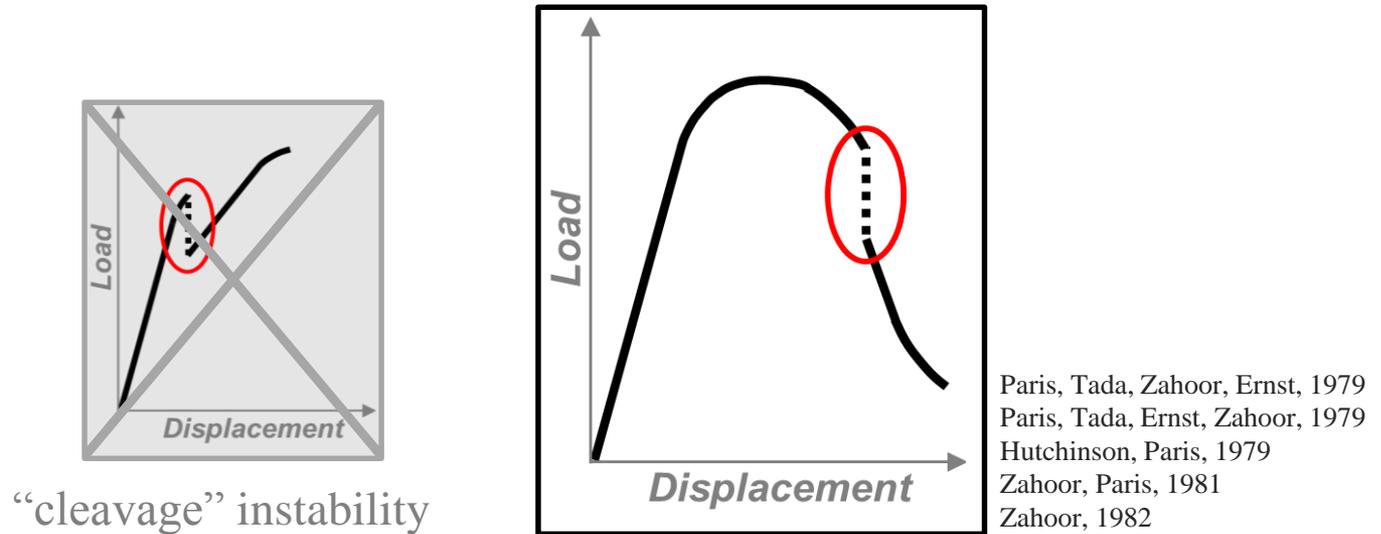


- Microstructural origin
- Before max load
- Typical for brittle fracture

→ First pop-in type:  
“Cleavage” instability



- ⇒ 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 :



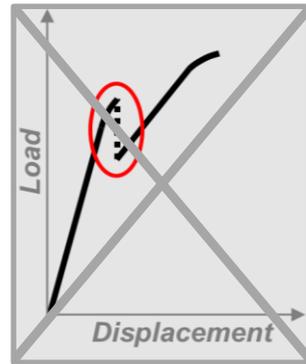
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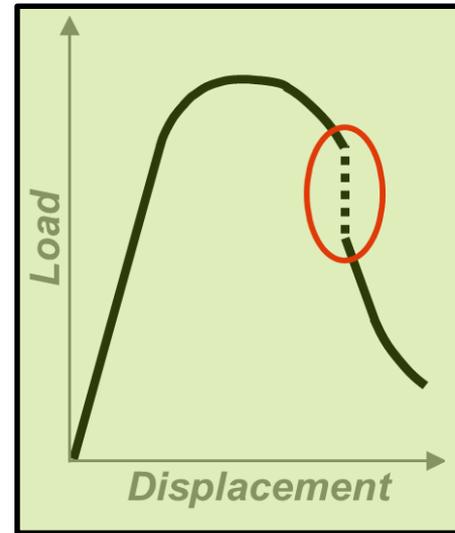
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- ⇒ Fracture toughness tests
- ⇒ “Pop-in” = **local instability** leading to **rapid but limited crack propagation** associated with a sudden decrease in load
- ⇒ Little studied in the literature. 2 types :



“cleavage” instability



“tearing” mechanism



System  
Machine stiffness

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



DEFINITION →

EXPERIMENTAL INVESTIGATIONS

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INSTABILITY CRITERIA

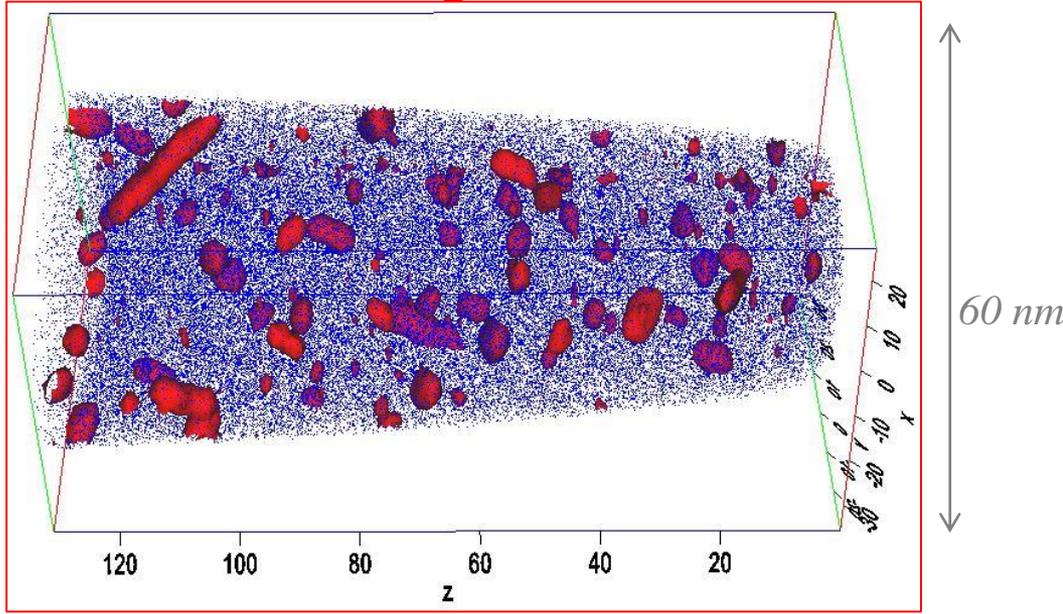
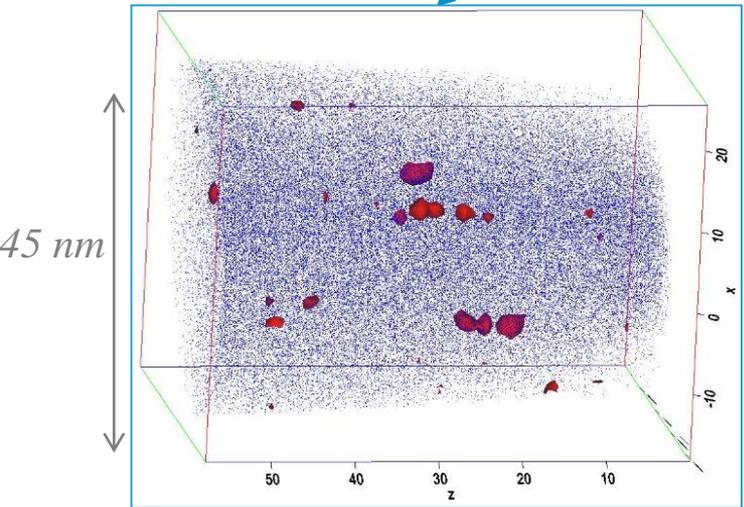
→ Aluminium 6061-T6

→ Age-hardened alloy → 4 aging times (175 °C) to obtain 4 metallurgical states:

Aging time (h)

4	8	12	16
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Strength ↗



Atom Probe Tomography

DEFINITION →

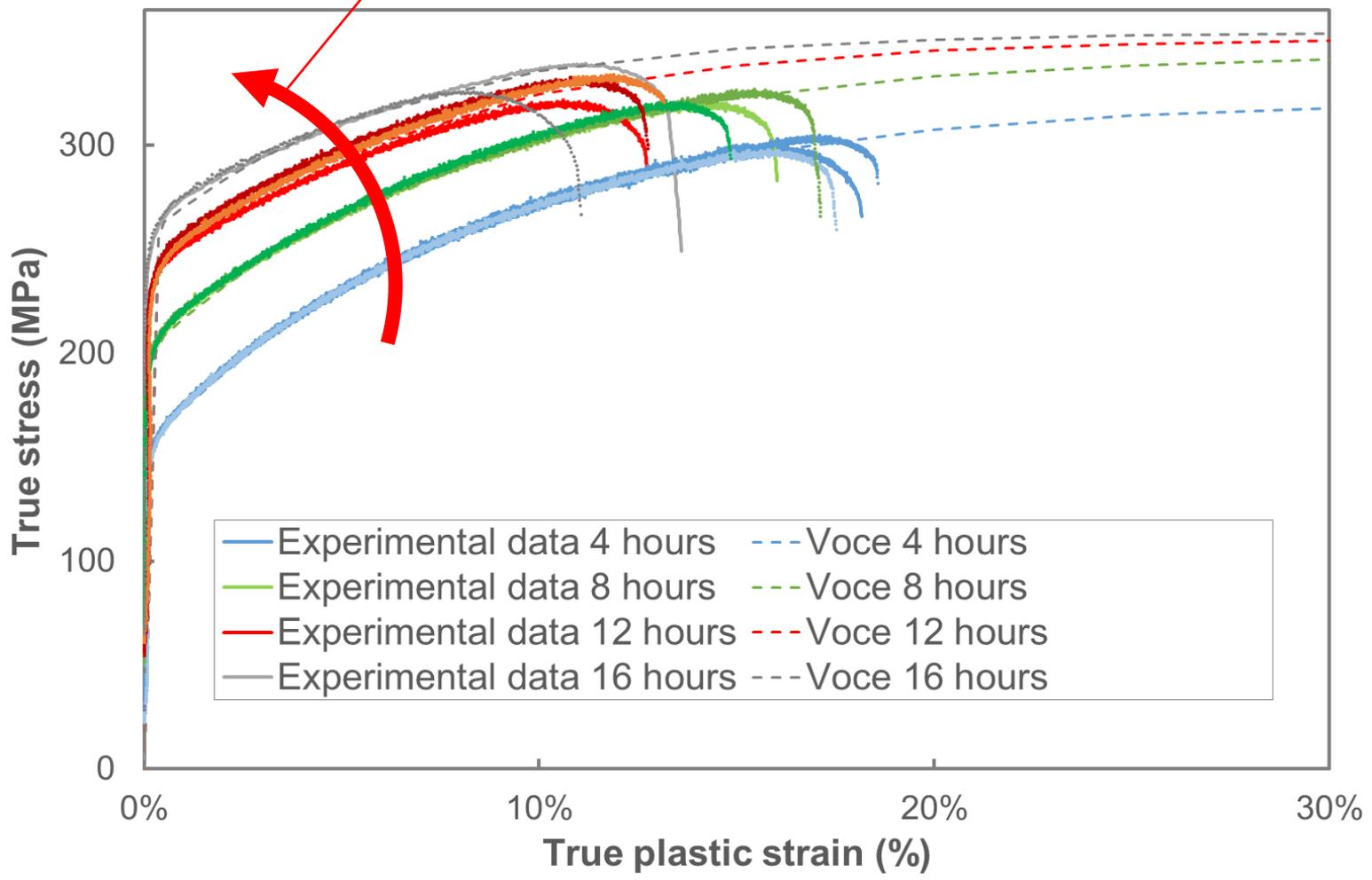
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→ INSTABILITY CRITERIA

→ Tensile tests:

Aging time **strongly hardens** the aluminum alloy



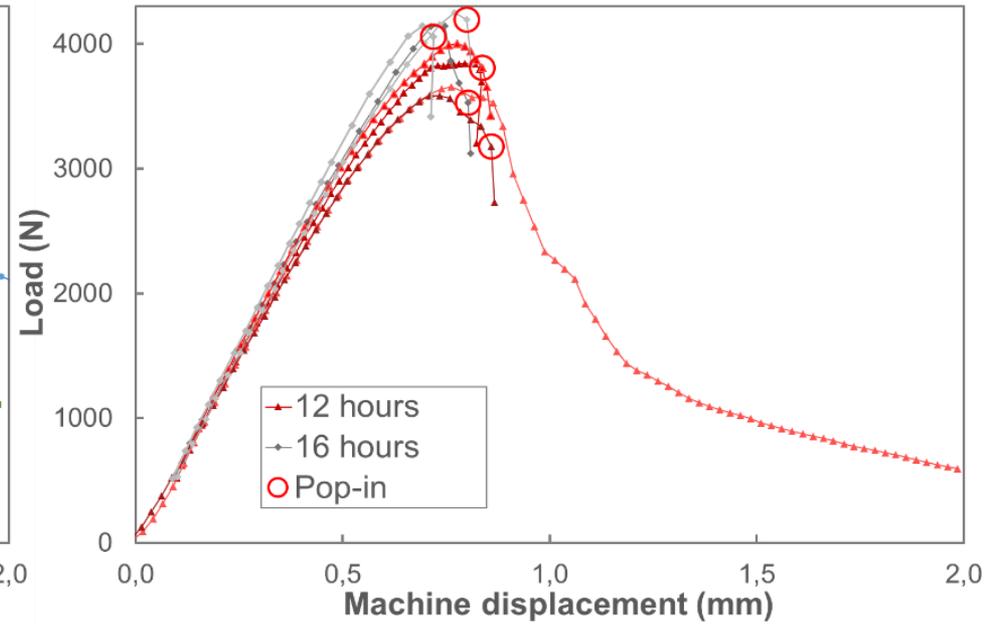
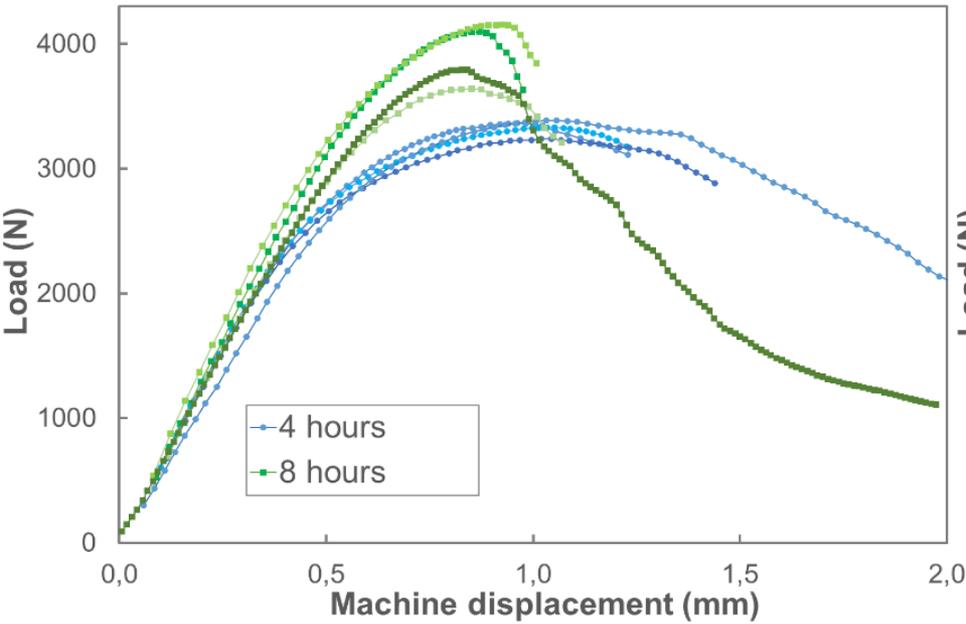
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→ Fracture toughness tests:



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

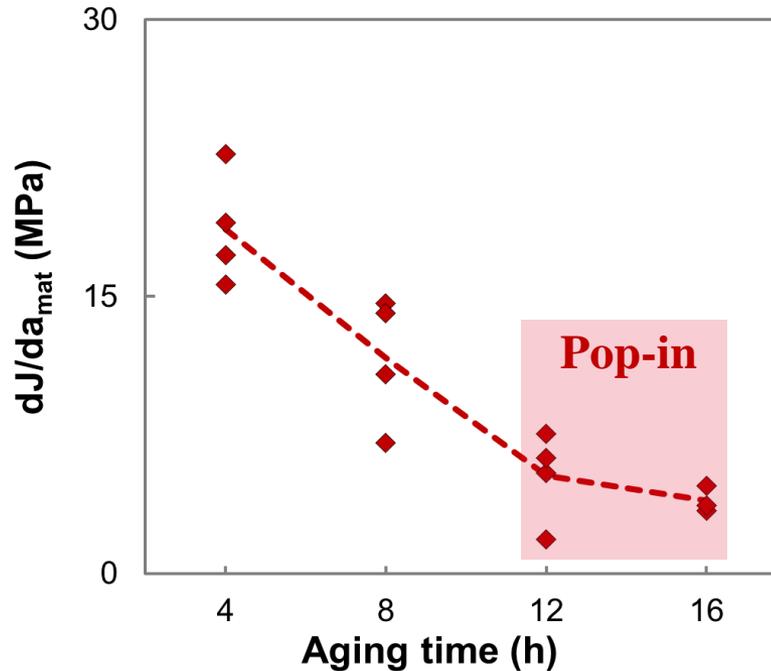
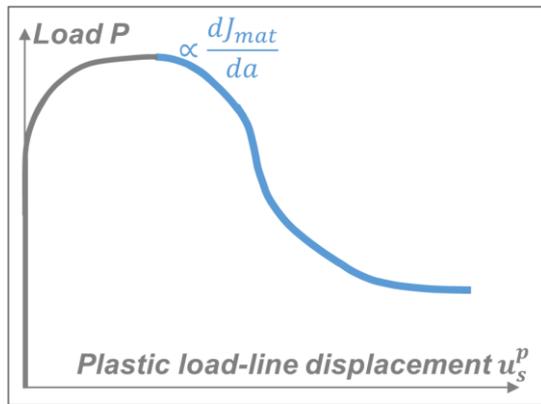
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→ Fracture toughness tests:



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

→ Link between :

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

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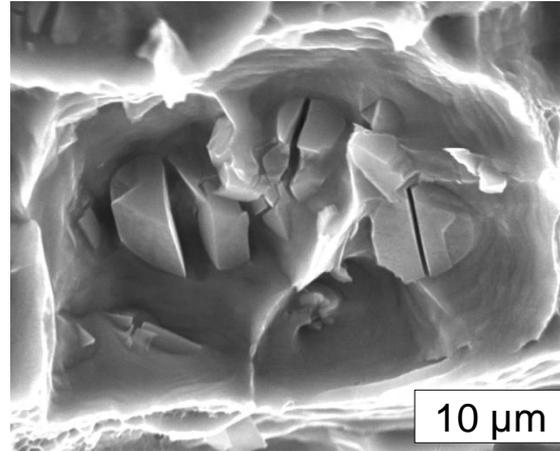
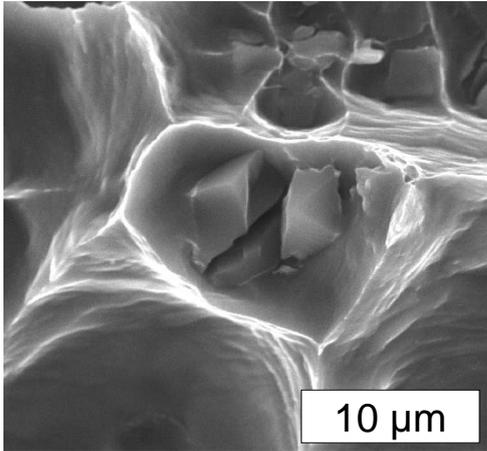
INSTABILITY CRITERIA

*Scanning electron microscope*

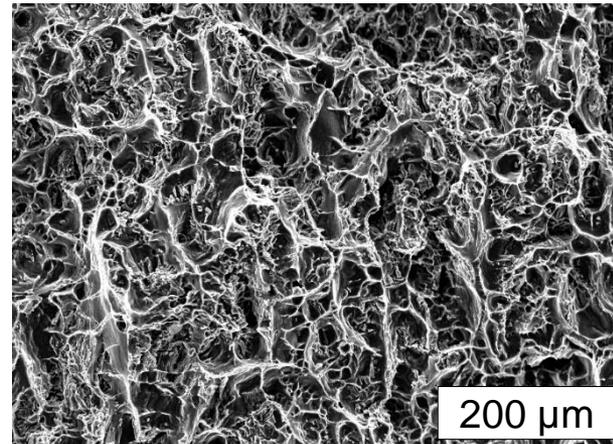
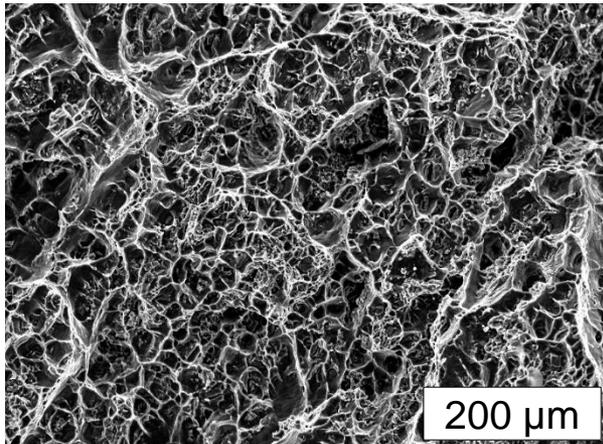
→ Fracture mechanisms:

No pop-in (aging: 4 h)

With pop-in (aging : 12 h)



- Broken coarse **Mg<sub>2</sub>Si** in dimples
- Nucleation controlled by **coarse precipitates** (Mg<sub>2</sub>Si & IMF)



- **Ductile failure** micromechanisms
- Void growth to coalescence by **internal necking** (and void-sheeting) mechanisms

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

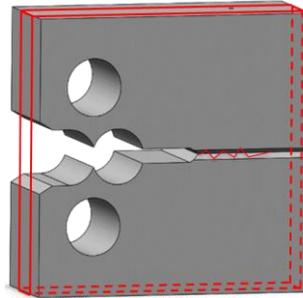
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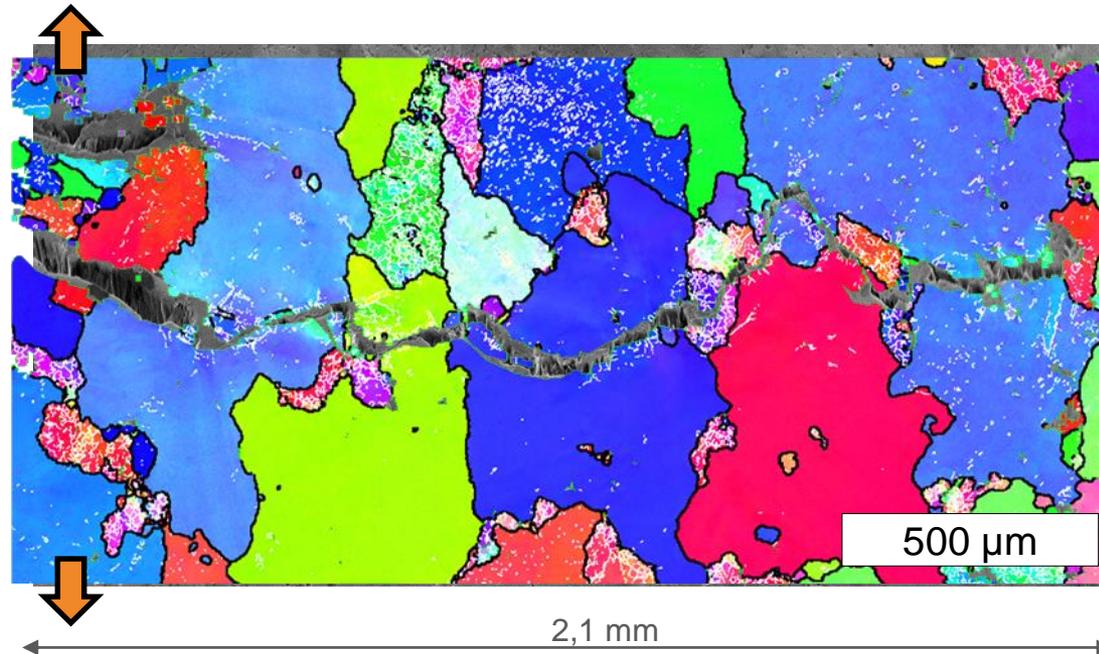
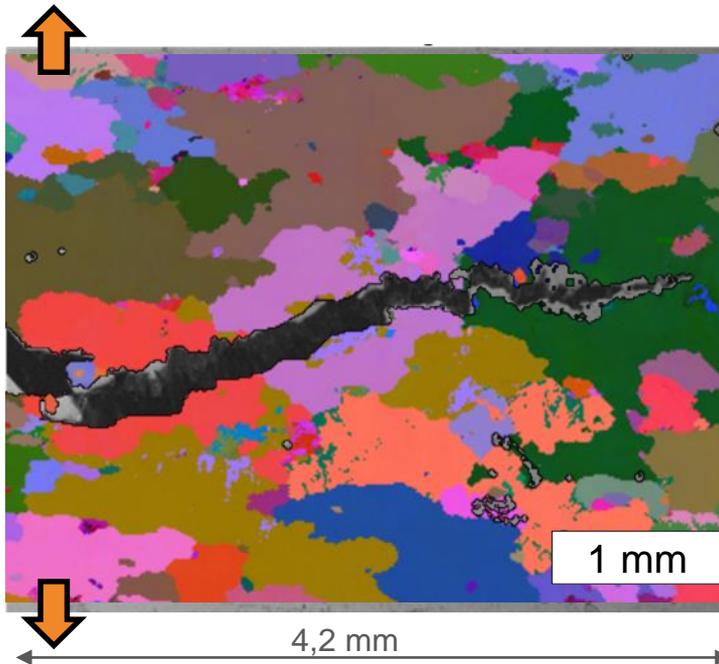
→ Fracture mechanisms:



Scanning electron microscope

+

EBSD



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

→ Intergranular fracture around the small grains

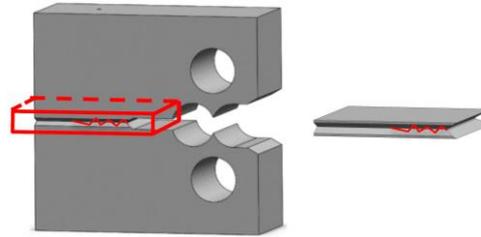
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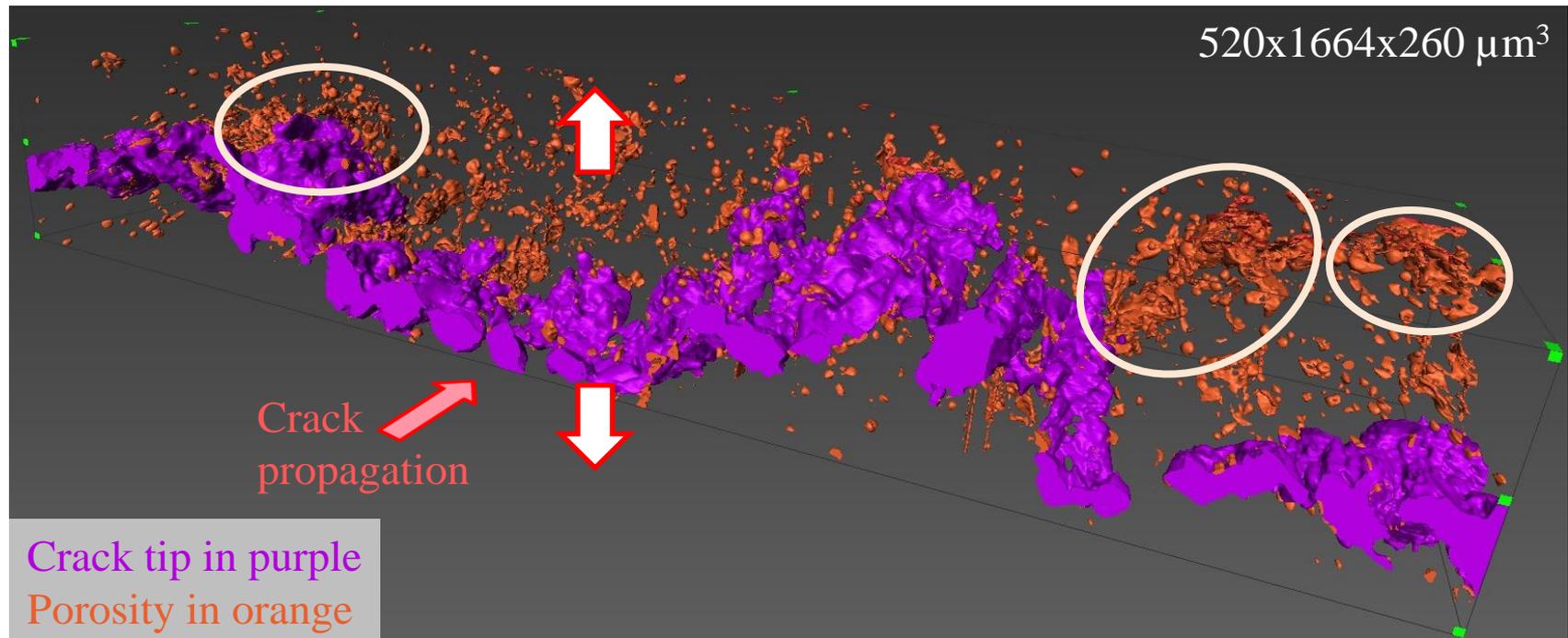
INSTABILITY  
CRITERIA

→ Fracture mechanisms:



Tomography:

Synchrotron laminography (ESRF, Grenoble)



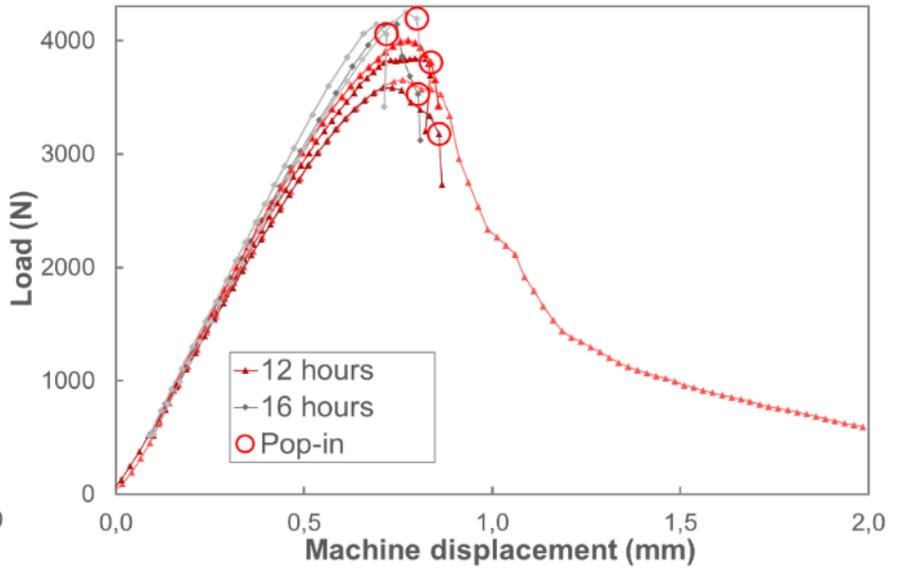
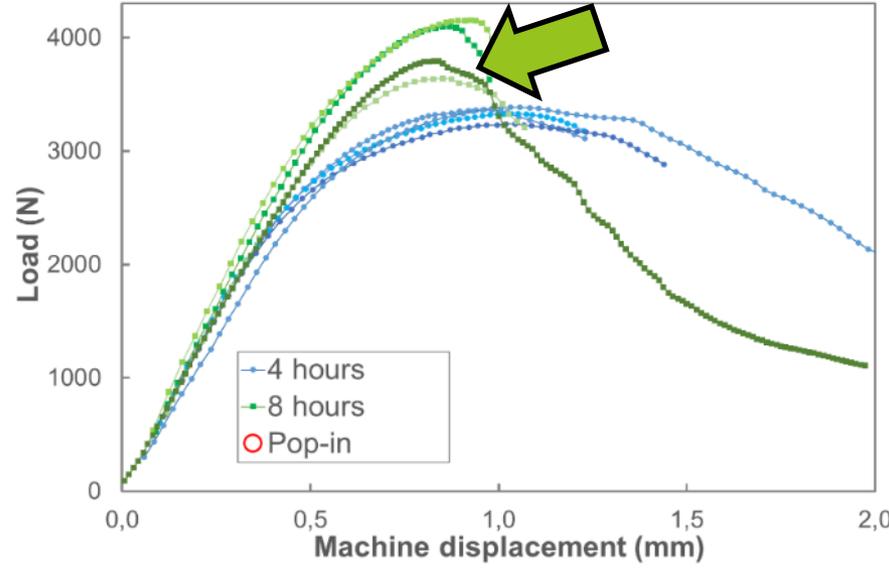
- **Ductile failure**, very rough crack surface
- Heterogeneous presence of large **clusters of porosity** at the crack tip
- **No difference in zone with and without pop-in**

DEFINITION →

EXPERIMENTAL INVESTIGATIONS

- Mechanical properties
- Fracture mechanisms
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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 ?

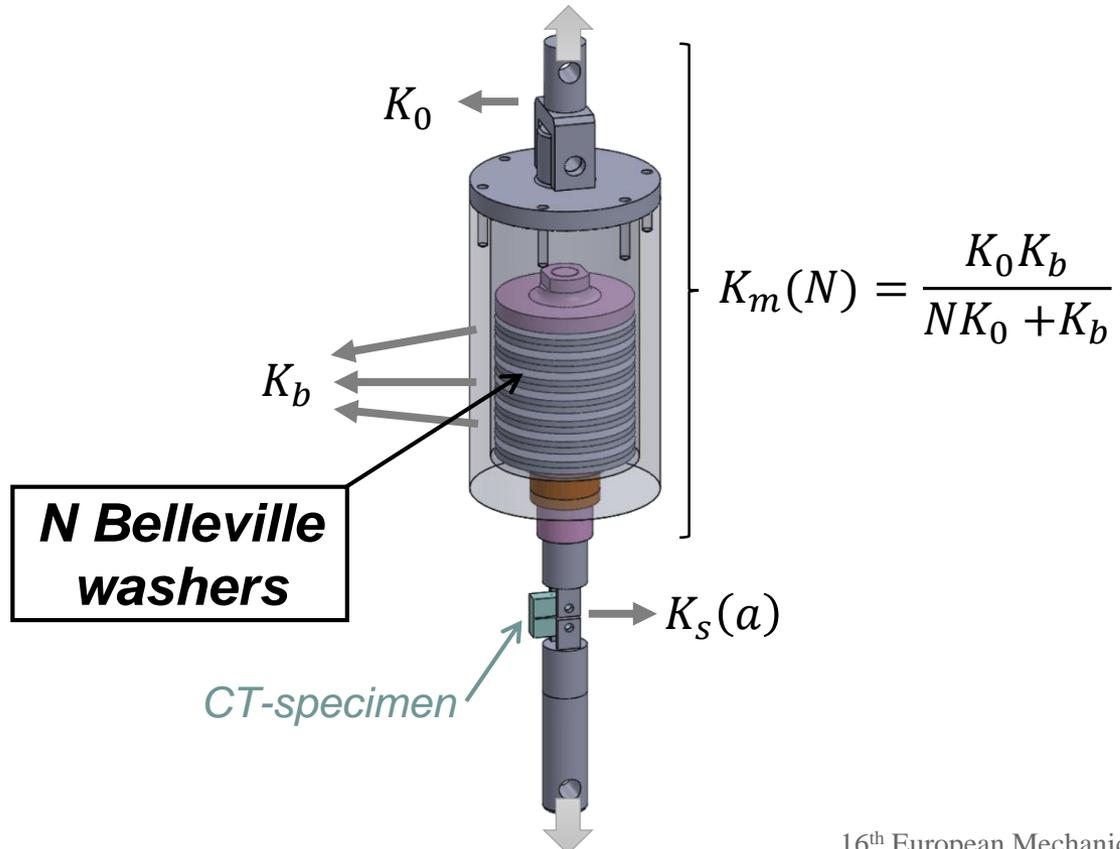
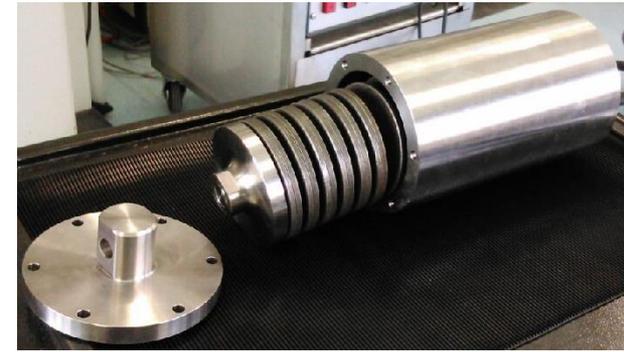
DEFINITION →

EXPERIMENTAL INVESTIGATIONS

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INSTABILITY CRITERIA

- Design of an assembly allowing to decrease the **stiffness  $K_t$**
- Use of **belleville washers**, to increase the compliance in compression



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

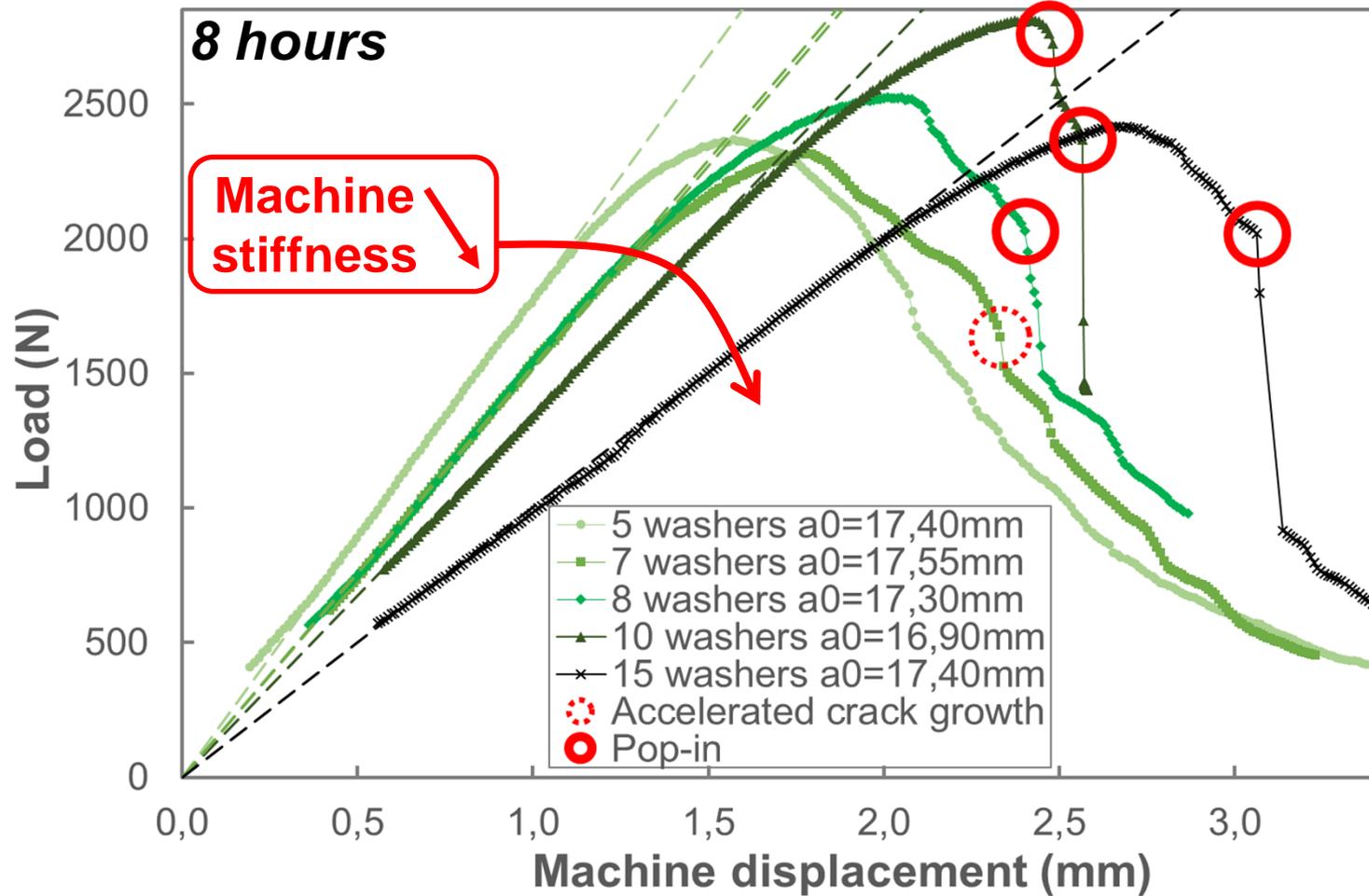
DEFINITION →

EXPERIMENTAL INVESTIGATIONS

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INSTABILITY CRITERIA

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



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

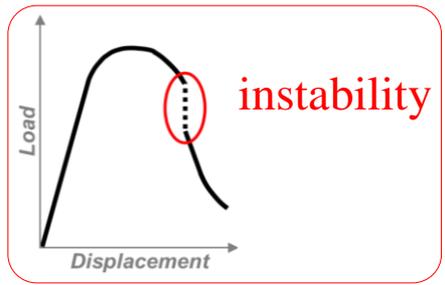
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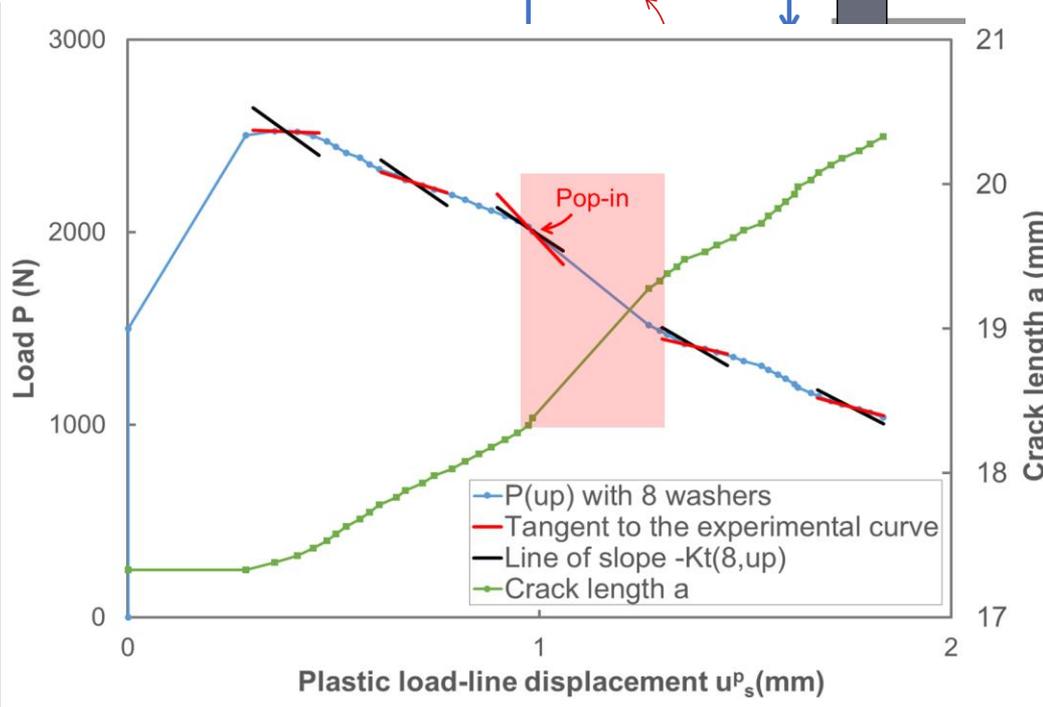
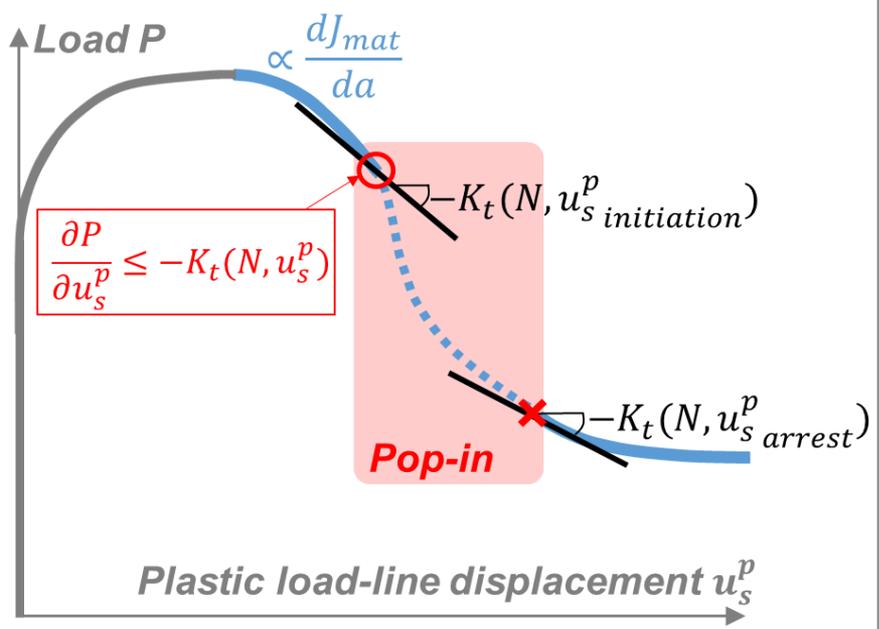
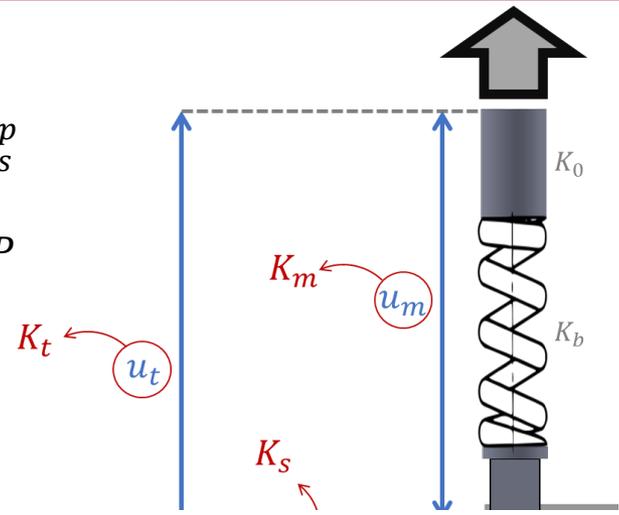
Instability criterion ? → 'Load' approach



$$u_t = u_m + u_s = u_m + u_s^e + u_s^p$$

$$\delta u_t = 0 = \frac{\delta P}{K_t(N, u_s^p)} + \frac{\partial u_s^p}{\partial P} \delta P$$

$$\frac{\partial P}{\partial u_s^p} \leq -K_t(N, u_s^p)$$



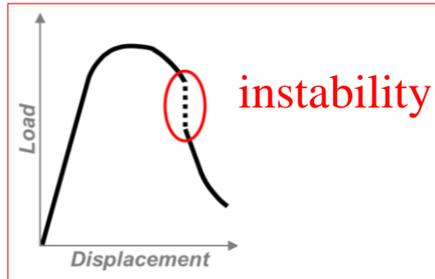
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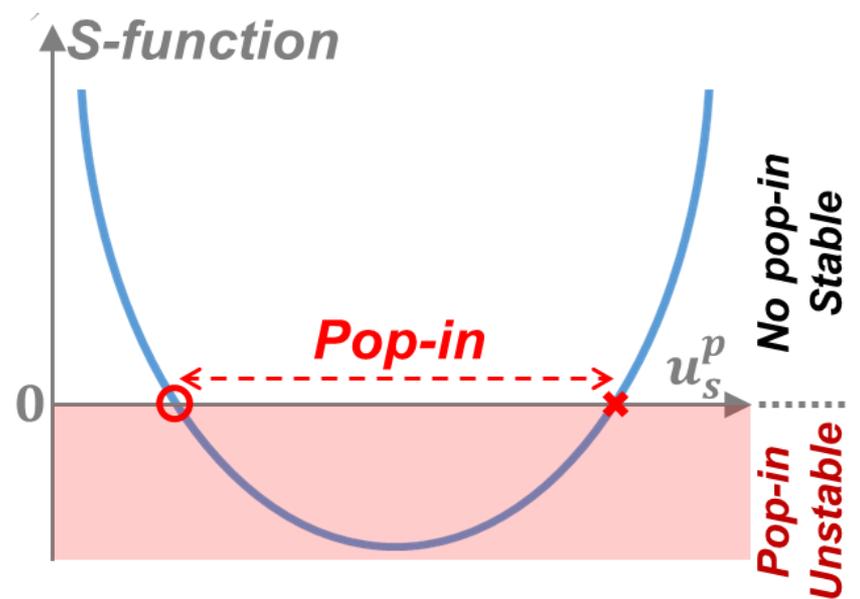
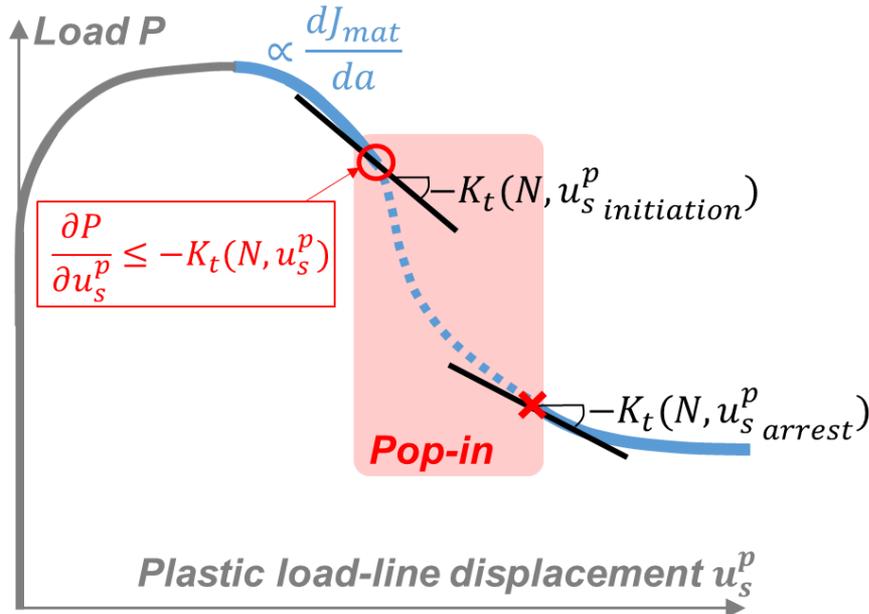


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$$\delta u_t = 0 = \frac{\delta P}{K_t(N, u_s^p)} + \frac{\partial u_s^p}{\partial P} \delta P$$

$$\frac{\partial P}{\partial u_s^p} \leq -K_t(N, u_s^p)$$

$$S(N, u_s^p) = \frac{\partial P}{\partial u_s^p} + K_t(N, u_s^p) \leq 0 ?$$



DEFINITION →

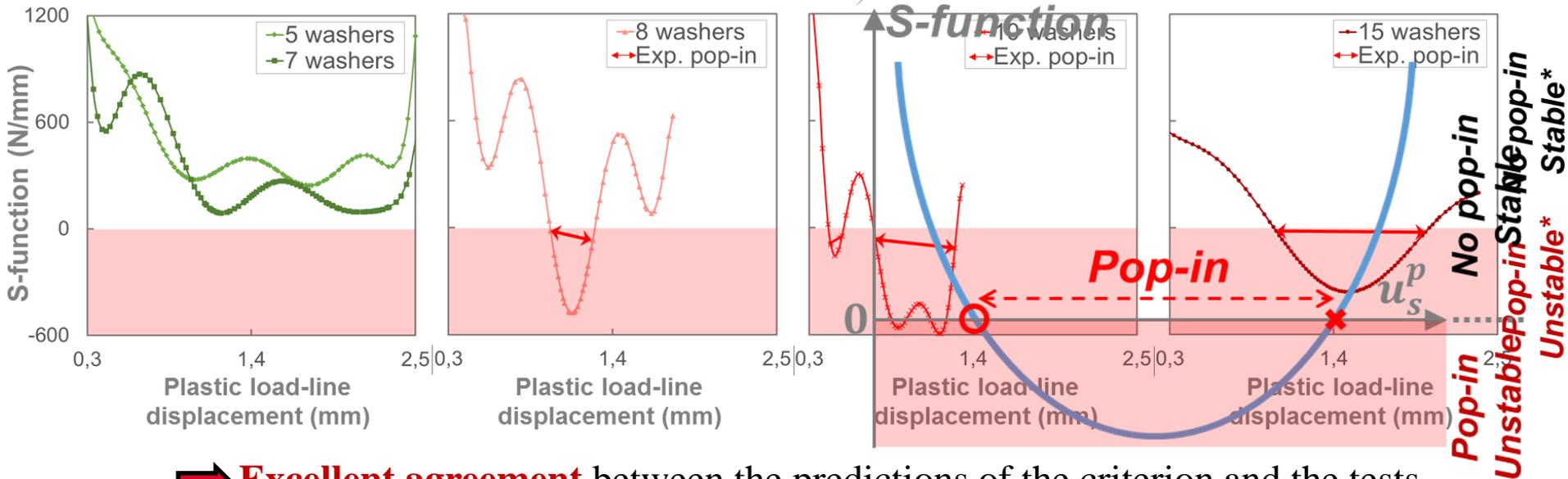
EXPERIMENTAL INVESTIGATIONS

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INSTABILITY CRITERIA

Instability criterion ? → 'Load' approach

$$\frac{\partial P}{\partial u_s^p} \leq -K_t(N, u_s^p) \Rightarrow S(N, u_s^p) = \frac{\partial P}{\partial u_s^p} + K_t(N, u_s^p) \leq 0 ?$$



→ Excellent agreement between the predictions of the criterion and the tests

DEFINITION →

EXPERIMENTAL  
INVESTIGATIONS
 → Mechanical properties  
 → Fracture mechanisms  
 → Machine stiffness
INSTABILITY  
CRITERIA

Instability criterion ?

→ *'Load' approach*→ *'J-integral' approach*

→ Reasoning developed by Paris et al., 1979

→ General small-scale yielding case

$$J(P, a) = \frac{K(P, a)^2}{E}$$

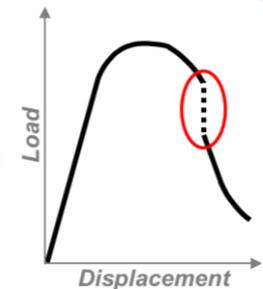
$$dJ(P, a) = \frac{\partial J(P, a)}{\partial P} f(P, a) da + \frac{\partial J(P, a)}{\partial a} da$$

$$\frac{dJ}{da}(P, a) = T_{app} = g(P, a)$$

$$T_{mat} = \frac{dJ_{mat}}{da} \leq T_{app}(P, a)$$

instability

$$du_t(P, a) = 0$$





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INSTABILITY CRITERIA

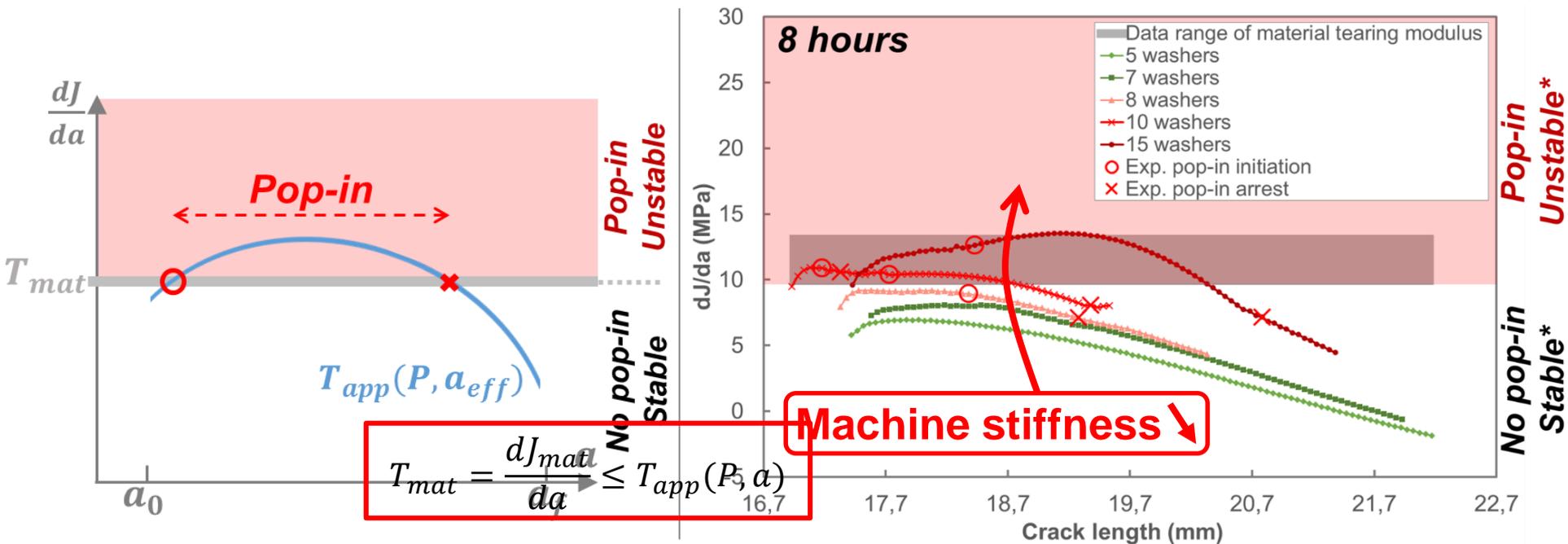
Instability criterion ?

→ 'Load' approach

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→ **Good agreement** between the predictions of the criterion and the tests

→ Experimental pop-ins seem to stop too late : some dynamic effects are not considered

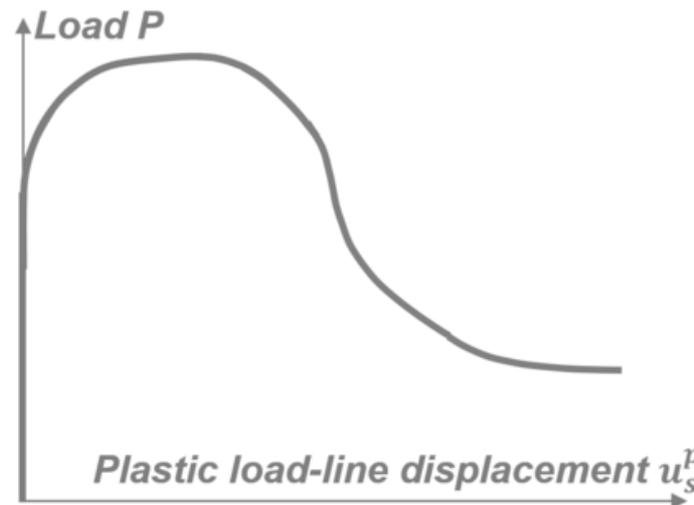
DEFINITION →

**EXPERIMENTAL  
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→ **INSTABILITY  
CRITERIA**

→ 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**



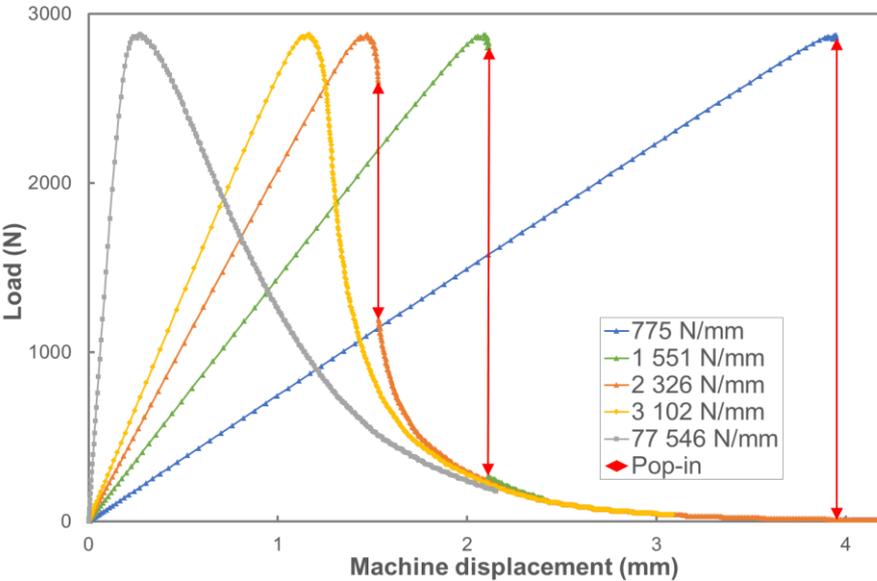
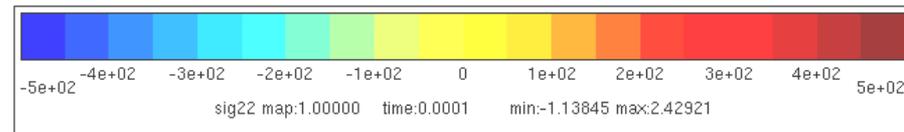
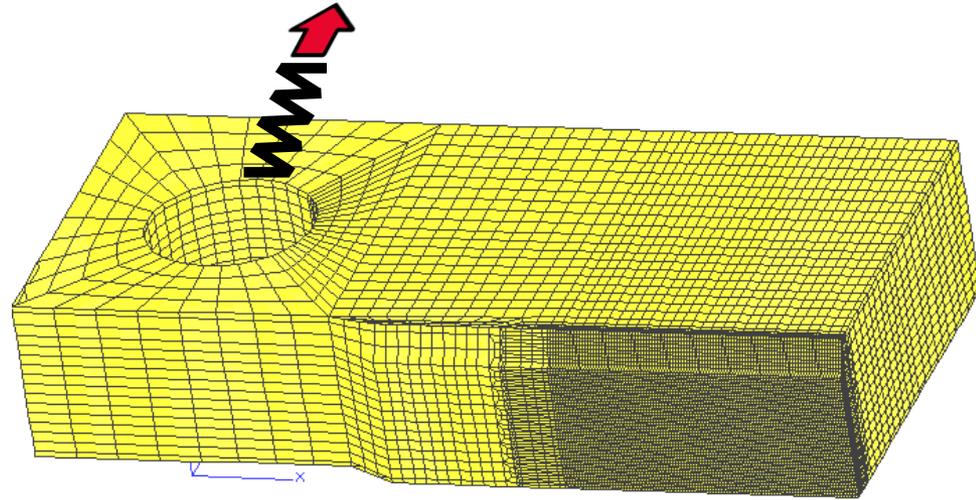
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INSTABILITY  
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- Finite-element simulation
- Gurson law
- Arc-Length method (Riks, 1979)



**Spring creates numerical pop-in**

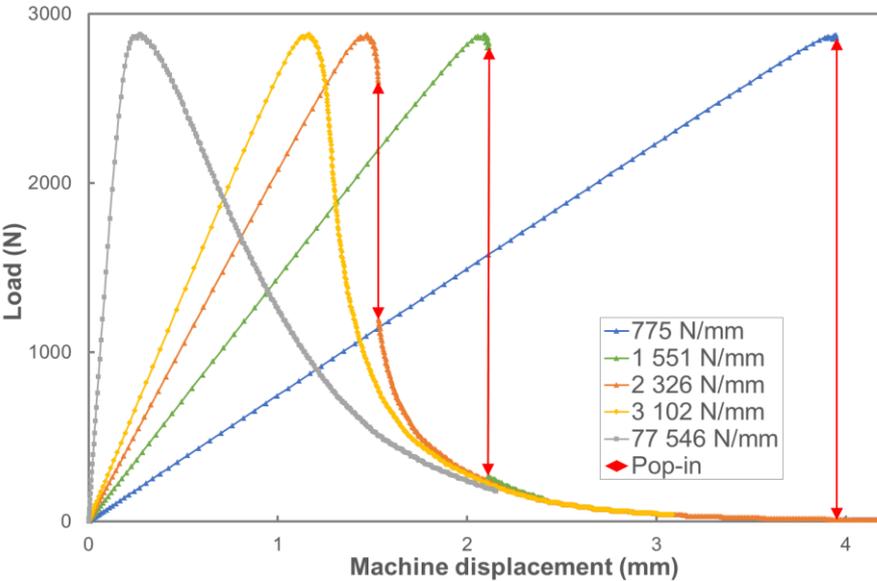
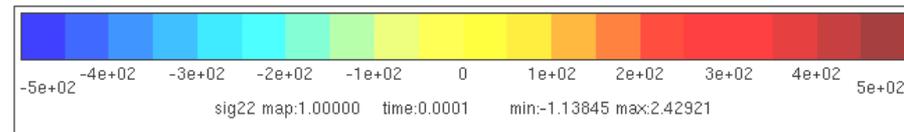
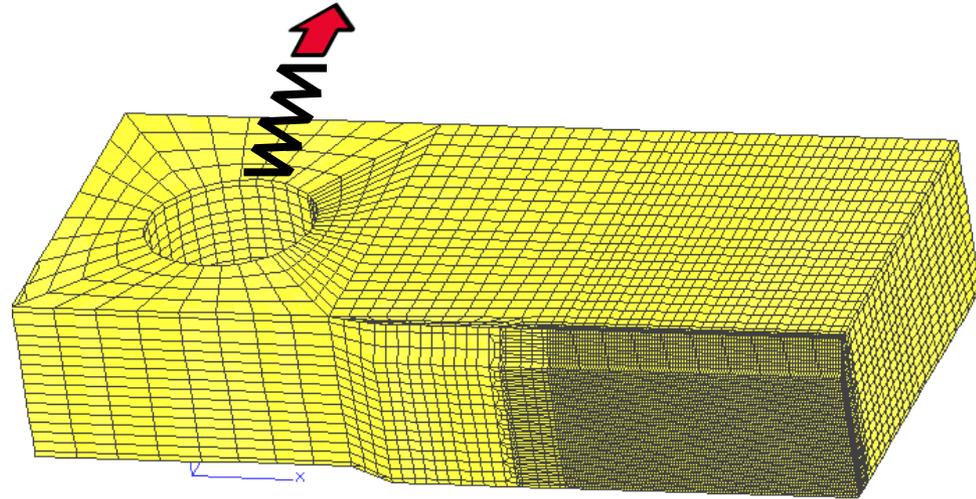
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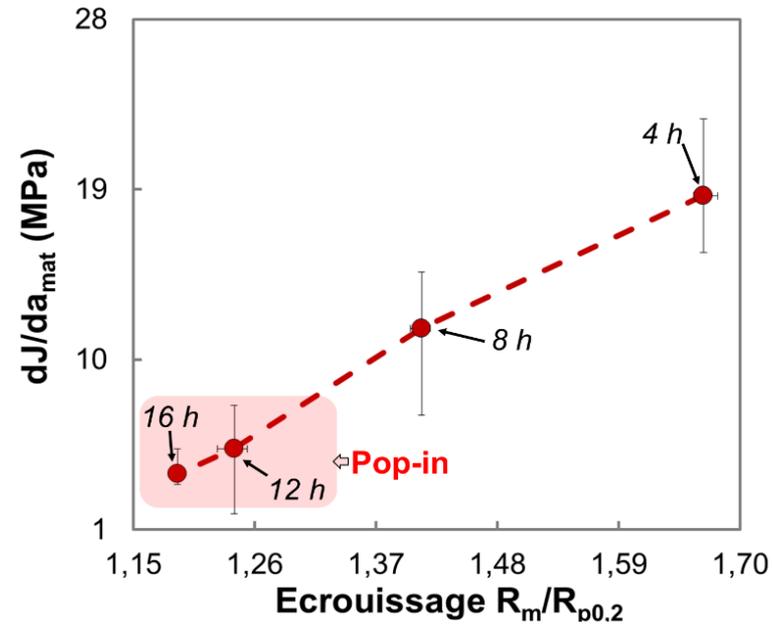
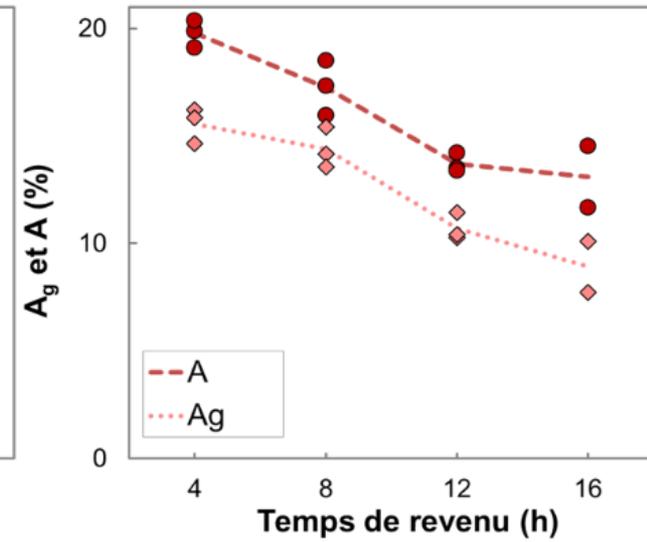
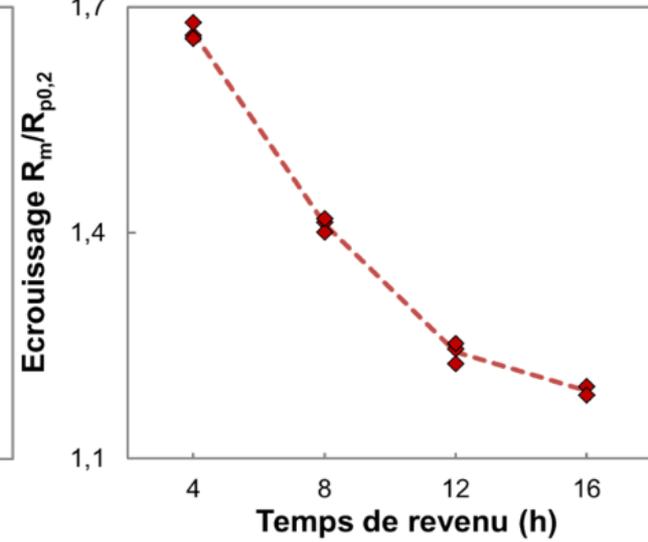
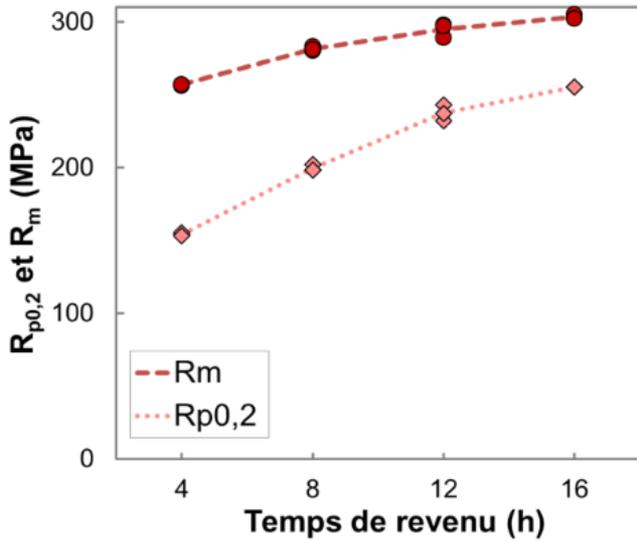
## THANK YOU FOR YOUR ATTENTION!

Thanks to K. Colas, B. Kapusta, B. Tanguy (CEA)  
L. Helfen (ANKA / ESRF)  
C. Varenne (Mines Paristech)

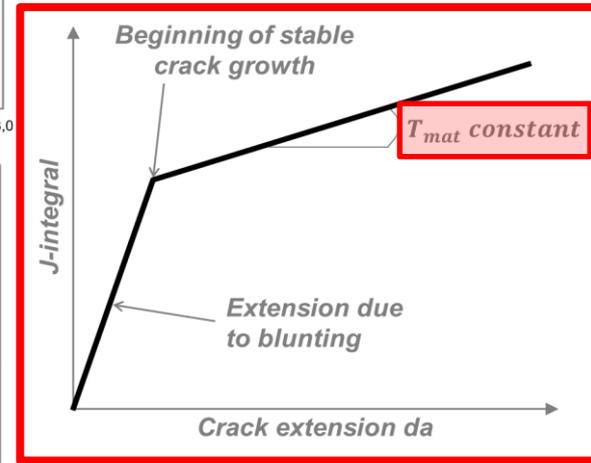
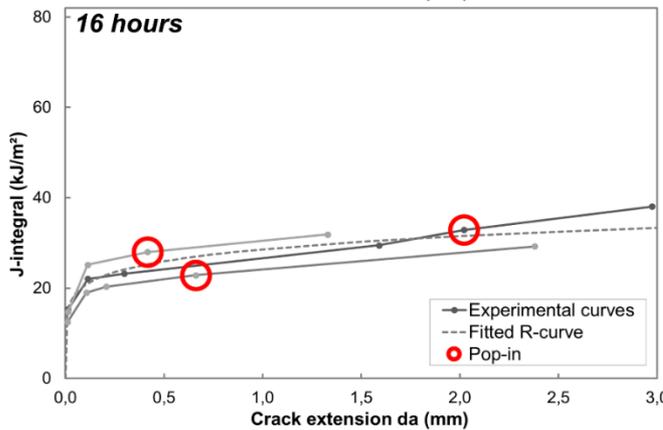
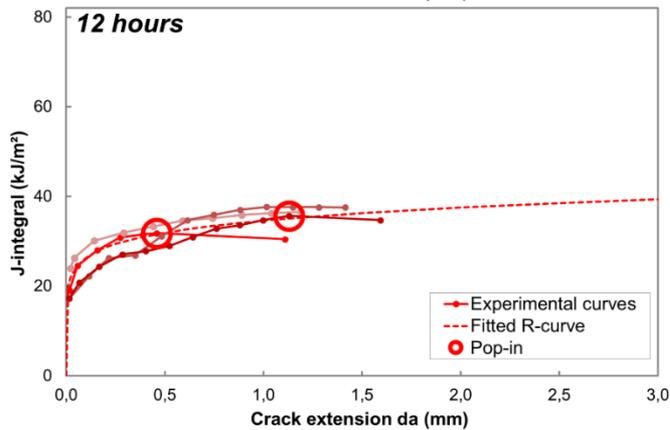
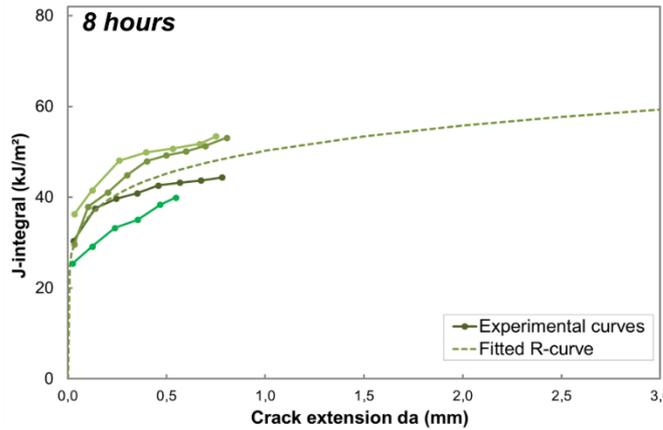
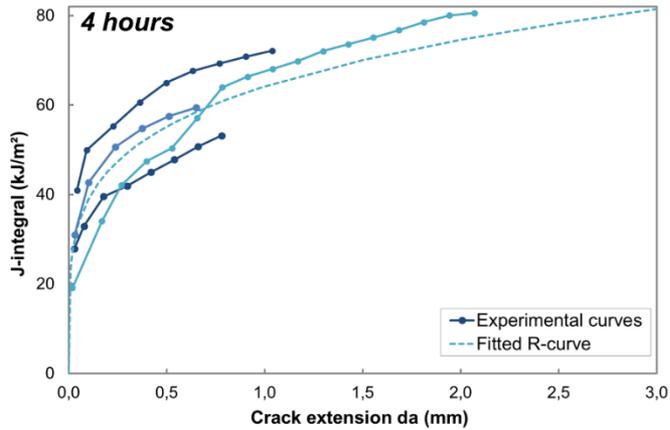


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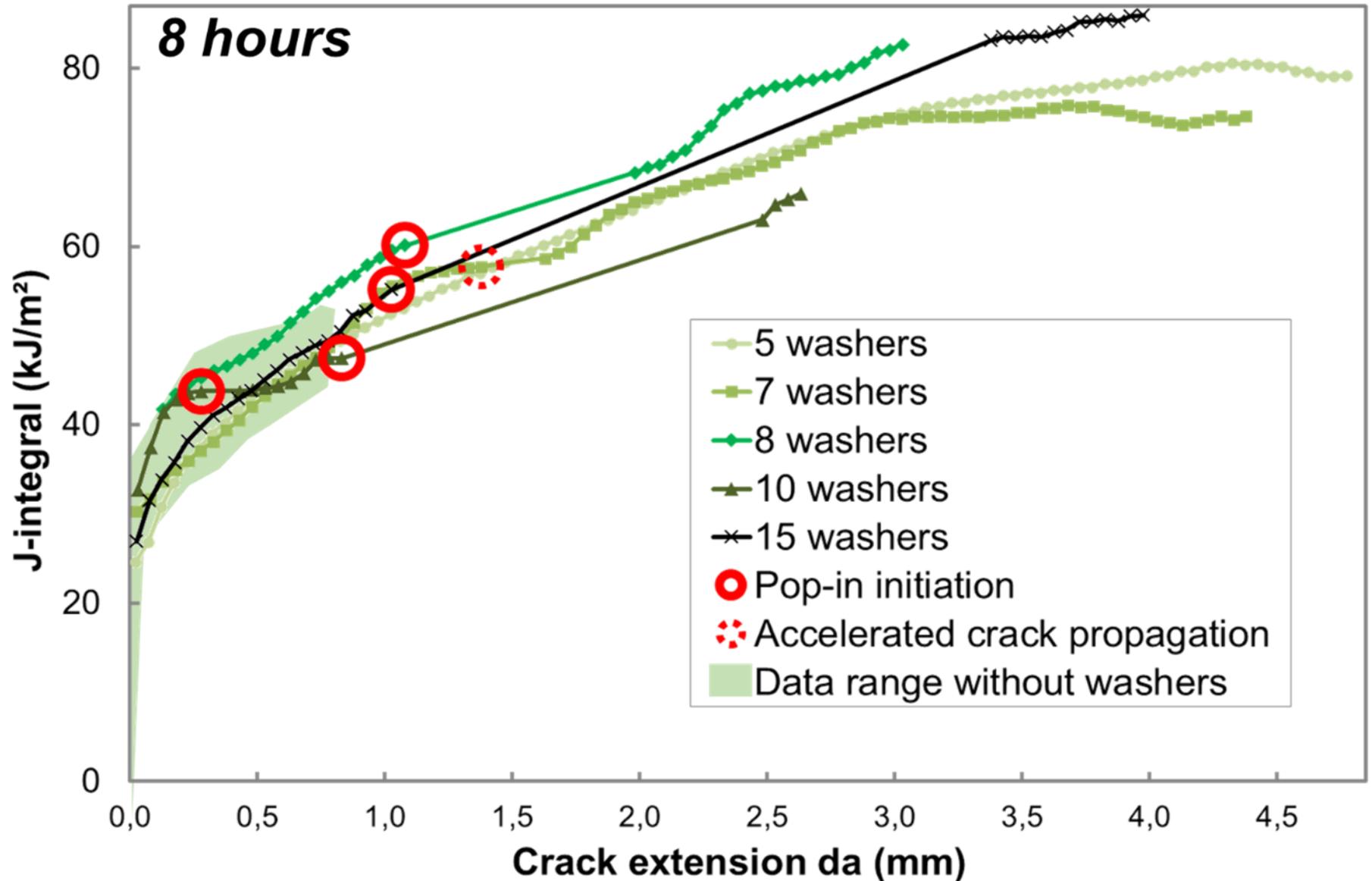
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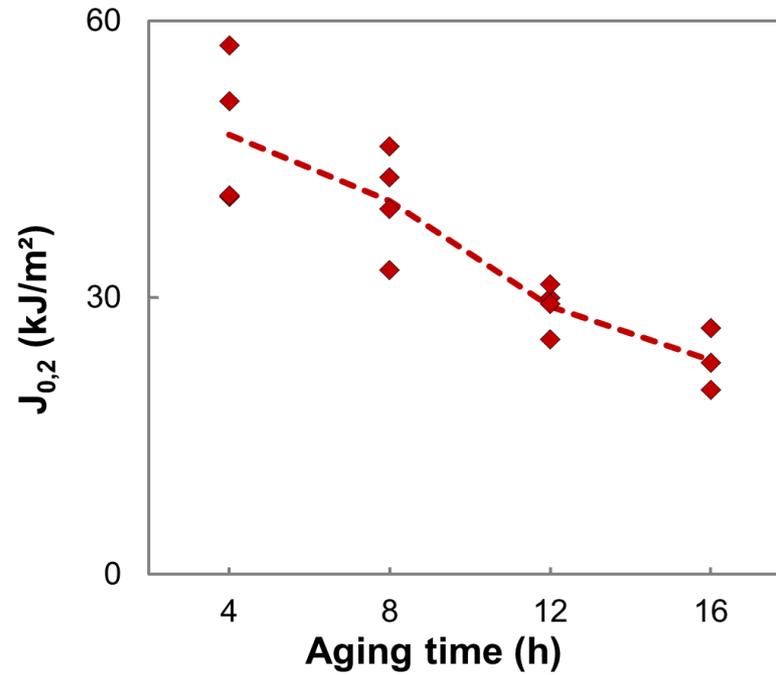


➔ Fracture toughness tests:

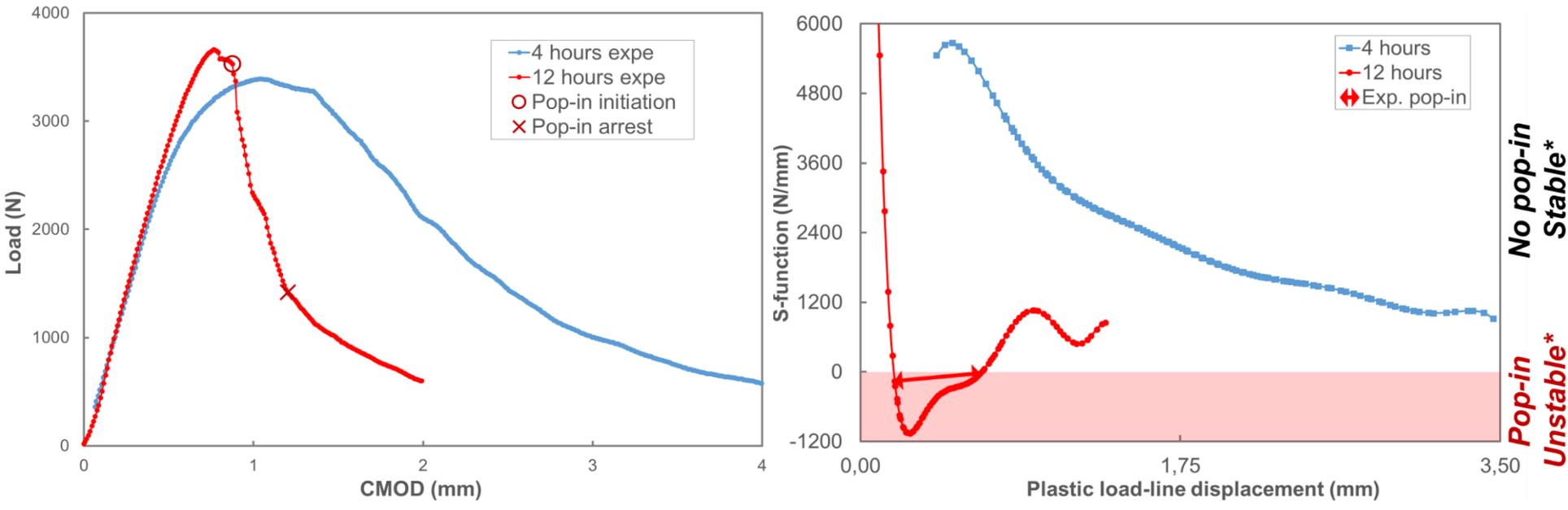


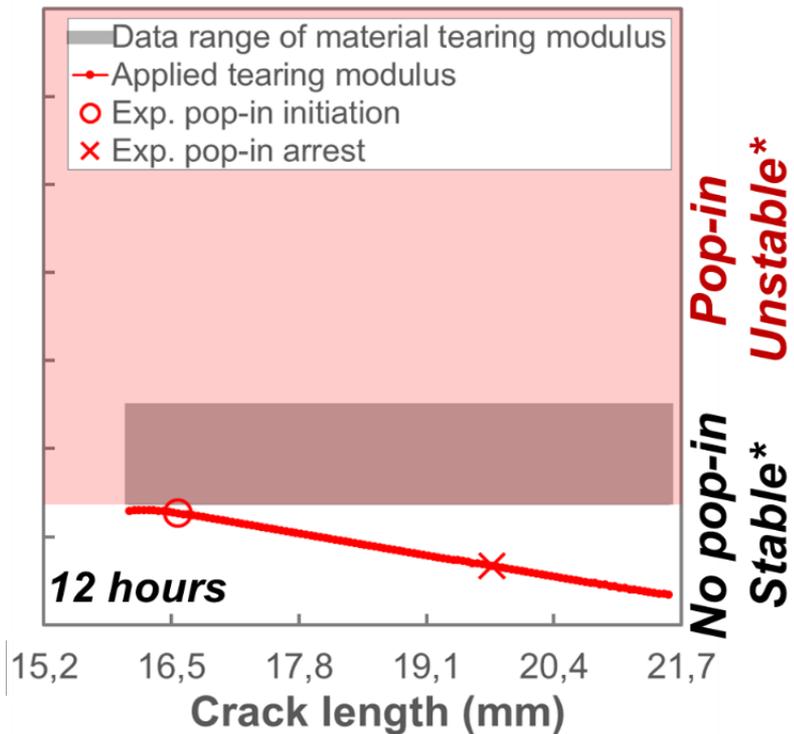
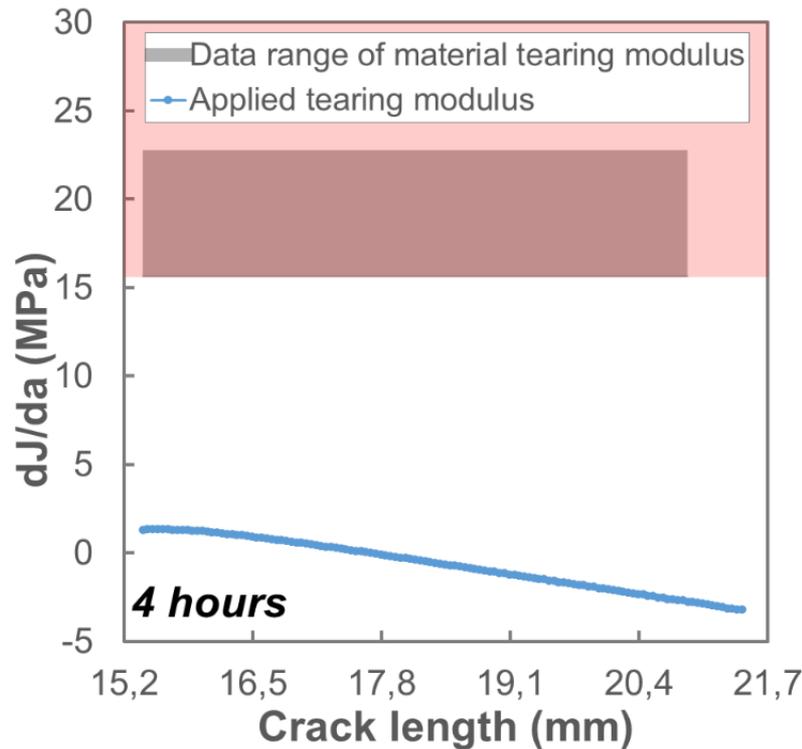
decrease in crack initiation toughness  $J_{0,2}$  and crack growth toughness  $dJ_{mat}/da$  with aging time.

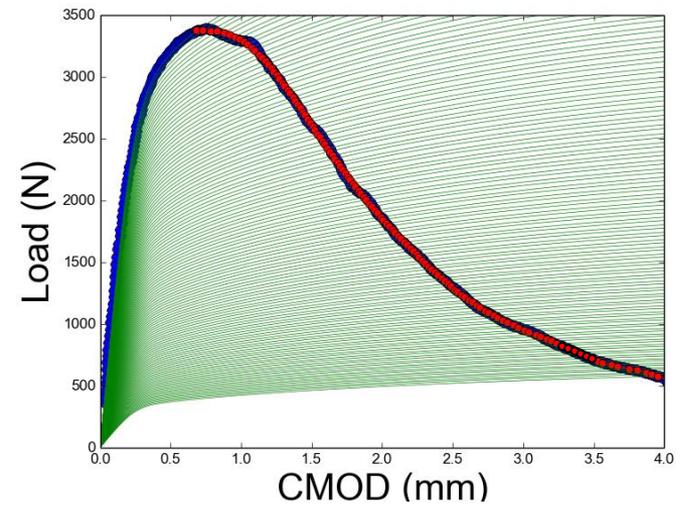
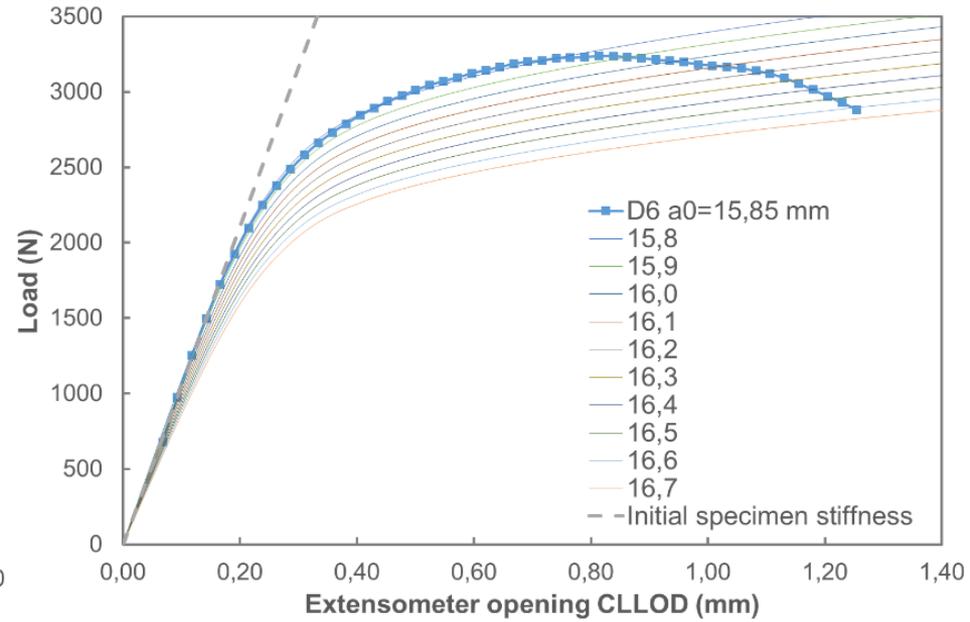
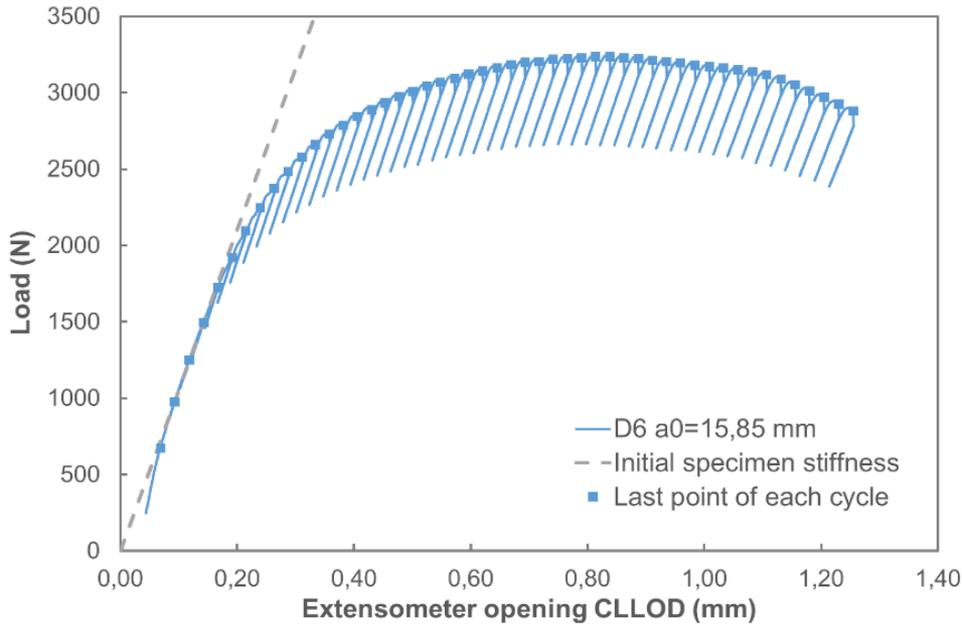




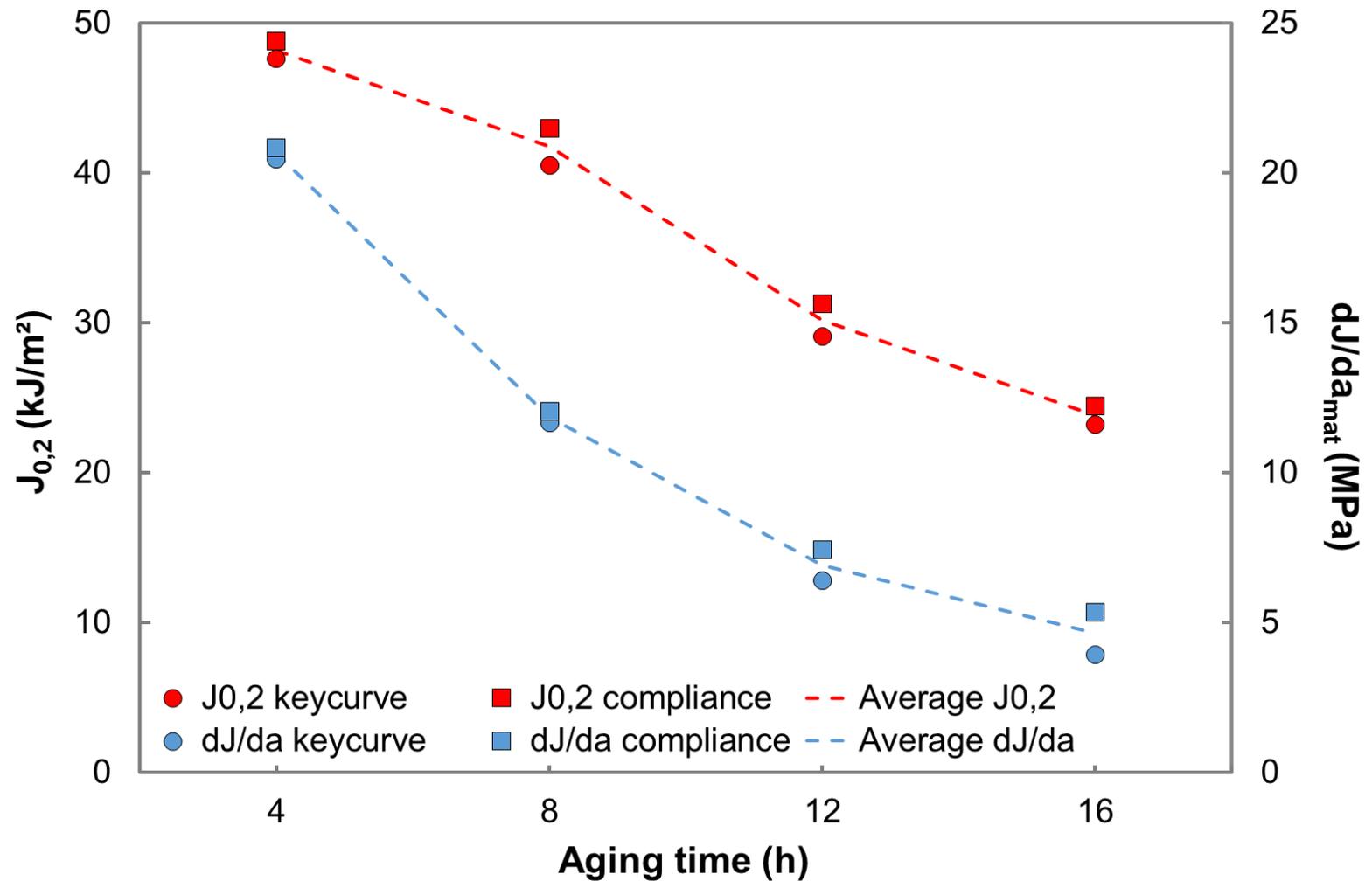
Crack initiation toughness  $J_{0,2}$







## Comparison of keycurve / compliance methods



➔ General small-scale yielding case

$$J(P, a) = \frac{K(P, a)^2}{E}$$

$$dJ(P, a) = \frac{\partial J(P, a)}{\partial P} dP + \frac{\partial J(P, a)}{\partial a} da$$

$$dJ(P, a) = \frac{\partial J(P, a)}{\partial P} f(P, a) da + \frac{\partial J(P, a)}{\partial a} da$$

$$\frac{dJ}{da}(P, a) = T_{app} = g(P, a)$$

$$T_{mat} = \frac{dJ_{mat}}{da} \leq T_{app}(P, a) = g(P, a)$$

$$T_{mat} = \frac{dJ_{mat}}{da} \leq T_{app}(P, a_{eff}) = \frac{g(P, a_{eff})}{1 - \frac{E}{\gamma\pi\sigma_y^2} g(P, a_{eff})}$$

$$du_t(P, a) = 0 = \frac{dP}{K_m} + C_s(a)dP + P \frac{\partial C_s(a)}{\partial a} da$$

$$a_{eff} = a + r_y$$

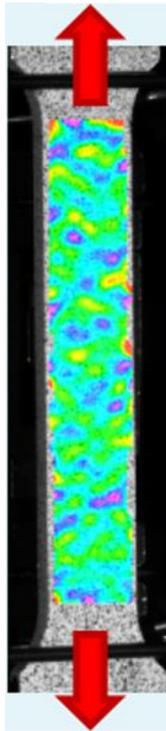
$$\frac{\partial J}{\partial P}(P, a) = \frac{2P(2 + \frac{a}{W})^2}{BB_NWE \left(1 - \frac{a}{W}\right)^3} \sum_{i=0}^4 \alpha_i \left(\frac{a}{W}\right)^i$$

$$\frac{\partial J}{\partial a}(P, a) = \frac{P^2(2 + \frac{a}{W})}{BB_NWE \left(1 - \frac{a}{W}\right)^3} \sum_{i=0}^4 \alpha_i \left(\frac{a}{W}\right)^i \left[ \left(2 + \frac{a}{W}\right) \sum_{i=0}^3 \beta_i \left(\frac{a}{W}\right)^i + \frac{2}{W} \sum_{i=0}^4 \alpha_i \left(\frac{a}{W}\right)^i + \frac{3(2 + \frac{a}{W})}{W(1 - \frac{a}{W})} \sum_{i=0}^4 \alpha_i \left(\frac{a}{W}\right)^i \right]$$

$$f(P, a) = -BK_m P \frac{\sum_{i=0}^7 \gamma_i W^{7-i} a^i}{BB_N E \sum_{i=0}^3 \delta_i W^{8-i} a^i + BK_m \sum_{i=0}^8 \varepsilon_i W^{8-i} a^i + EB_n^2 \sum_{i=0}^3 \zeta_i W^{8-i} a^i}$$

$$g(P, a) = \frac{P^2(2 + \frac{a}{W})}{BB_NWE \left(1 - \frac{a}{W}\right)^3} \left[ \sum_{i=0}^4 \alpha_i \left(\frac{a}{W}\right)^i \right]^2 \left[ \frac{2}{W} + \frac{3(2 + \frac{a}{W})}{W(1 - \frac{a}{W})} + \frac{(2 + \frac{a}{W}) \sum_{i=0}^3 \beta_i \left(\frac{a}{W}\right)^i}{\sum_{i=0}^4 \alpha_i \left(\frac{a}{W}\right)^i} \right] + \frac{-2BK_m \left(2 + \frac{a}{W}\right) \sum_{i=0}^7 \gamma_i W^{7-i} a^i}{BB_N E \sum_{i=0}^3 \delta_i W^{8-i} a^i + BK_m \sum_{i=0}^8 \varepsilon_i W^{8-i} a^i + EB_n^2 \sum_{i=0}^3 \zeta_i W^{8-i} a^i}$$

	0	1	2	3	4	5	6	7	8
$\alpha_i$	0.886	4.64	-13.32	14.72	-5.6				
$\beta_i$	9.28	-53.28	88.32	-44.8					
$\gamma_i$	11564	13440	-47940	16036	82907	-48357	-38547	26865	
$\delta_i$	1000	-3000	3000	-1000					
$\varepsilon_i$	1403	7355	-6417	-18321	15994	16573	-16353	-5607	5373
$\zeta_i$	-500	1500	-1500	500					



- *No mobile strain bands*
- *No serration on the stress-strain curve*
- *No reverse sensitivity to strain rate*



No PLC effect (contrary to the literature)



**No link PLC / pop-in**

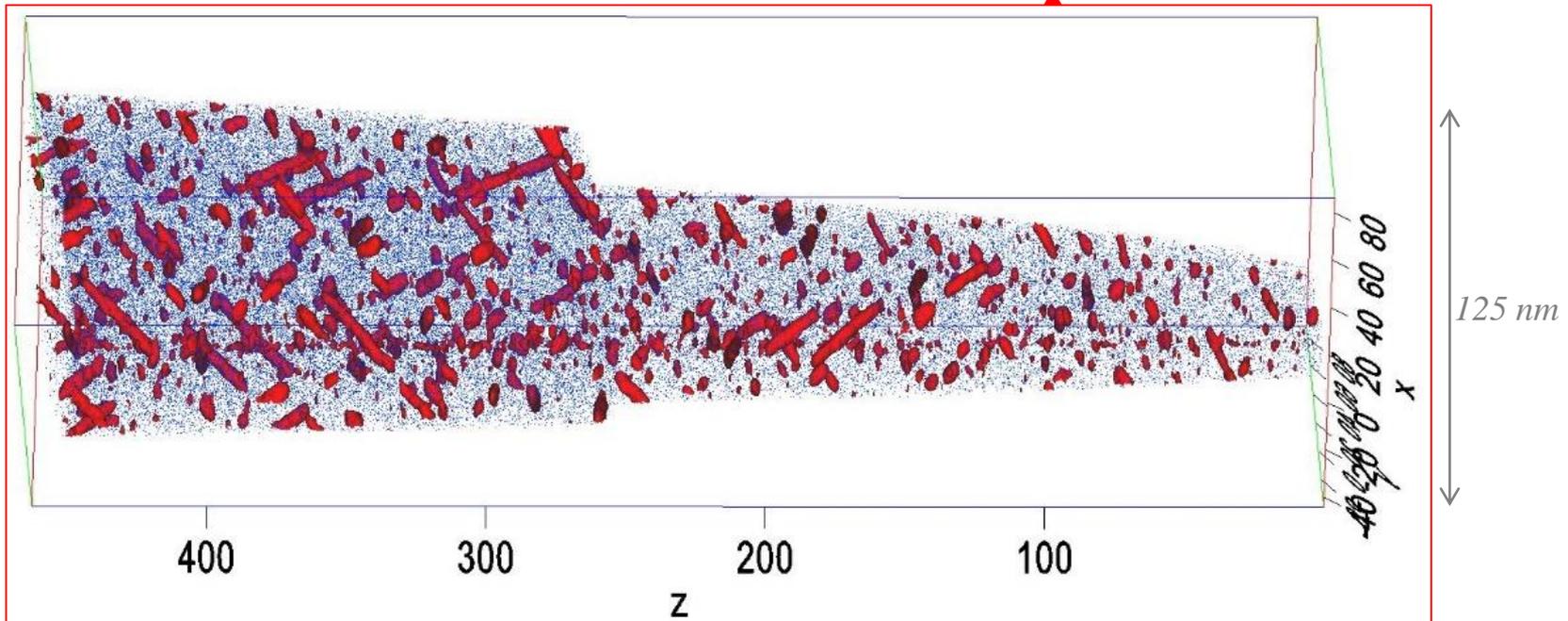
➔ Aluminium 6061-T6

➔ Age-hardened alloy → 4 aging times (175 °C) to obtain 4 metallurgical states:

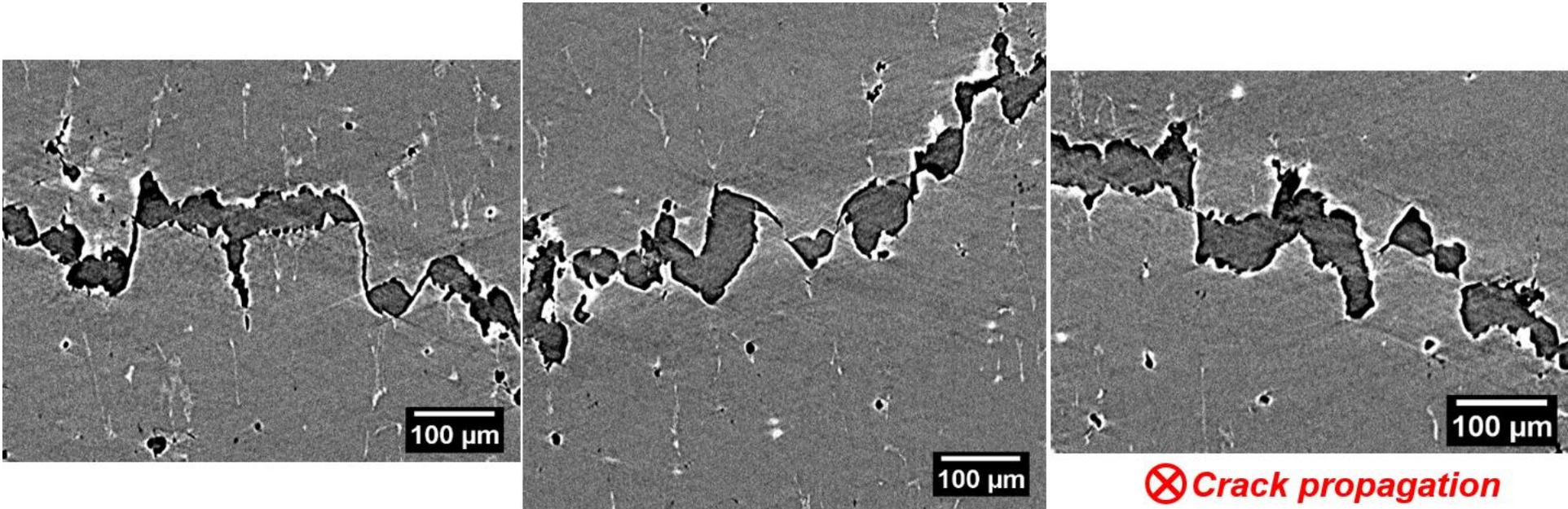
Aging time (h)

4	8	12	16
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Strength ↗



*Atom Probe Tomography*



Impurity

Resistance to grain growth

	Mg	Si	Fe	Cu	Cr	Mn	Zn	Ti
Min %	0.8	0.4	0.04	0.15	0.04	0.15		
Max %	1.2	0.8	0.7	0.4	0.35	0.15	0.25	0.15

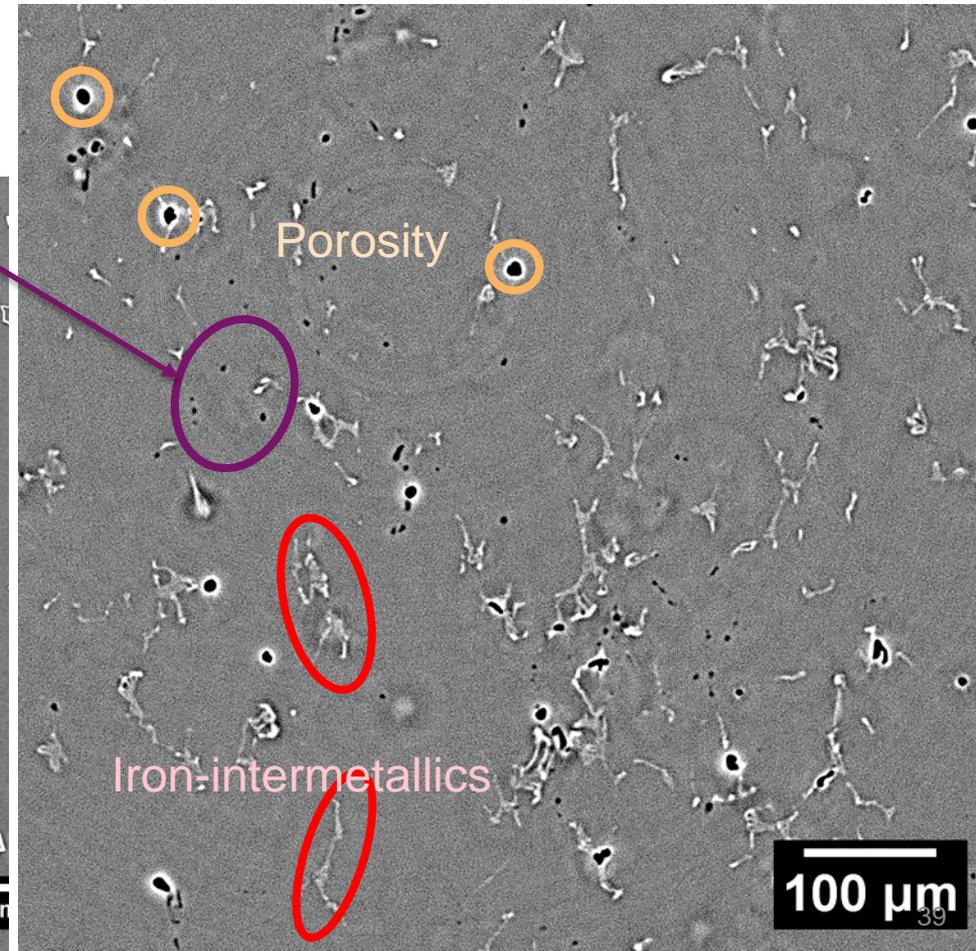
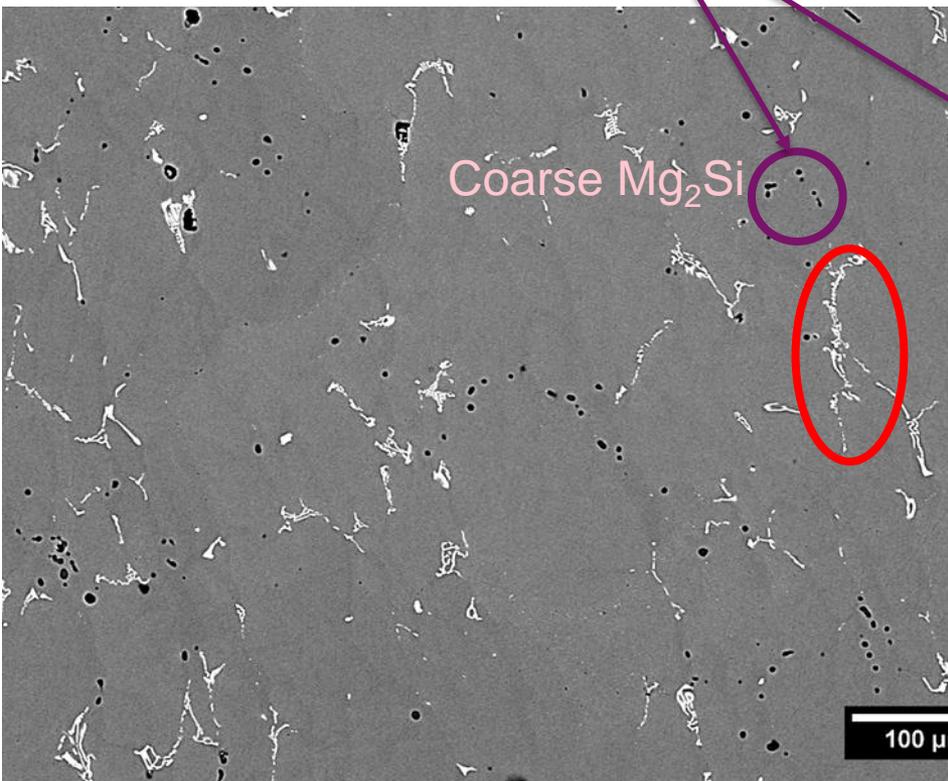
Norme NF EN 573-1

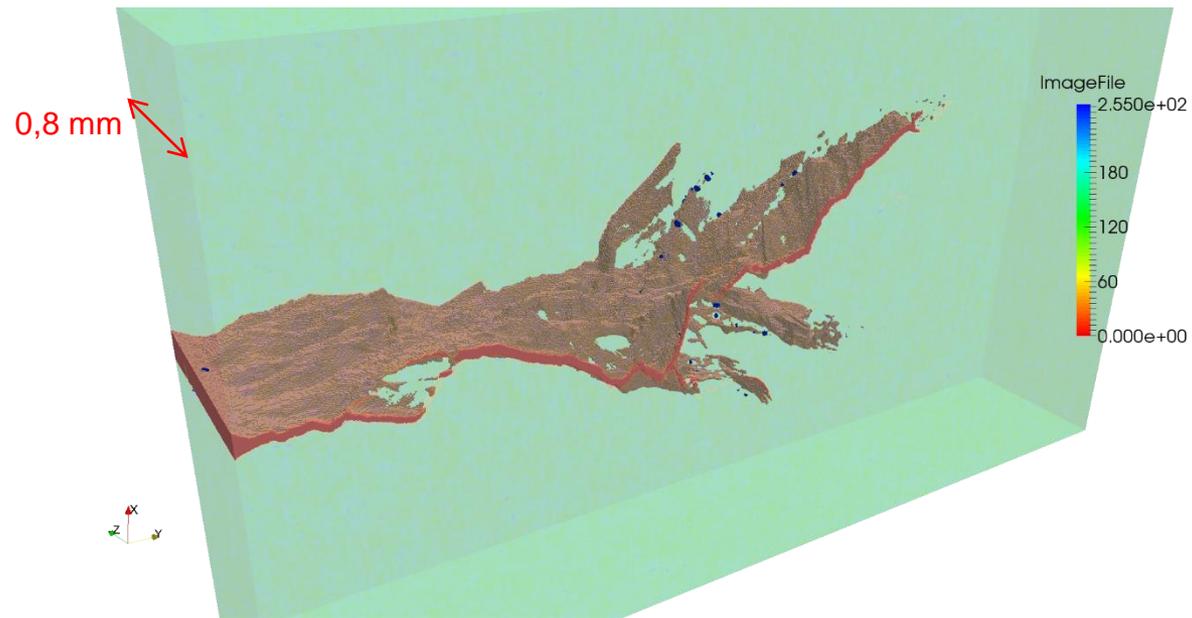
+++ Structural hardening (during ageing)

--- Clusters of coarse precipitates (during quench)

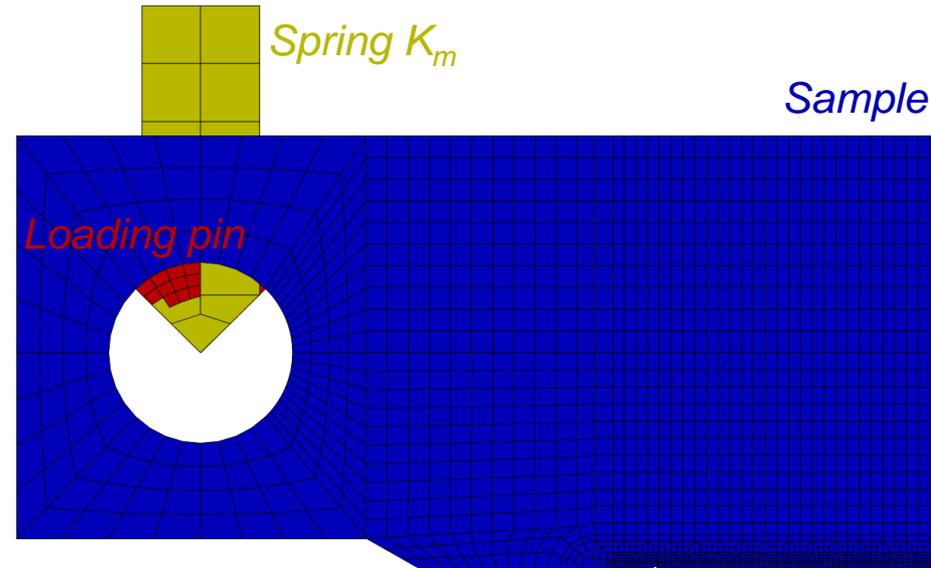
Synchrotron laminography

SEM

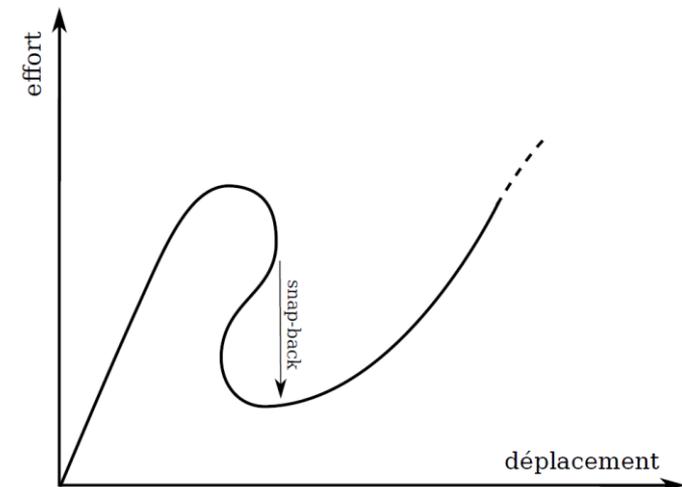


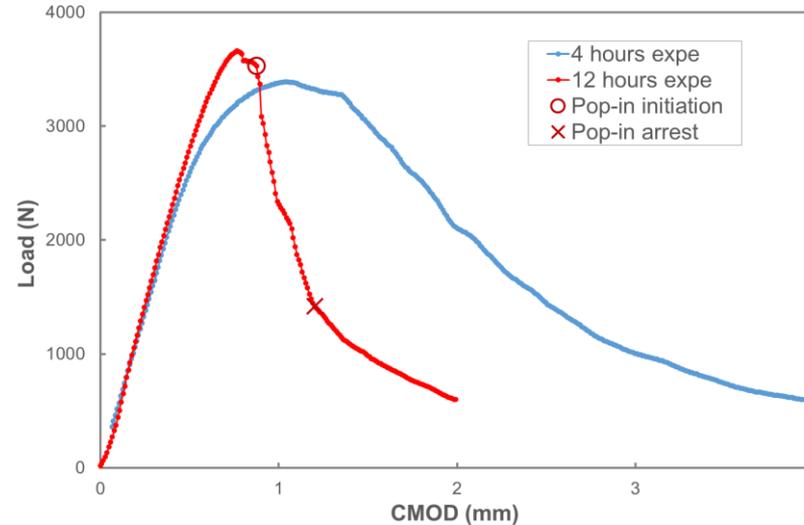


- Rajout d'un ressort à raideur variable dans la simu 2D :

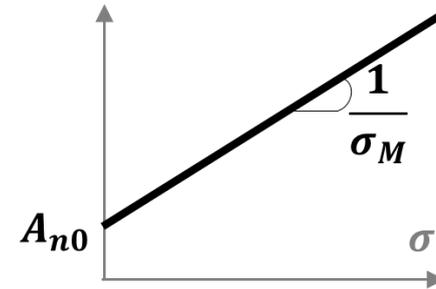


- Pilotage en longueur d'arc : méthode incrémentale de Riks
- Principe : ajouter aux équations d'équilibre une équation imposant la longueur du vecteur incrémental dans le plan charge/déplacement -> le chargement appliqué devient une variable additionnelle du problème





Nucleation



• Méthode :

- Extraction de la contrainte principal  $\sigma_I$
- $\dot{f}_n = A(\sigma_I)\dot{p}$
- $A(\sigma_I) = A_{n0} + \frac{\sigma_I}{\sigma_M}$

• Paramètres d'optimisation :

- $q_1$  (Tvergaard). Potentiel plastique :  $\phi(\sigma_{eq}, \sigma_m, \bar{\sigma}, f) = \left(\frac{\sigma_{eq}}{\bar{\sigma}}\right)^2 + 2q_1 f \cosh\left(\frac{3q_2 \sigma_m}{2\bar{\sigma}}\right) - (1 + q_3 f)^2 = 0$
- $A_{n0}$
- $\sigma_M$
- *fact* (facteur géométrique permettant de dilater le maillage fin)

- Zebulon
- Éléments quadrangles (8 noeuds) linéaires à intégration sélective
- Comparaison 2D déf planes – 3D validée
- Différents traitements thermiques :
  - **Loi élastoplastiques** (Voce) **différentes**
  - **Lois d'endommagement** (Gurson et nucléation par les contraintes) **identiques**
- Après optimisation des paramètres :

