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16TH EUROPEAN MECHANICS OF MATERIALS CONFERENCE

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

NANTES | TUESDAY, MARCH 27TH 2018

16TH EUROPEAN MECHANICS OF MATERIALS CONFERENCE

DE LA RECHERCHE À L'INDUSTRIE

DEFINITION

EXPERIMENTAL INVESTIGATIONS

INSTABILITY CRITERIA

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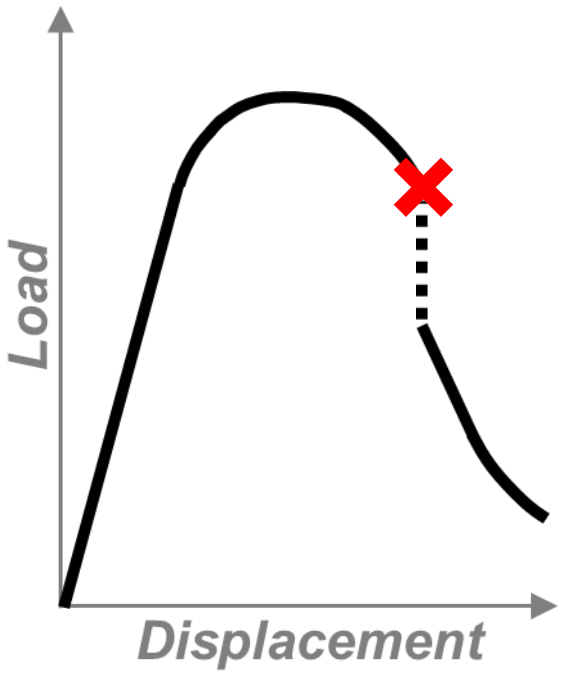
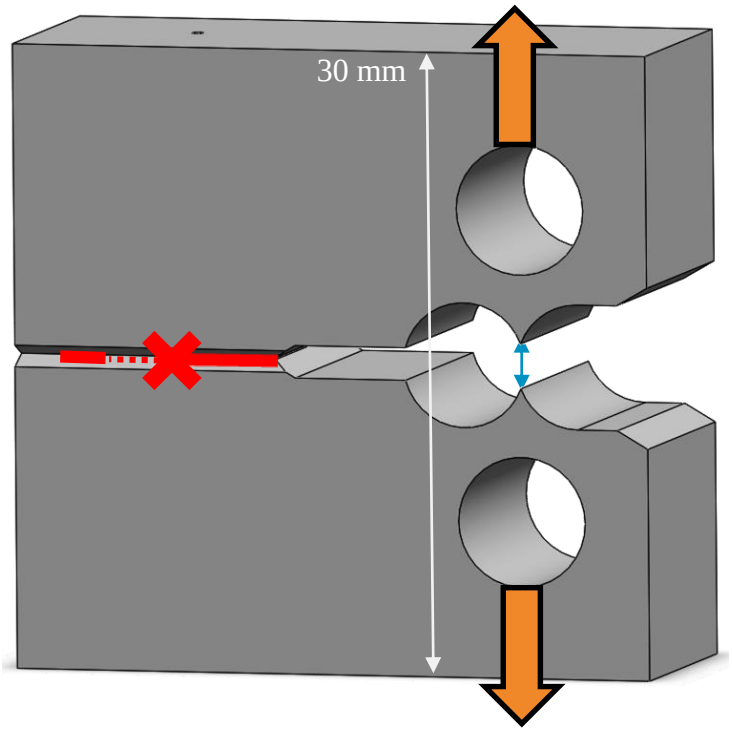
NANTES | TUESDAY, MARCH 27TH 2018

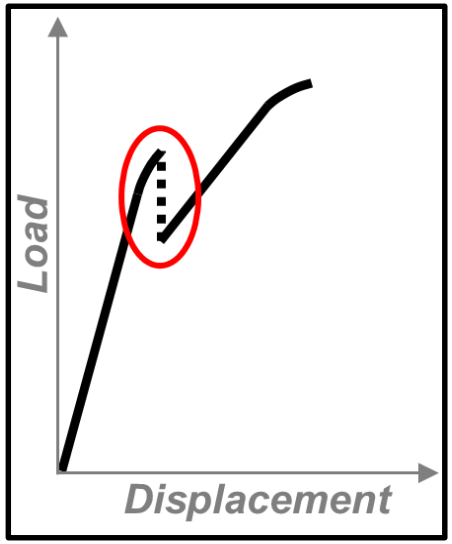
➡ Fracture toughness tests

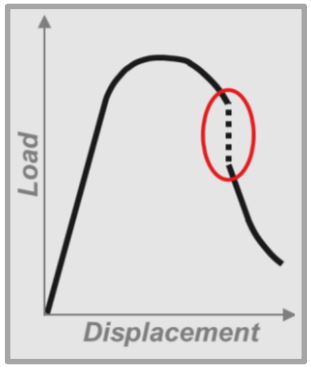
➡ "**Pop-in**" = **local instability** leading to **rapid but limited crack propagation** associated with a sudden decrease in load





- 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 :

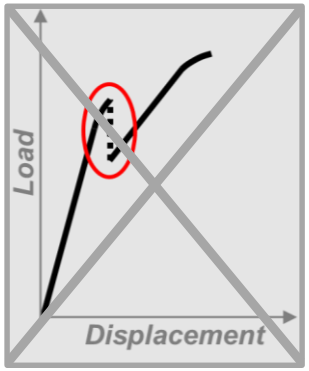




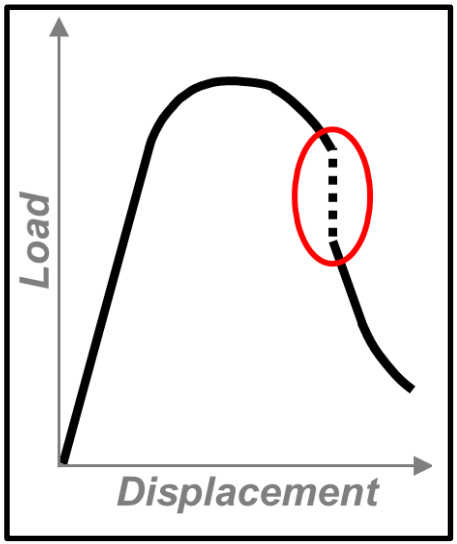
➡ Microstructural origin
Before max load
Typical for brittle fracture

➡ 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

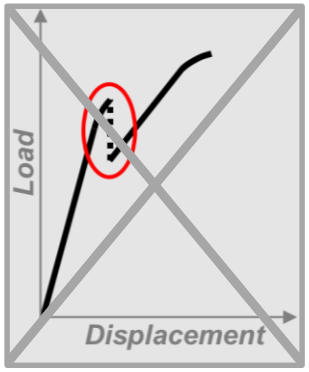
Mechanical origin
After max load
Typical for ductile fracture

Second pop-in type: "Tearing" mechanism

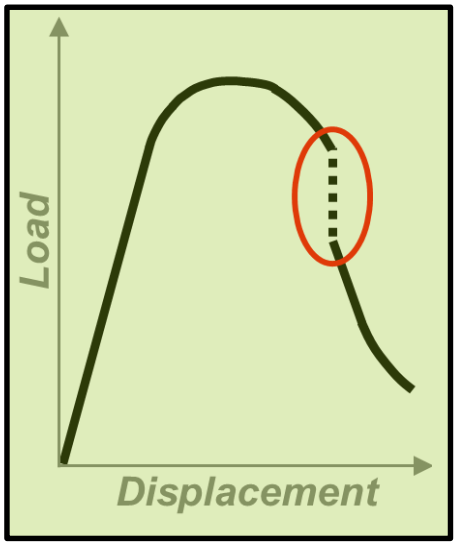
Origin ?

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	Crack growth toughness

POP-IN ?

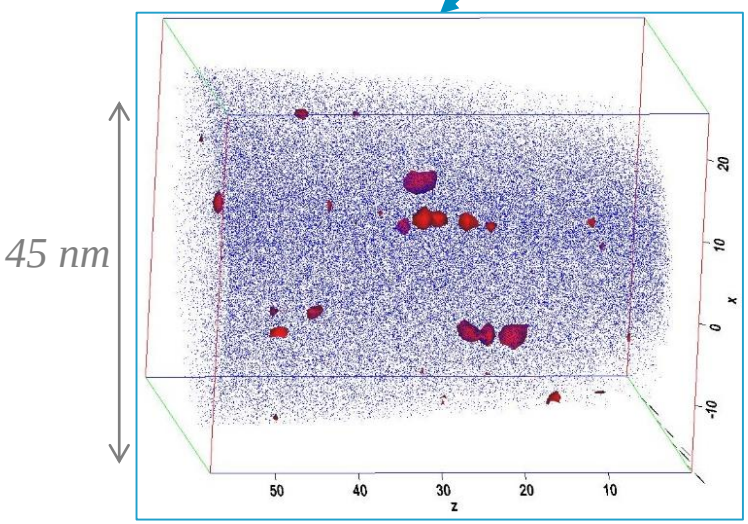
➡ Aluminium 6061-T6

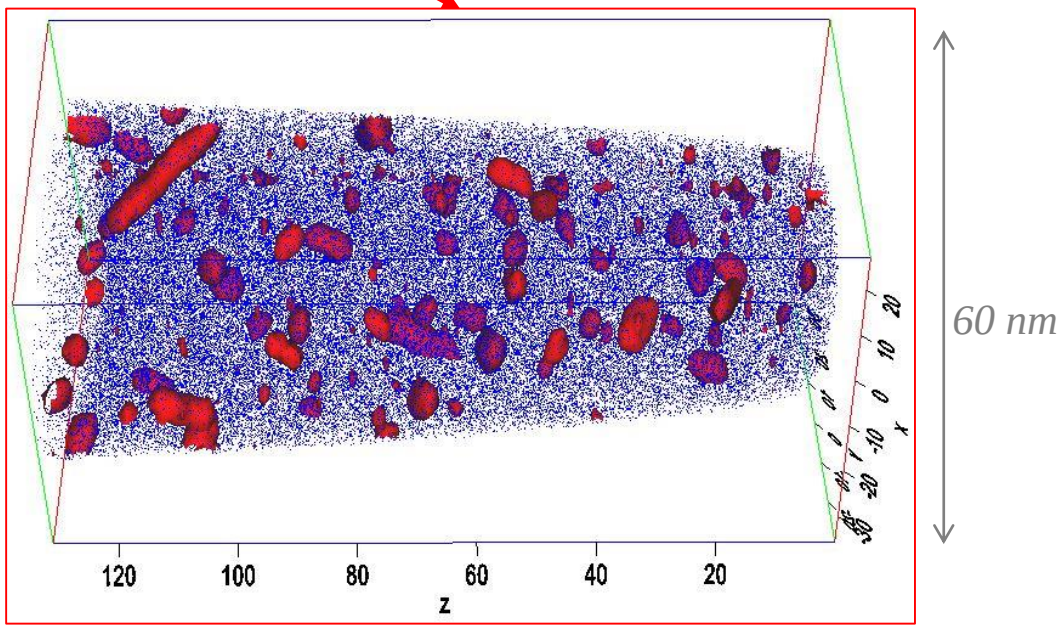
➡ Age-hardened alloy → 4 aging times (175 °C) to obtain 4 metallurgical states:

Aging time (h)

4	8	12	16

Strength ↗

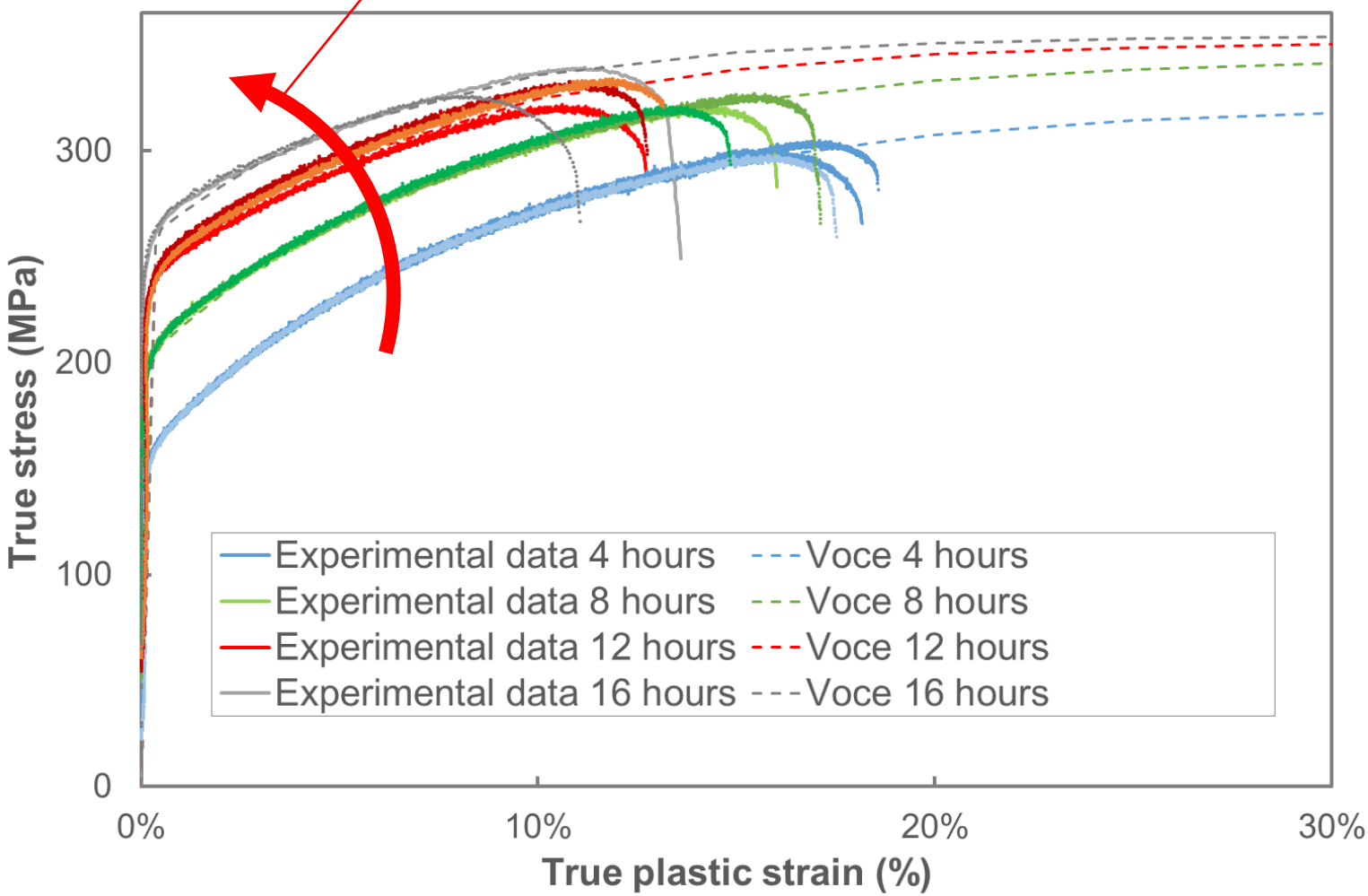




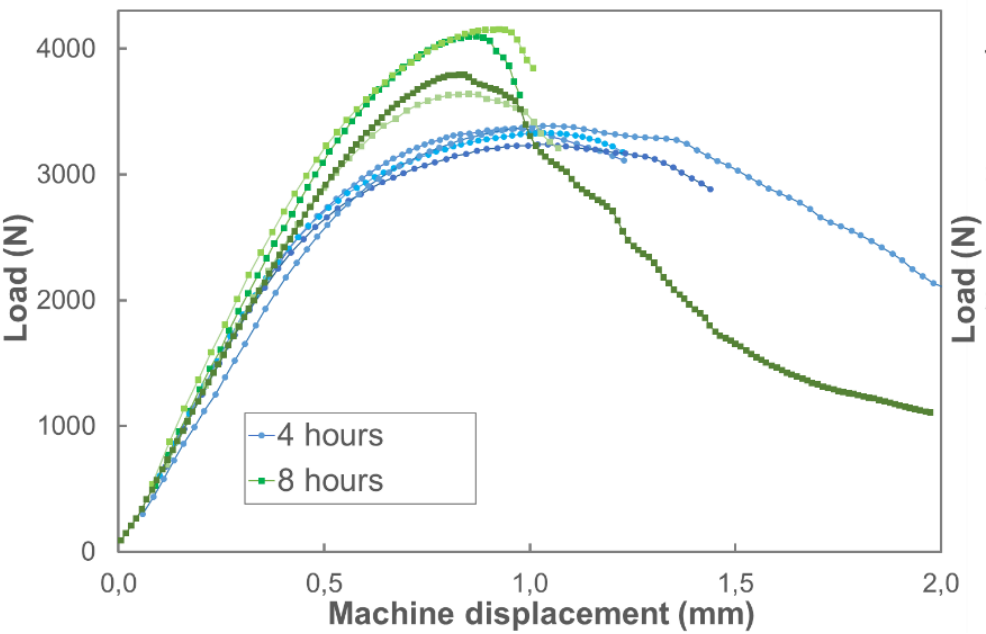
Atom Probe Tomography

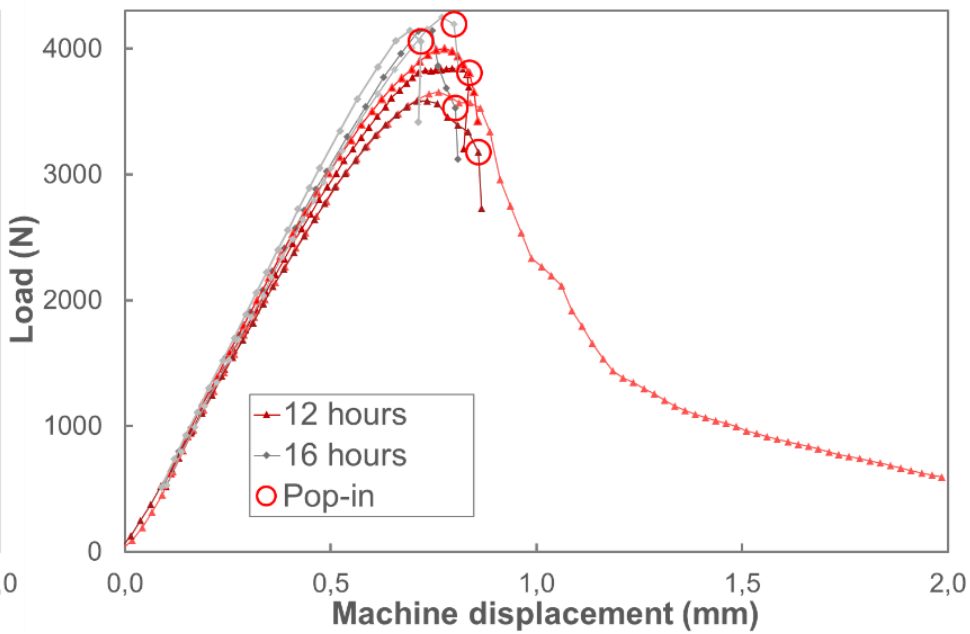
➡ Tensile tests:

Aging time **strongly hardens** the aluminum alloy



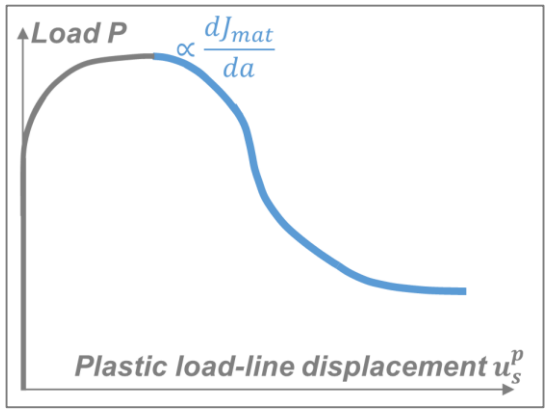
➡ Fracture toughness tests:

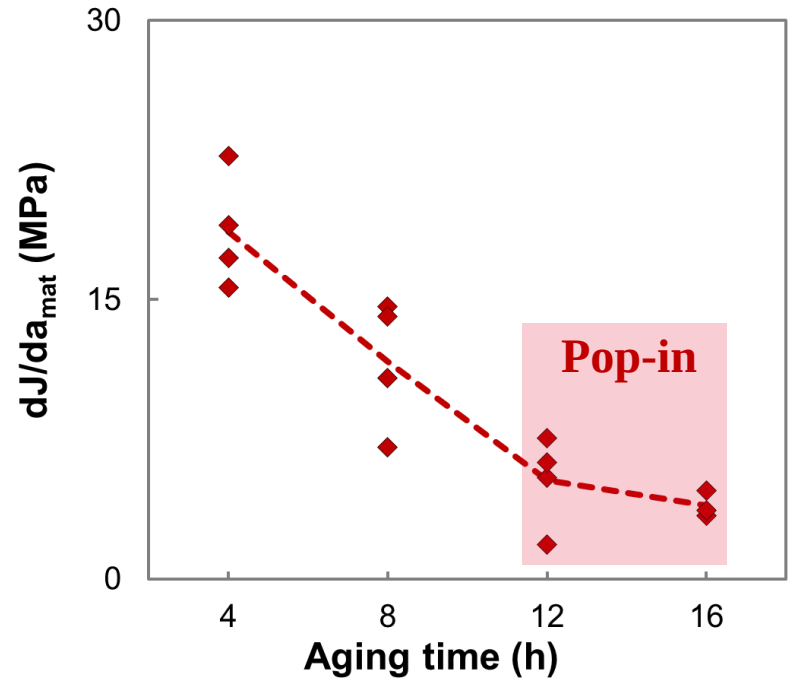




➡ **Pop-in appearance** after 12 and 16 hours of aging time

➡ Fracture toughness tests:





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

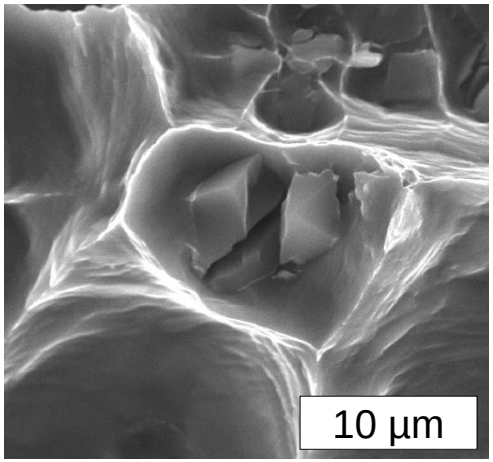
➡ Link between :

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

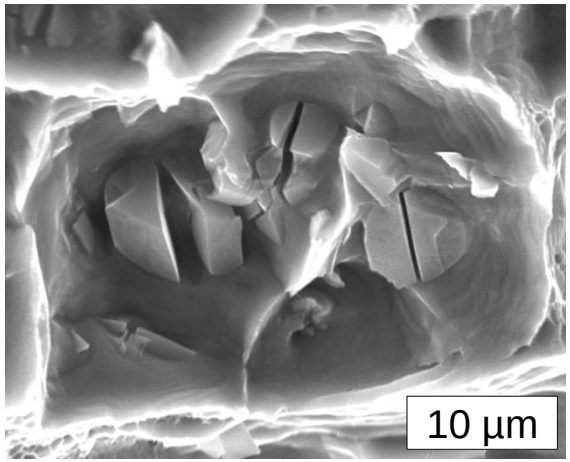
➡ Fracture mechanisms:

Scanning electron microscope

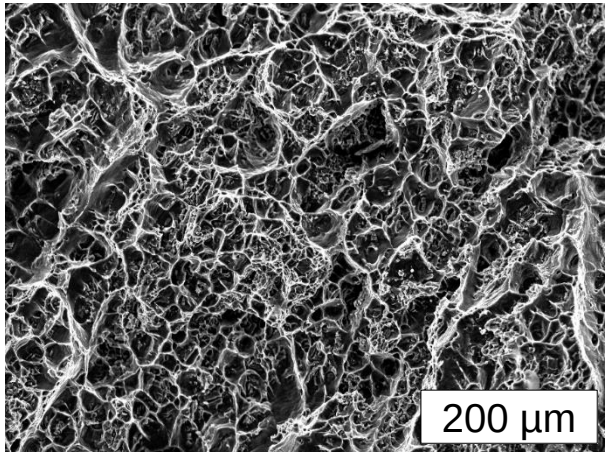
No pop-in *(aging: 4 h)*

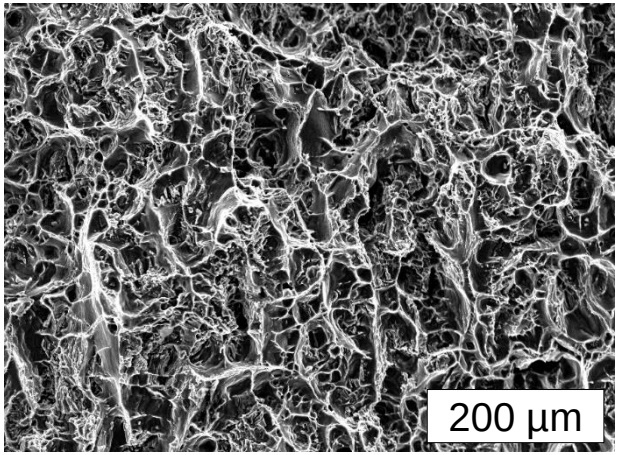


With pop-in *(aging : 12 h)*



- Broken coarse **Mg_2Si** in dimples
- Nucleation controlled by **coarse precipitates** (Mg_2Si & IMF)

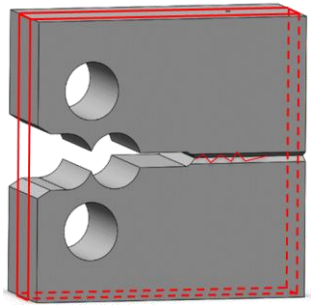




- **Ductile failure** micromechanisms
- Void growth to coalescence by **internal necking** (and void-sheeting) mechanisms

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

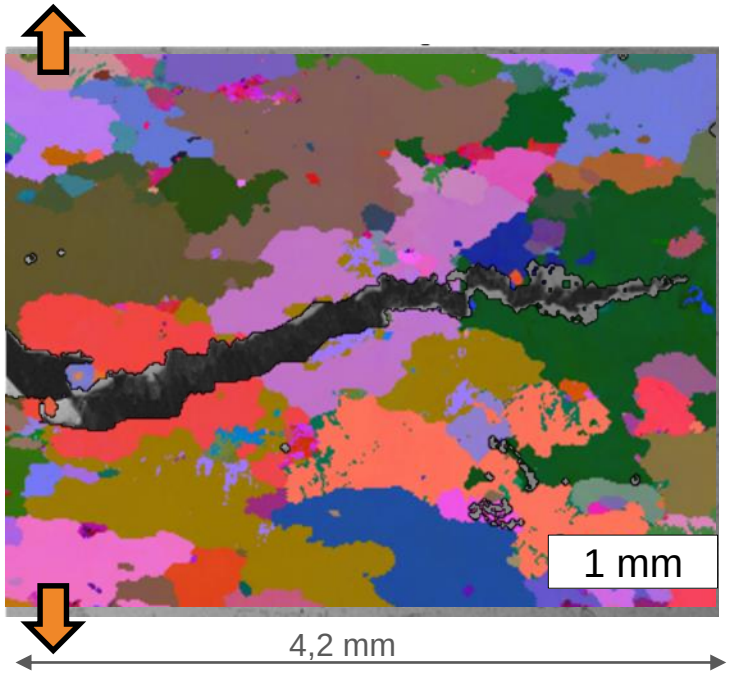
➡ Fracture mechanisms:

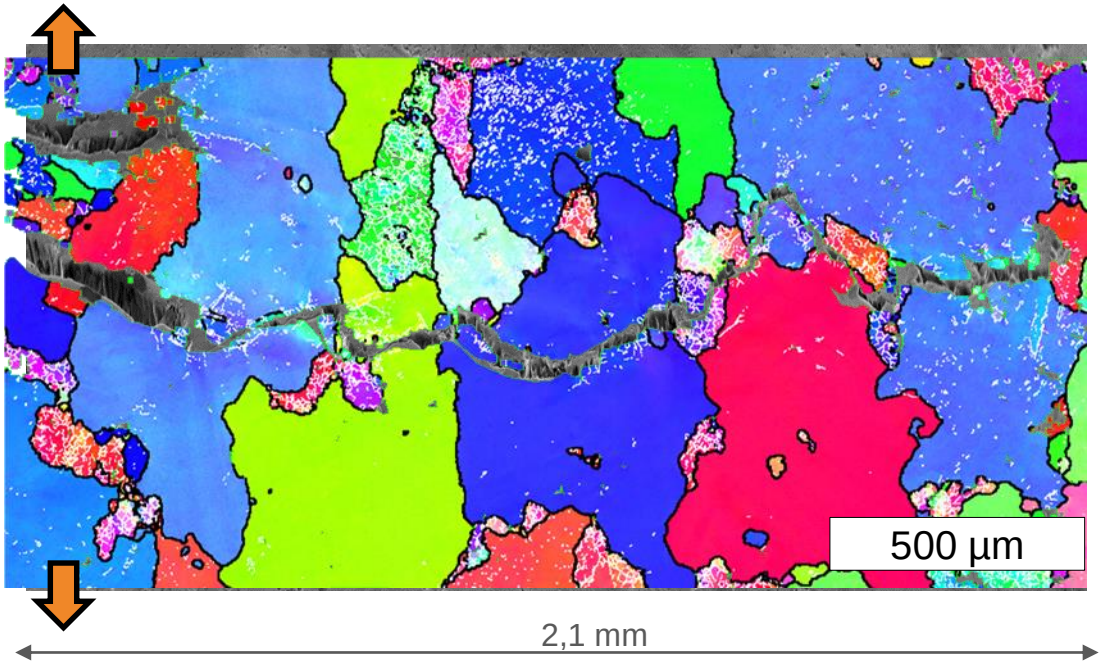


Scanning electron microscope

+

EBSD

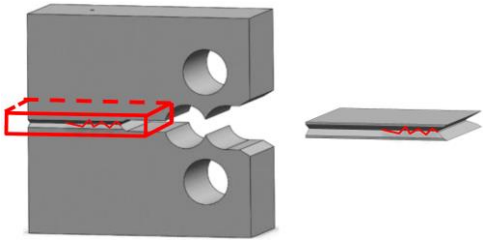




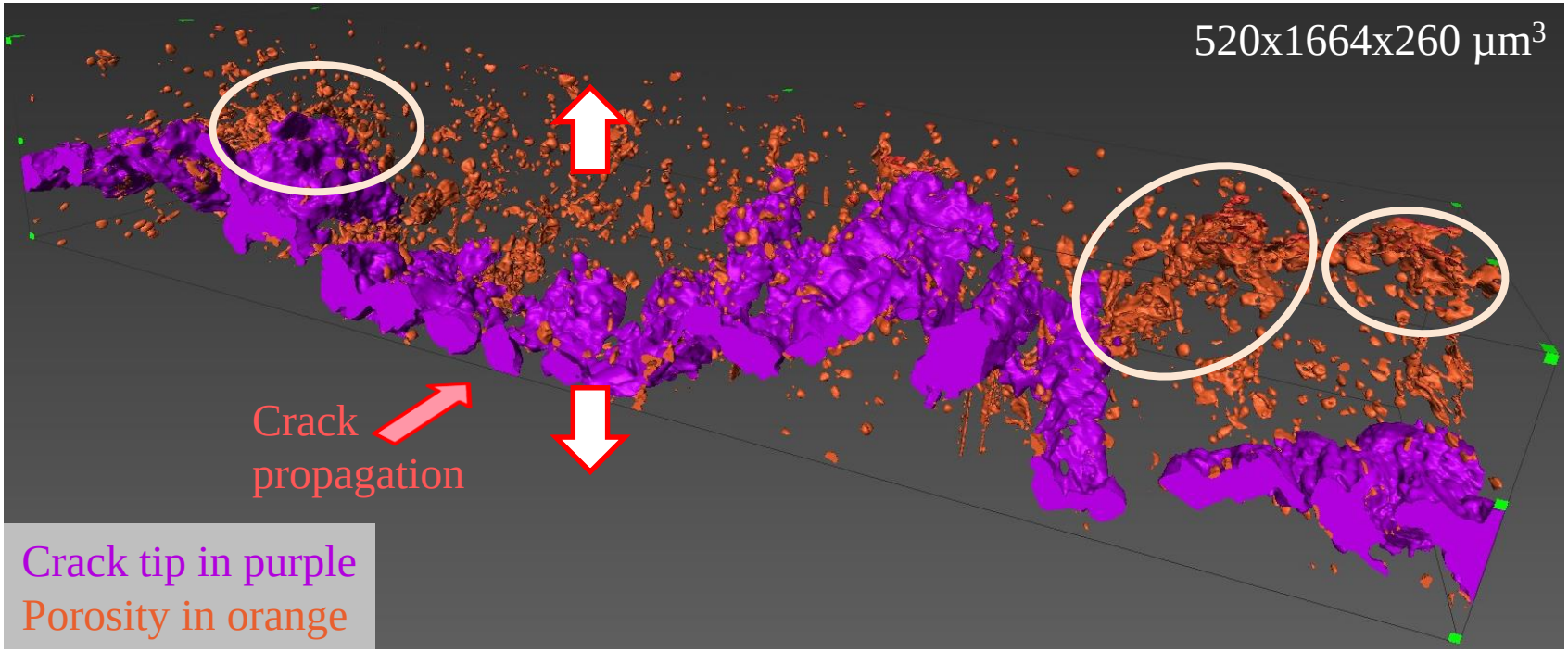
➡ No preferential localization of coarse particles: mainly **transgranular fracture**

➡ Intergranular fracture around the small grains

➡ Fracture mechanisms:

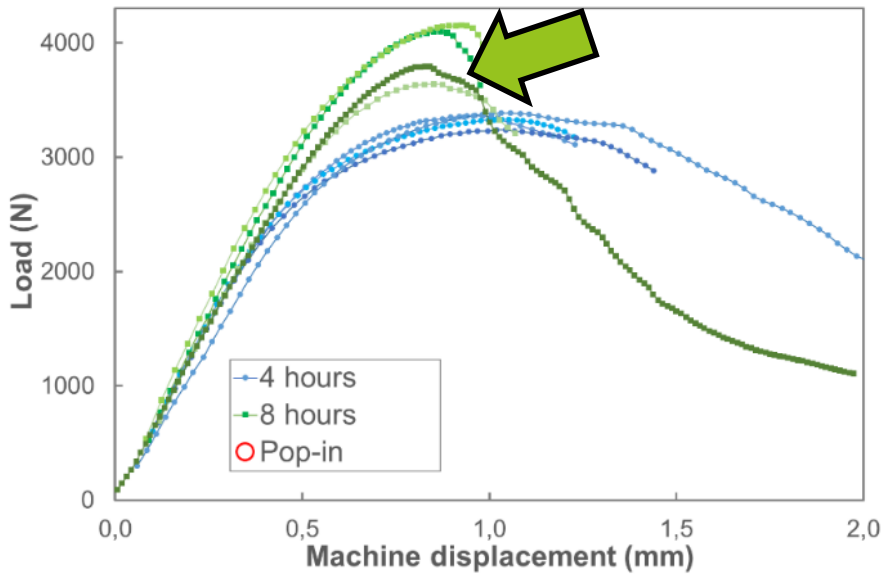


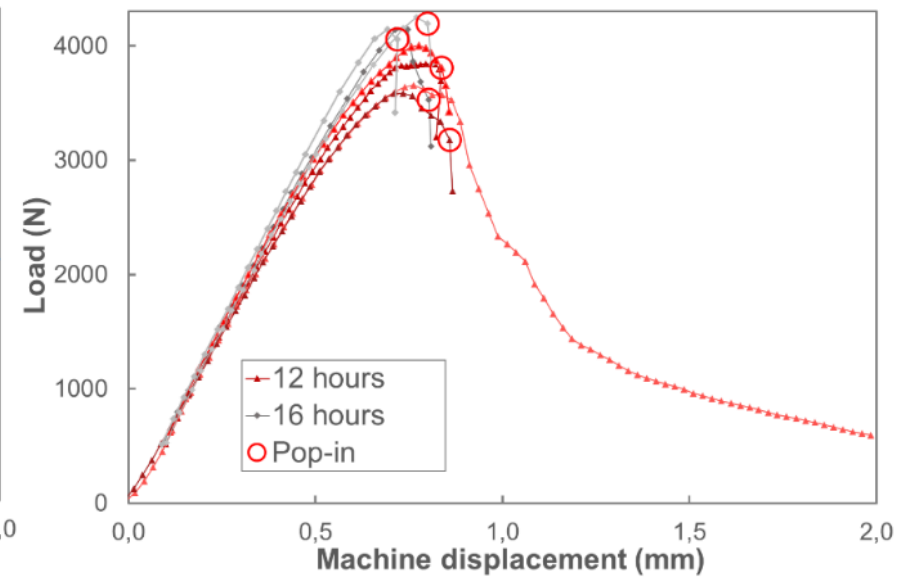
Tomography:
Synchrotron laminography (ESRF, Grenoble)



- ➡ **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 ➡ 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**

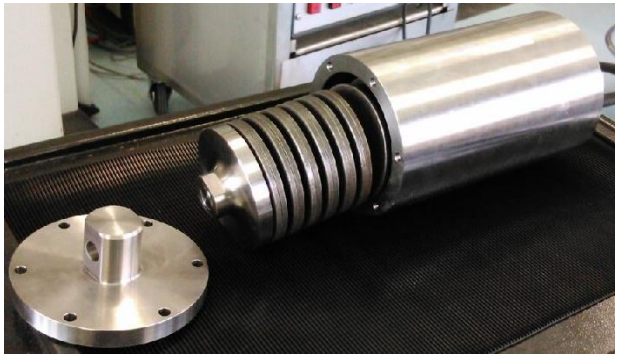
Low **strain hardening** ability
↔
Low **tearing modulus**
↔
Pop-in

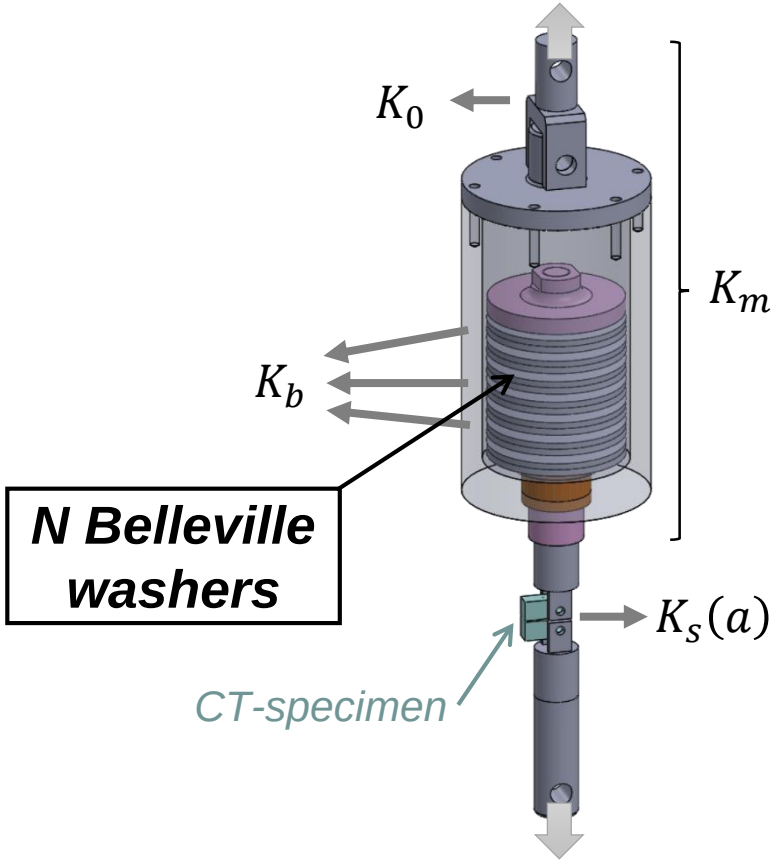
System
Machine stiffness

POP-IN ?

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

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

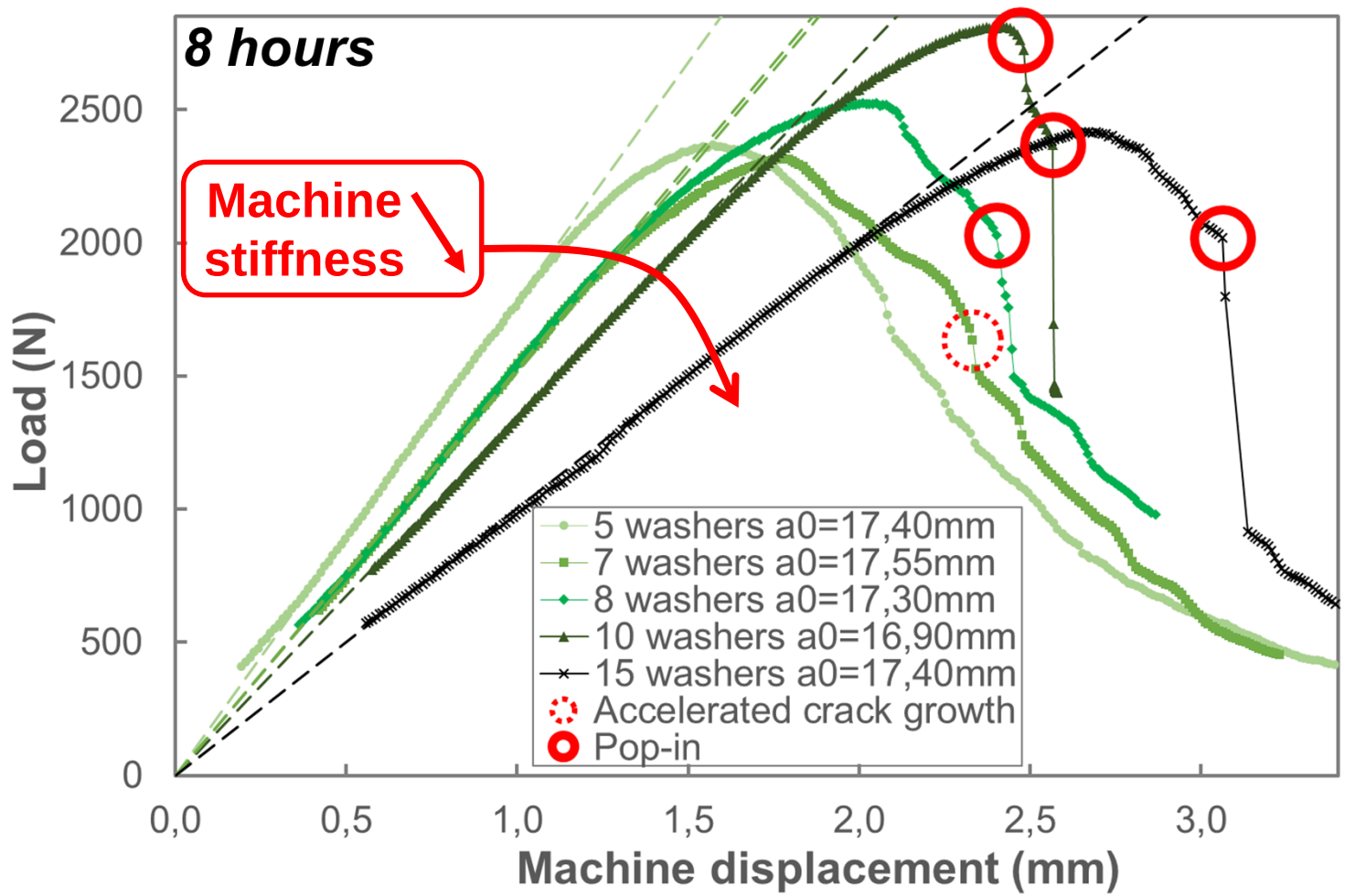




$$K_m(N) = \frac{K_0 K_b}{N K_0 + K_b}$$

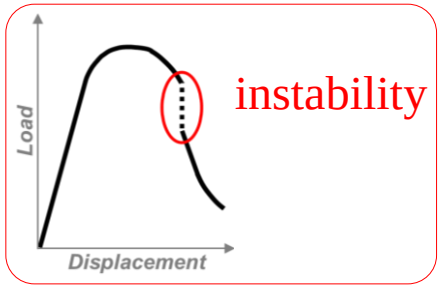
$$K_t(N,a) = \frac{K_m(N) K_s(a)}{K_m(N) + K_s(a)}$$

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



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

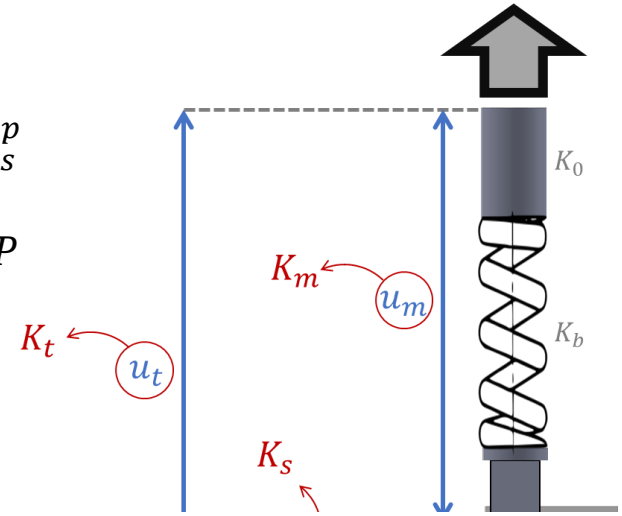
Instability criterion ? ➡ *'Load' approach*

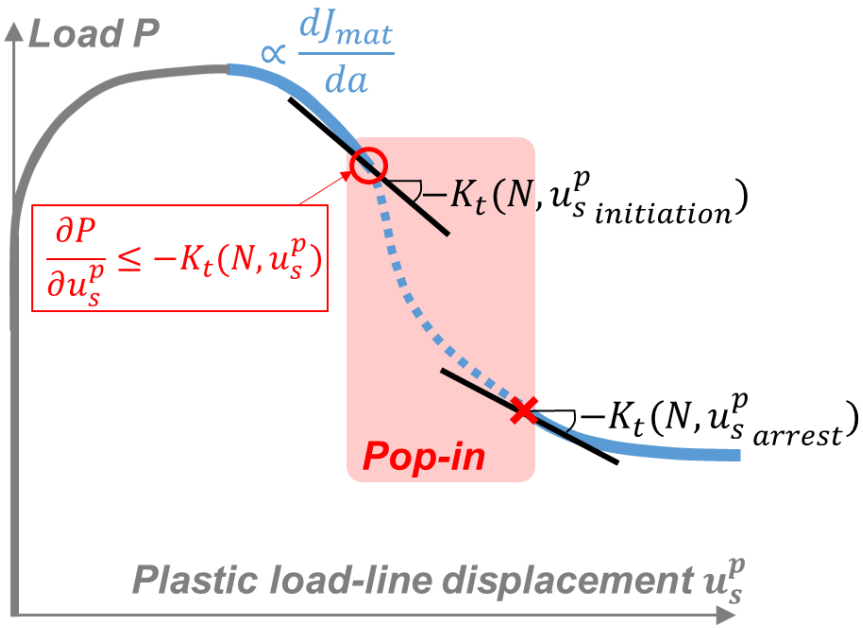


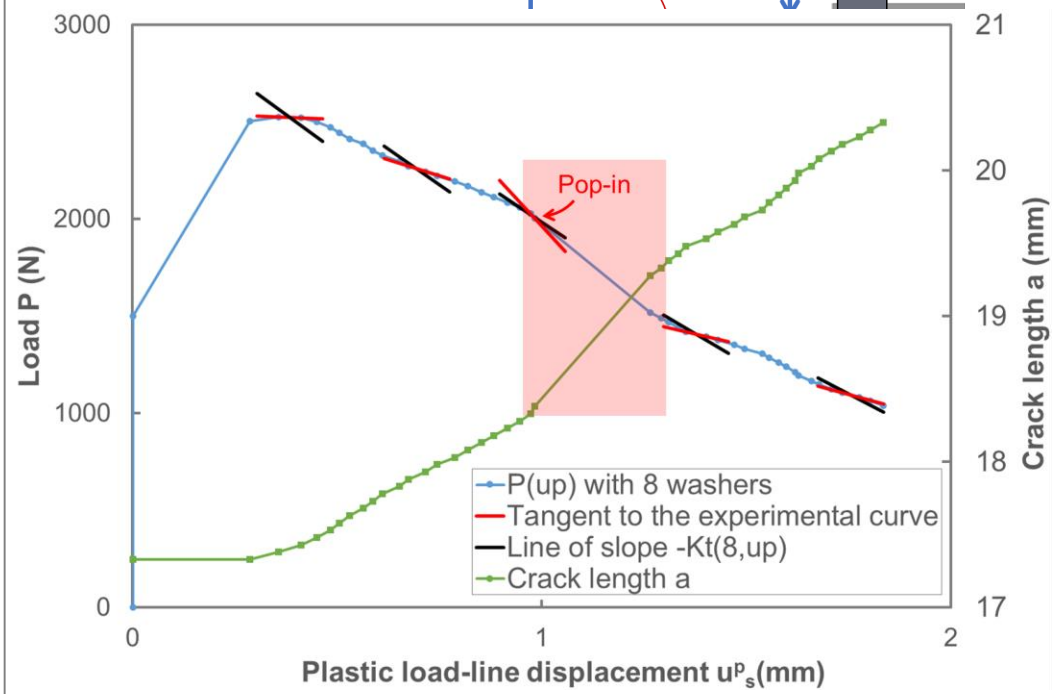
$$u_t = u_m + u_s = u_m + u_s^e + u_s^p$$

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

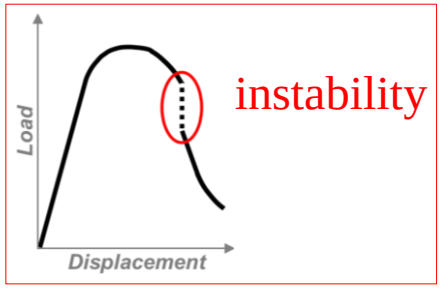
$$\boxed{\frac{\partial P}{\partial u_s^p} \leq -K_t(N, u_s^p)}$$







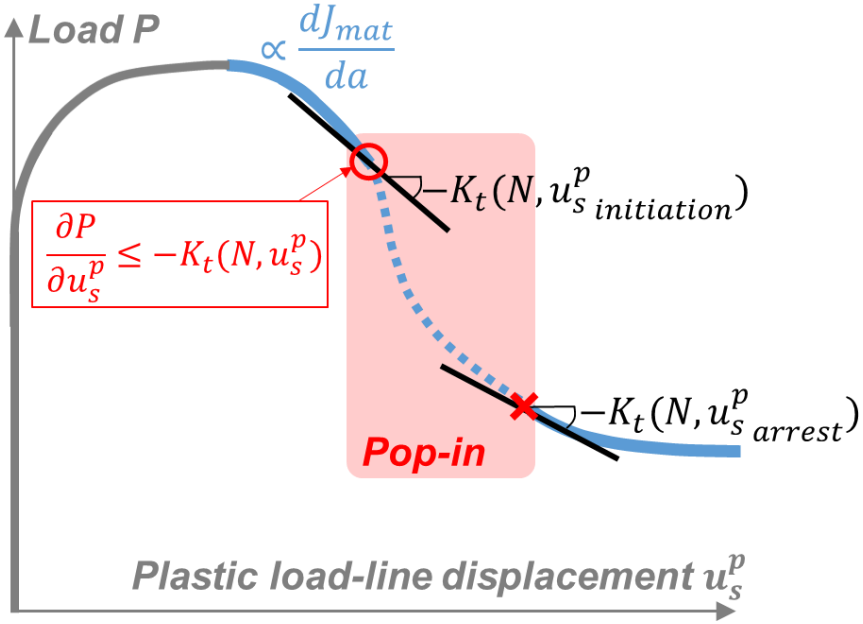
Instability criterion ? ➡ *'Load' approach*

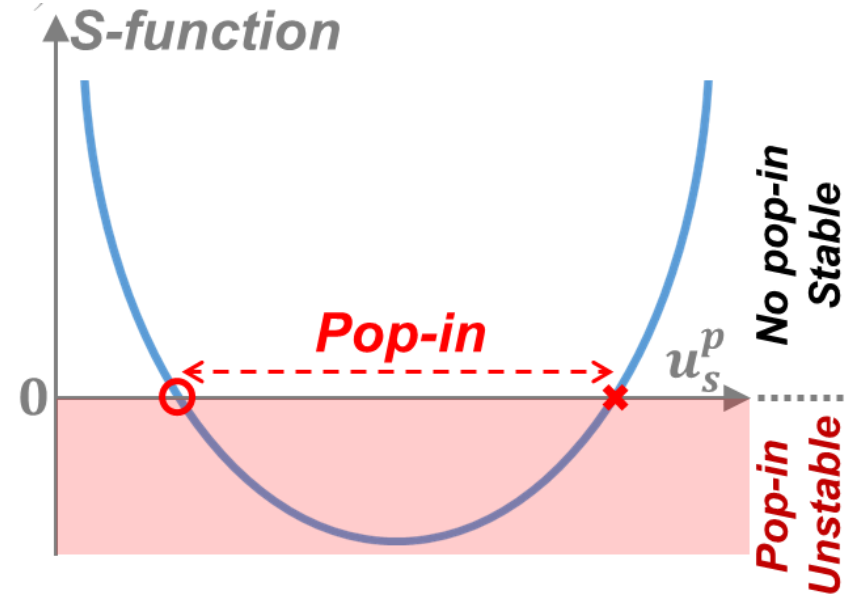


$$u_t = u_m + u_s = u_m + u_s^e + u_s^p$$

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

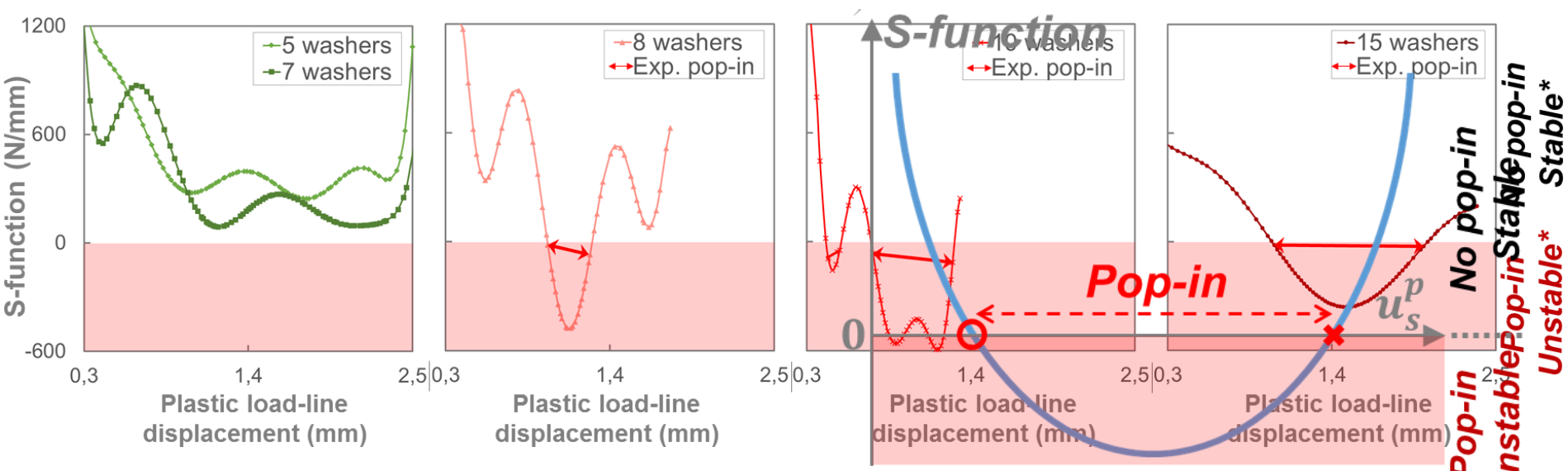
$$\frac{\partial P}{\partial u_s^p} \leq -K_t(N, u_s^p) \Rightarrow S(N, u_s^p) = \frac{\partial P}{\partial u_s^p} + K_t(N, u_s^p) \leq 0\ ?$$





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

Instability criterion ? ➡ *'Load' approach*

➡ ***'J-integral' approach***

- ➡ Reasoning developed by Paris et al., 1979
- ➡ General small-scale yielding case

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

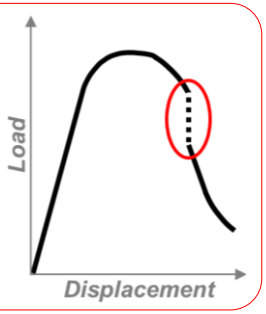
$$dJ(P,a) = \frac{\partial J(P,a)}{\partial P} f(P,a)da + \frac{\partial J(P,a)}{\partial a} da$$

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

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

instability

$du_t(P,a) = 0$



Instability criterion ? ➡ *'Load' approach*

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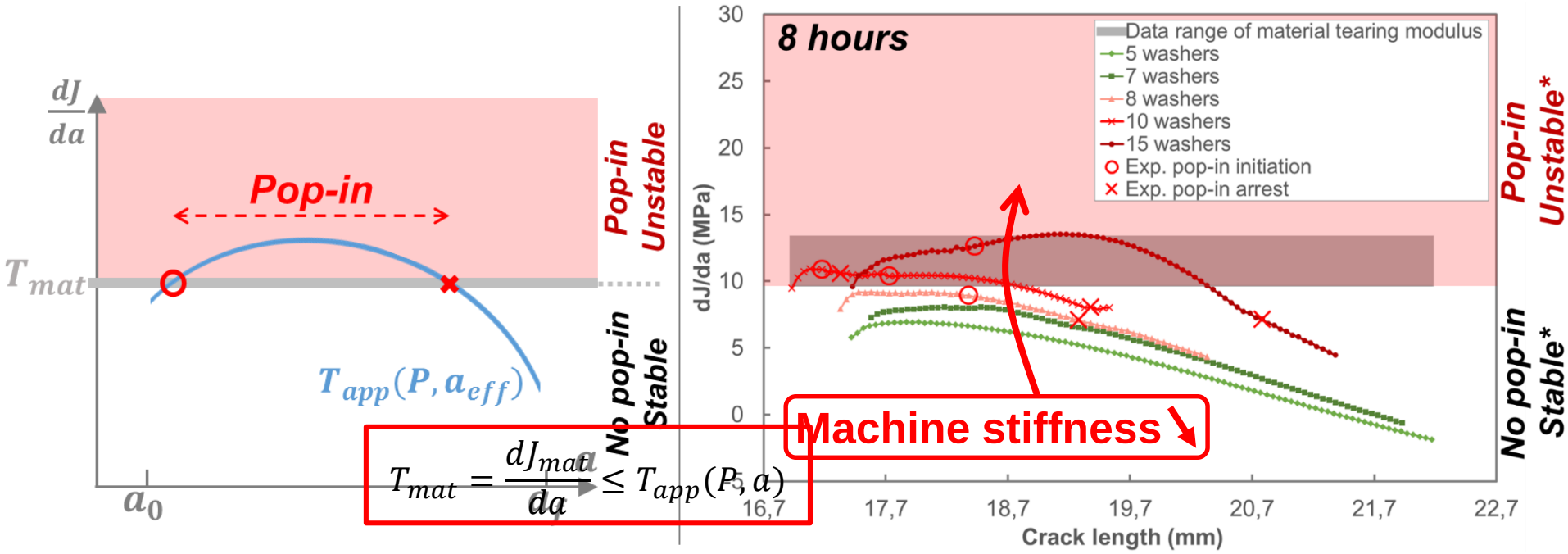
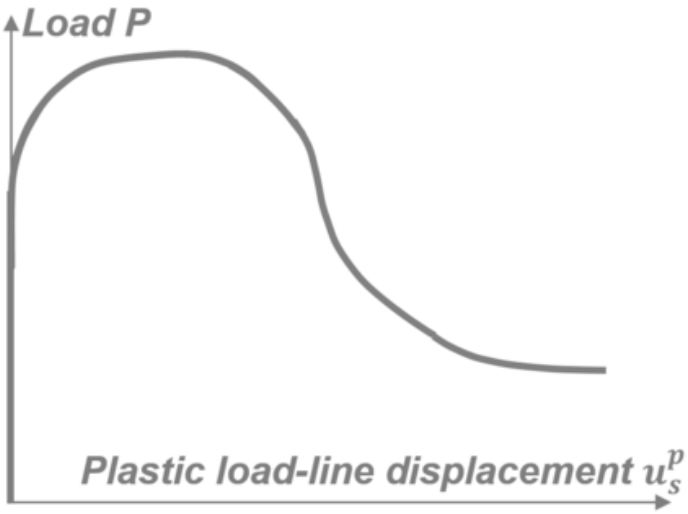


$$T_{mat} = \frac{dJ_{mat}}{da} \leq T_{app}(P, a)$$

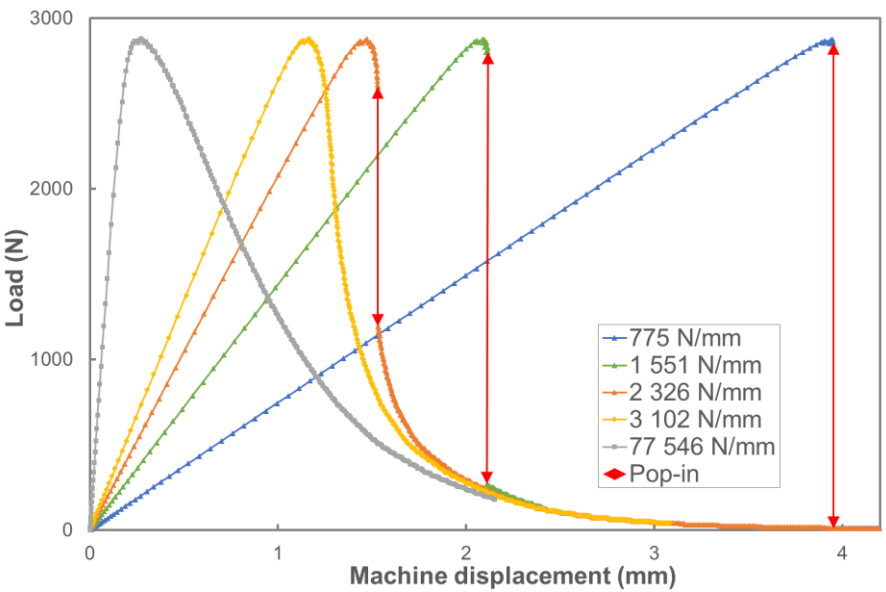
- ➡ **Good agreement** between the predictions of the criterion and the tests
- ➡ Experimental pop-ins seem to stop too late : some dynamic effects are not considered

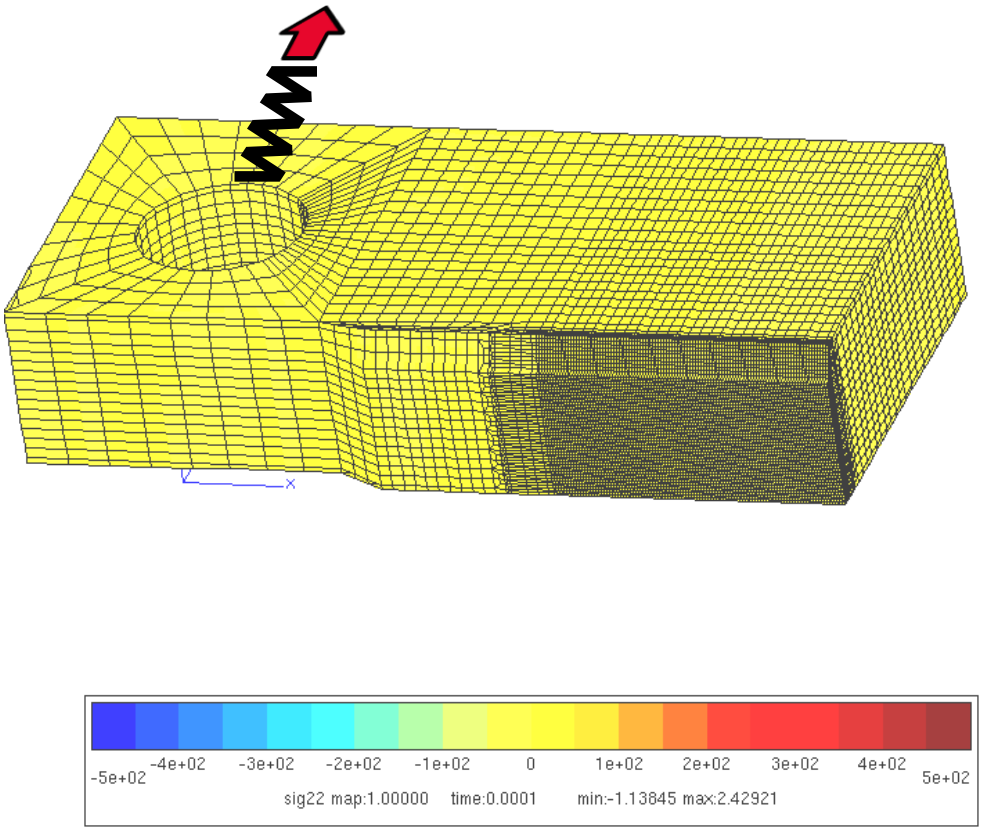
➡ Conclusions :

- 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**



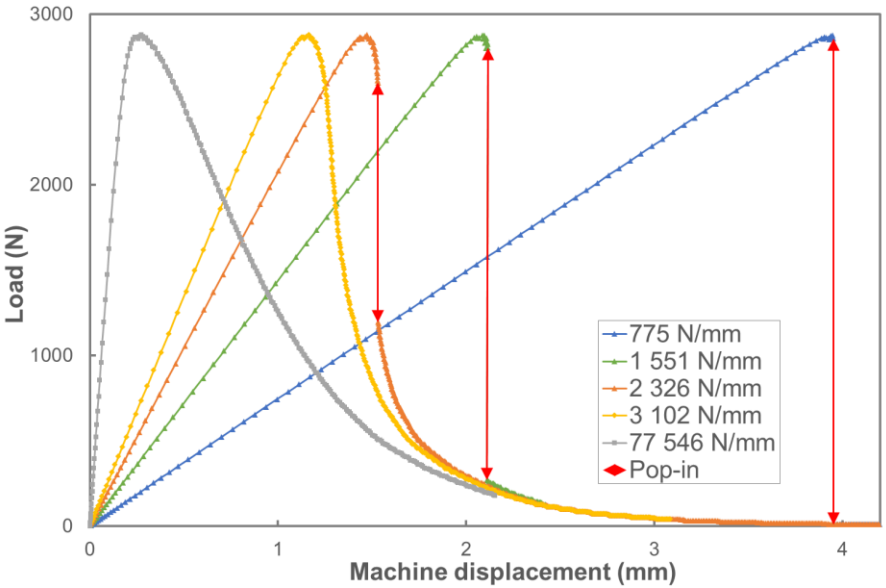
- ➡ Finite-element simulation
- ➡ Gurson law
- ➡ Arc-Length method (Riks, 1979)

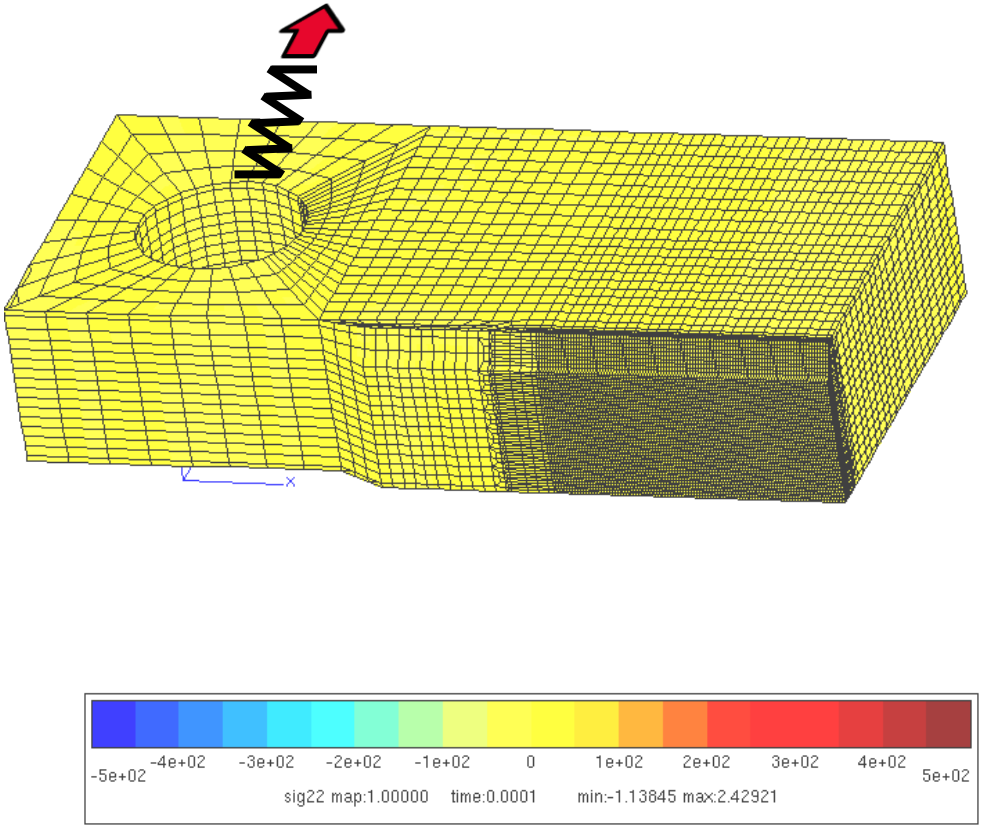




➡ **Spring creates numerical pop-in**

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





➡ **Spring creates numerical pop-in**

DE LA RECHERCHE À L'INDUSTRIE

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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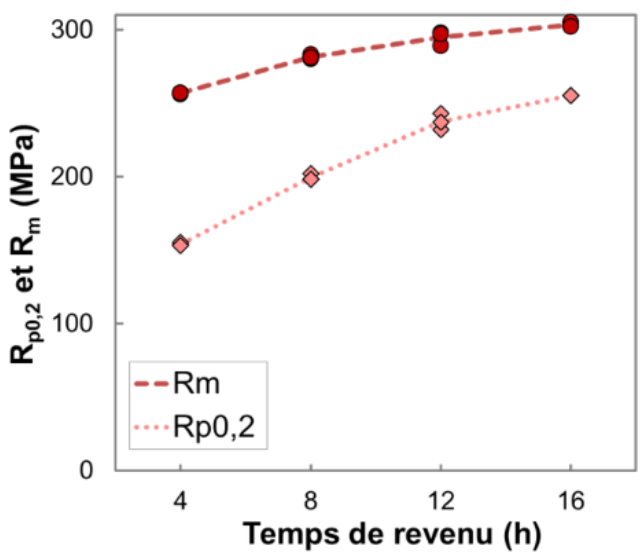
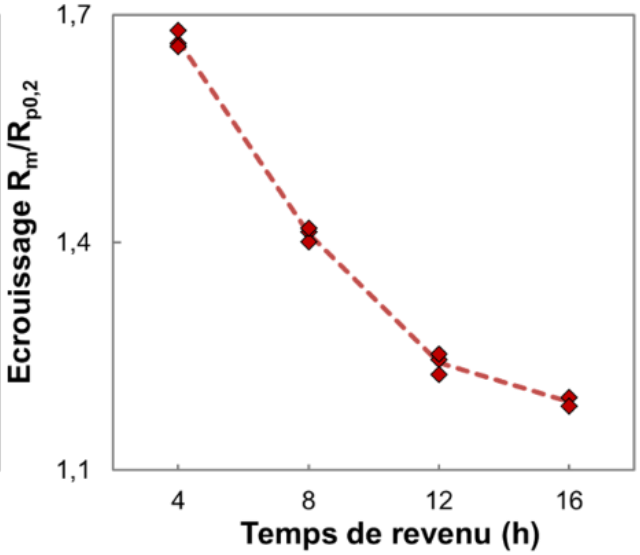
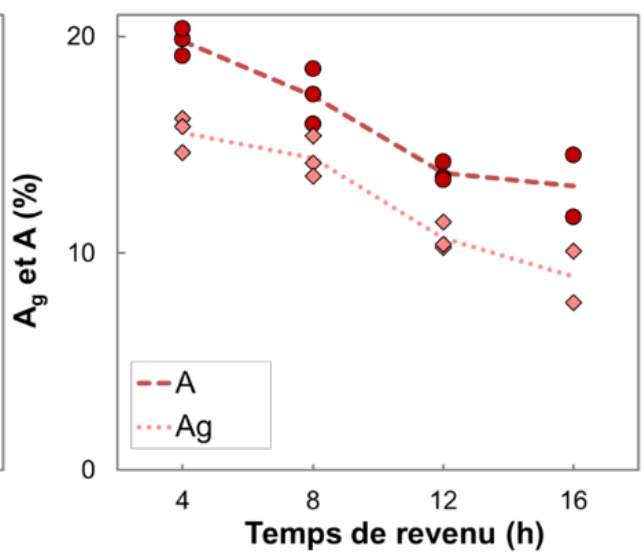
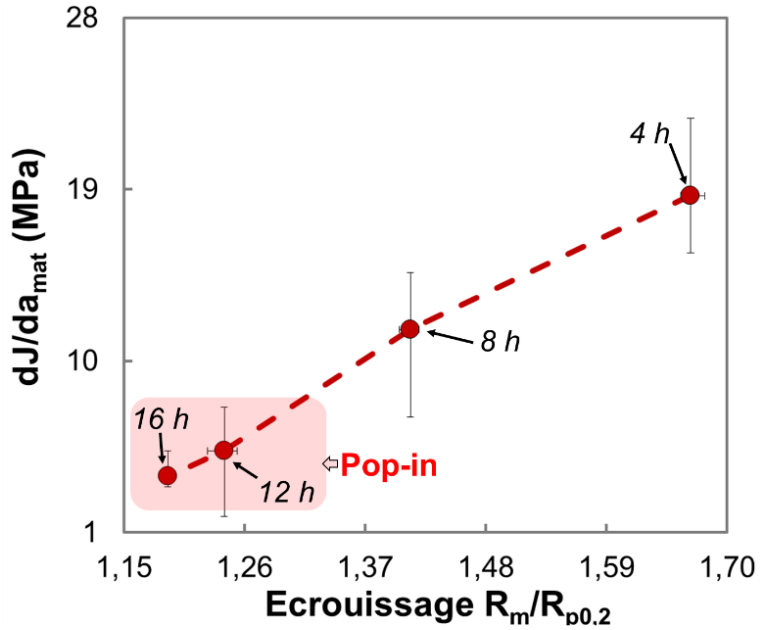
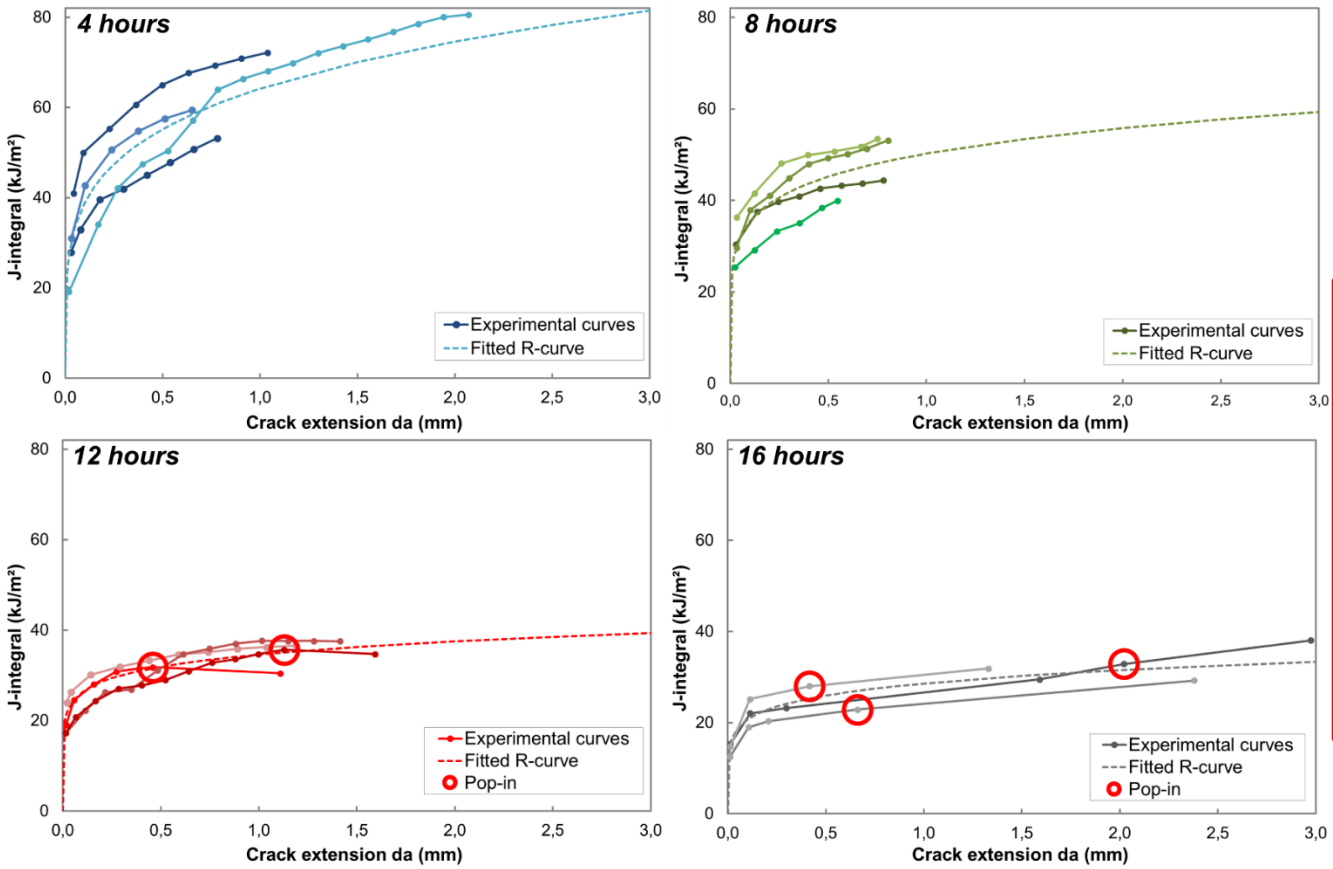

300
200
100
0
$R_{p0,2}$ et R_m (MPa)
Rm
Rp0,2
4
8
12
16
Temps de revenu (h)

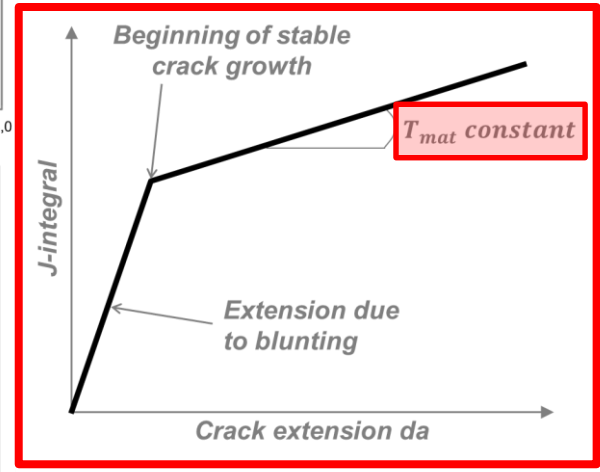

1,7
1,4
1,1
Ecrouissage $R_m/R_{p0,2}$
4
8
12
16
Temps de revenu (h)


20
10
0
A_g et A (%)
A
Ag
4
8
12
16
Temps de revenu (h)

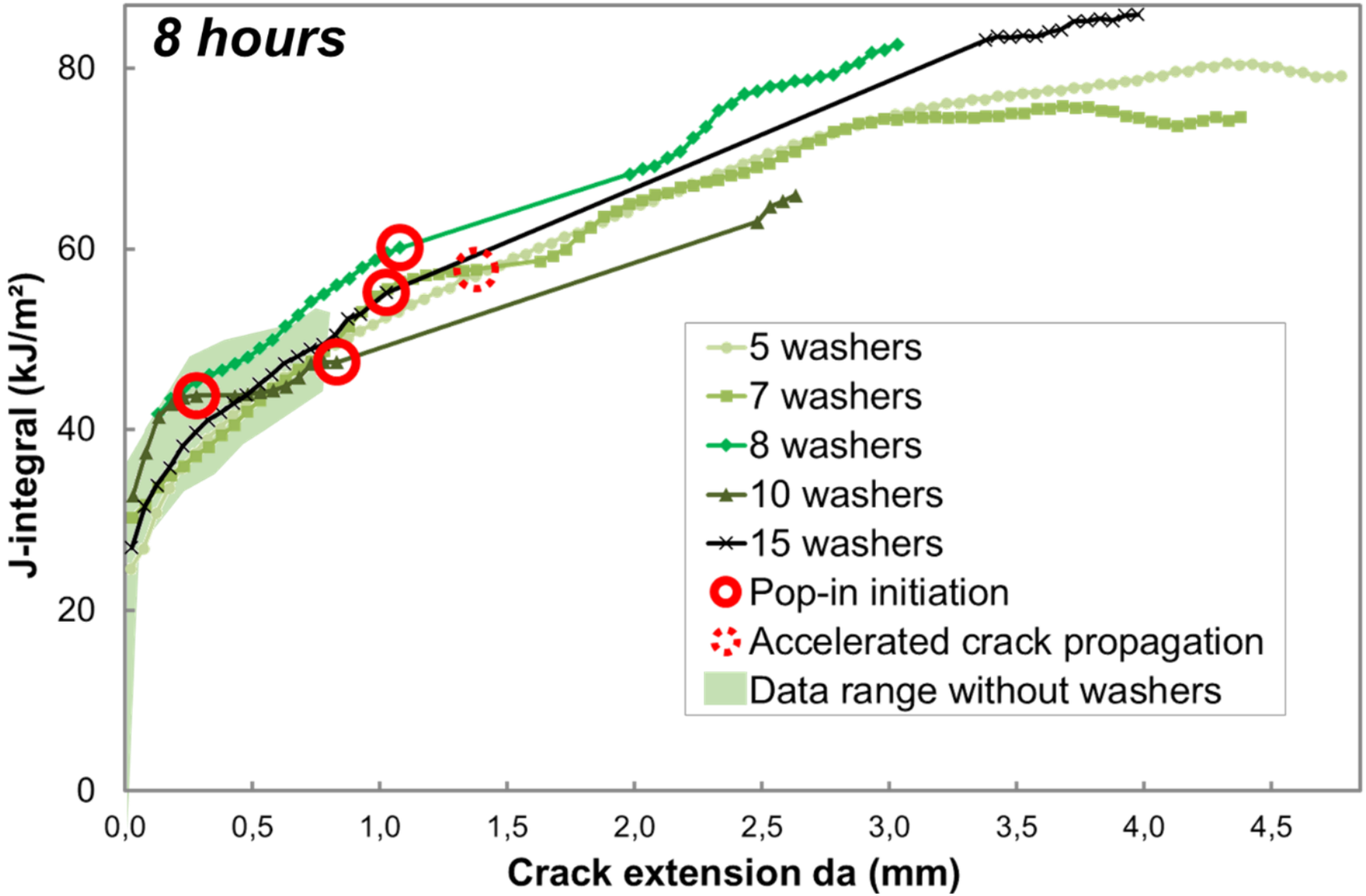

28
19
10
1
dJ/da_{mat} (MPa)
4 h
8 h
16 h
12 h
Pop-in
1,15
1,26
1,37
1,48
1,59
1,70
Ecrouissage $R_m/R_{p0.2}$

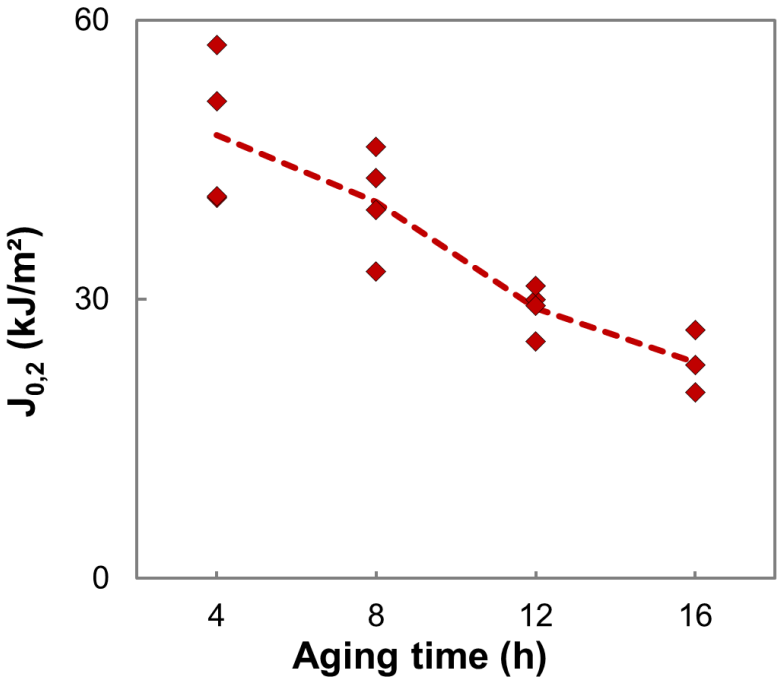
Fracture toughness tests:



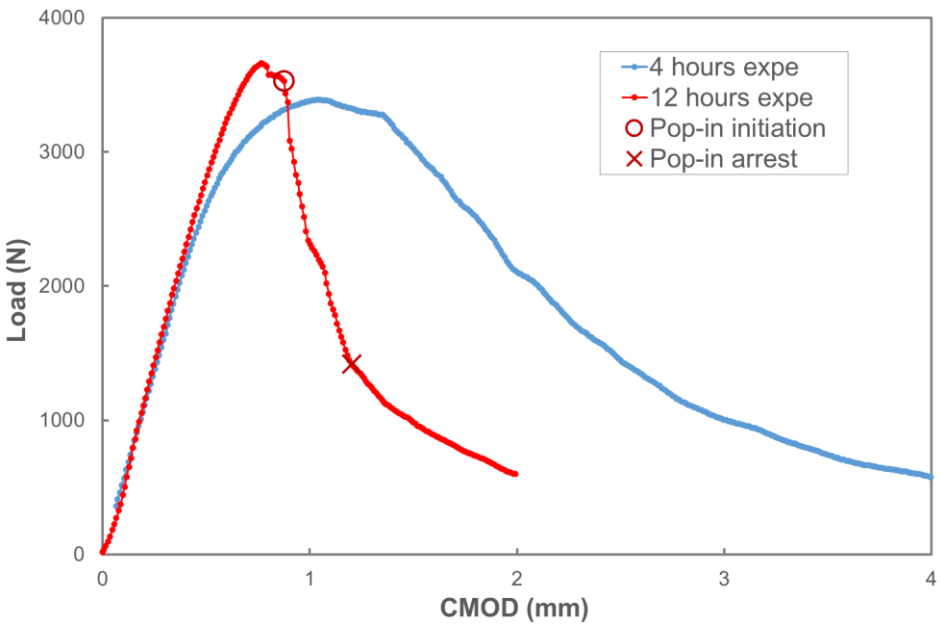


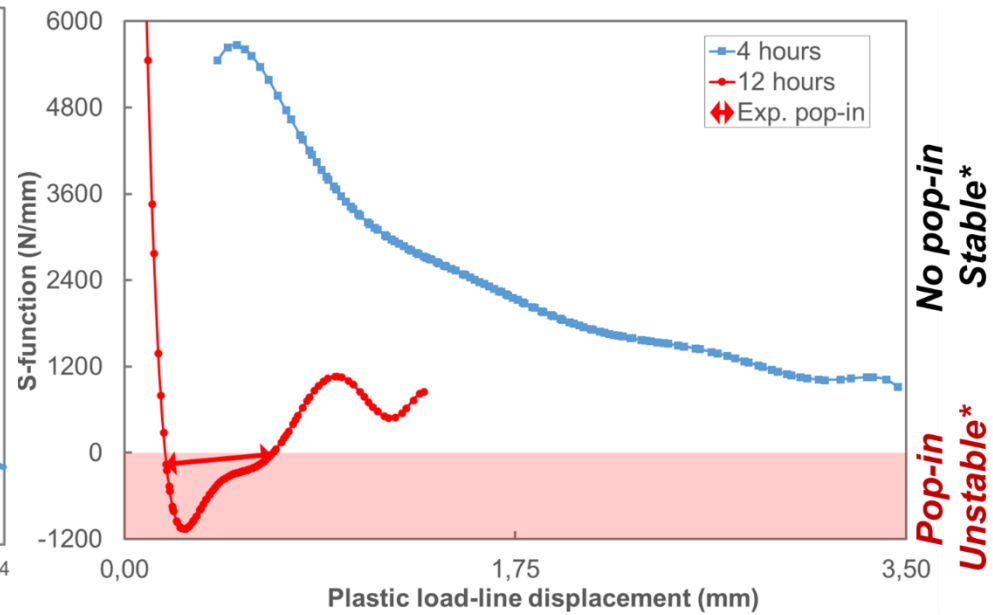
decrease in crack initiation toughness J0,2 and crack growth toughness dJ_mat/da with aging time.

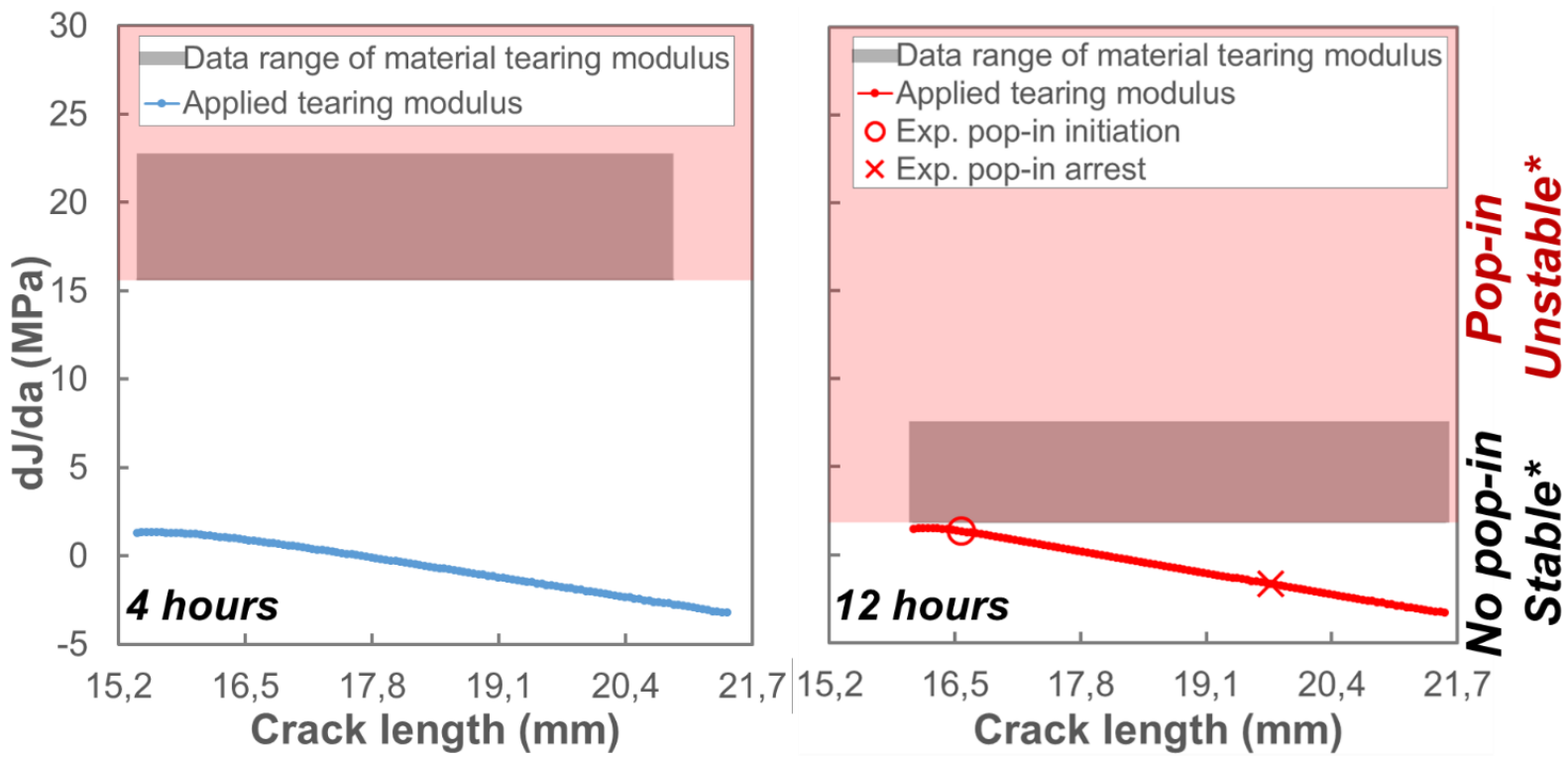

8 hours
J-integral (kJ/m²)
Crack extension da (mm)
0
20
40
60
80
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5
4,0
4,5
5 washers
7 washers
8 washers
10 washers
15 washers
Pop-in initiation
Accelerated crack propagation
Data range without washers

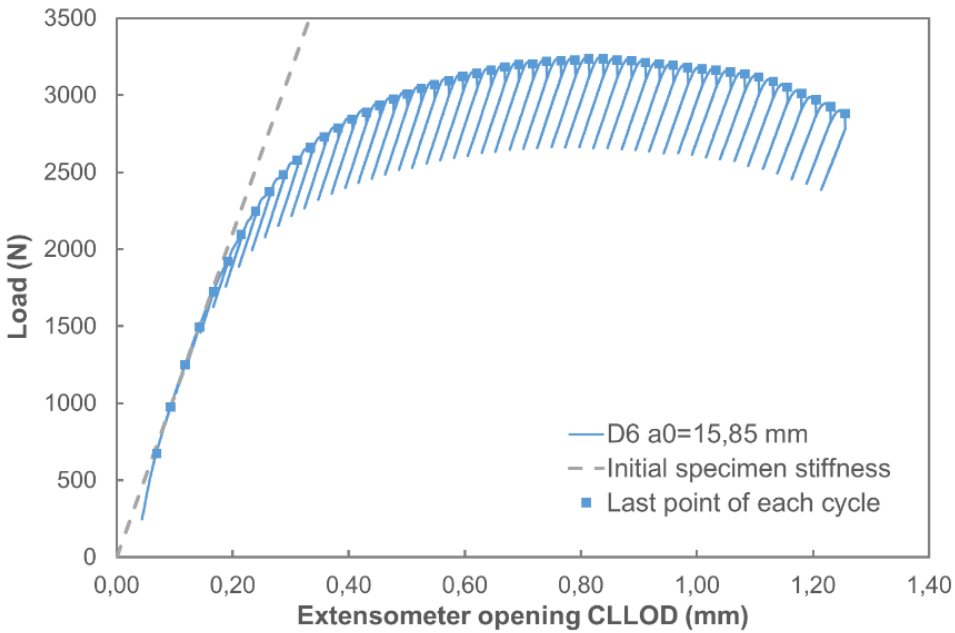


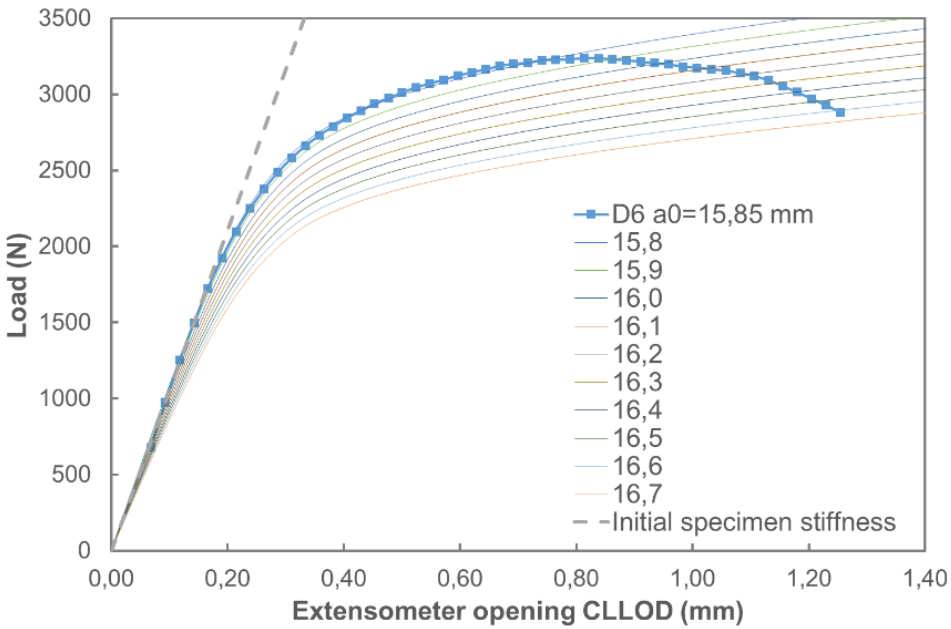
Crack initiation toughness $J_{0,2}$

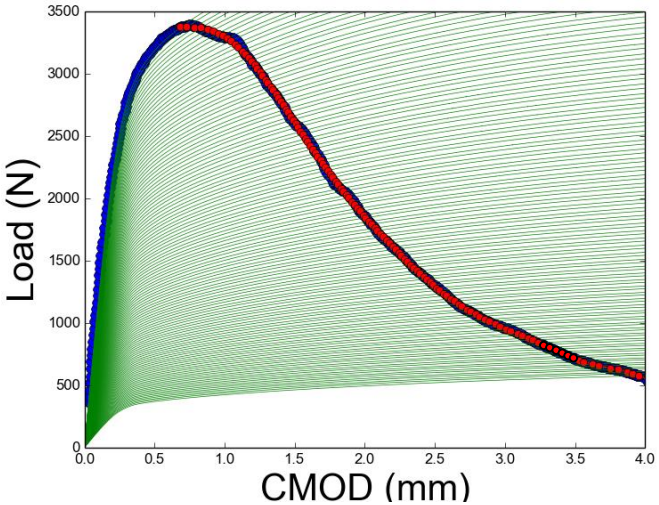

4000
3000
2000
1000
0
Load (N)
0
1
2
3
4
CMOD (mm)
4 hours expe
12 hours expe
Pop-in initiation
Pop-in arrest


6000
4800
3600
2400
1200
0
-1200
S-function (N/mm)
0,00
1,75
3,50
Plastic load-line displacement (mm)
4 hours
12 hours
Exp. pop-in
No pop-in
Stable*
Pop-in
Unstable*

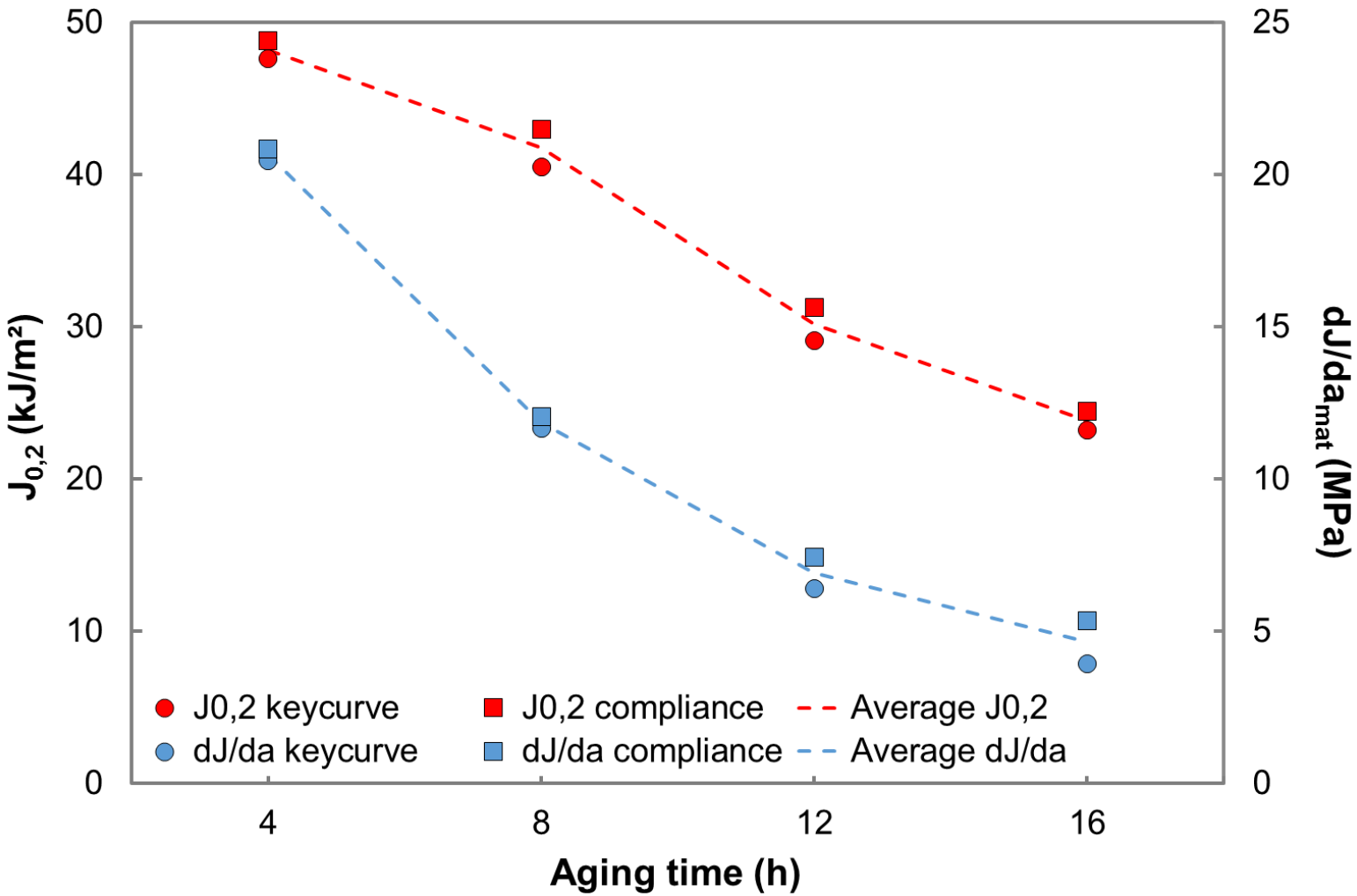

30
25
20
15
10
5
0
-5
dJ/da (MPa)
Data range of material tearing modulus
Applied tearing modulus
4 hours
15,2
16,5
17,8
19,1
20,4
21,7
Crack length (mm)
Data range of material tearing modulus
Applied tearing modulus
Exp. pop-in initiation
Exp. pop-in arrest
12 hours
15,2
16,5
17,8
19,1
20,4
21,7
Crack length (mm)
Pop-in
Unstable*
No pop-in
Stable*


Load (N)
Extensometer opening CLLOD (mm)
D6 a0=15,85 mm
Initial specimen stiffness
Last point of each cycle


Load (N)
Extensometer opening CLLOD (mm)
D6 a0=15,85 mm
15,8
15,9
16,0
16,1
16,2
16,3
16,4
16,5
16,6
16,7
Initial specimen stiffness


Load (N)
CMOD (mm)

Comparison of keycurve / compliance methods



General small-scale yielding case

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

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

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

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

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

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

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

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

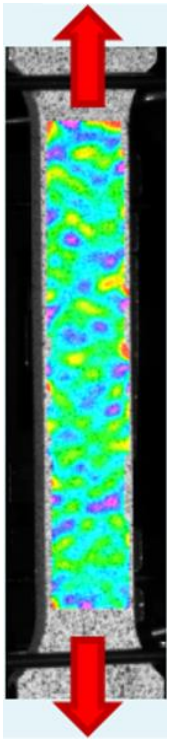
$$\frac{\partial J}{\partial P}(P,a) = \frac{2P(2+\frac{a}{W})^2}{BB_N WE\left(1-\frac{a}{W}\right)^3}\sum_{i=0}^{4}\alpha_i\left(\frac{a}{W}\right)^i$$

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

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

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

	0	1	2	3	4	5	6	7	8
α_i	0.886	4.64	-13.32	14.72	-5.6				
β_i	9.28	-53.28	88.32	-44.8					
γ_i	11564	13440	-47940	16036	82907	-48357	-38547	26865	
δ_i	1000	-3000	3000	-1000					
ε_i	1403	7355	-6417	-18321	15994	16573	-16353	-5607	5373
ζ_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

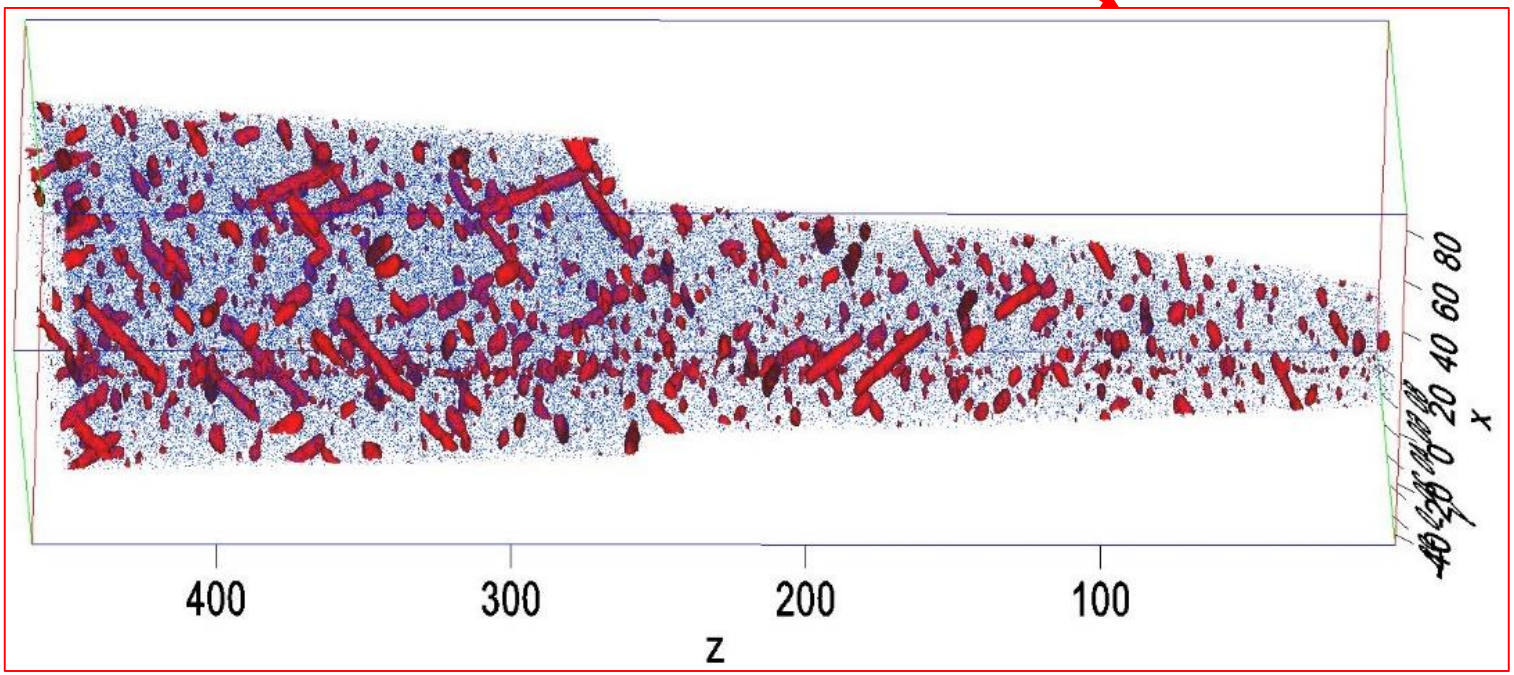
➡ Aluminium 6061-T6

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

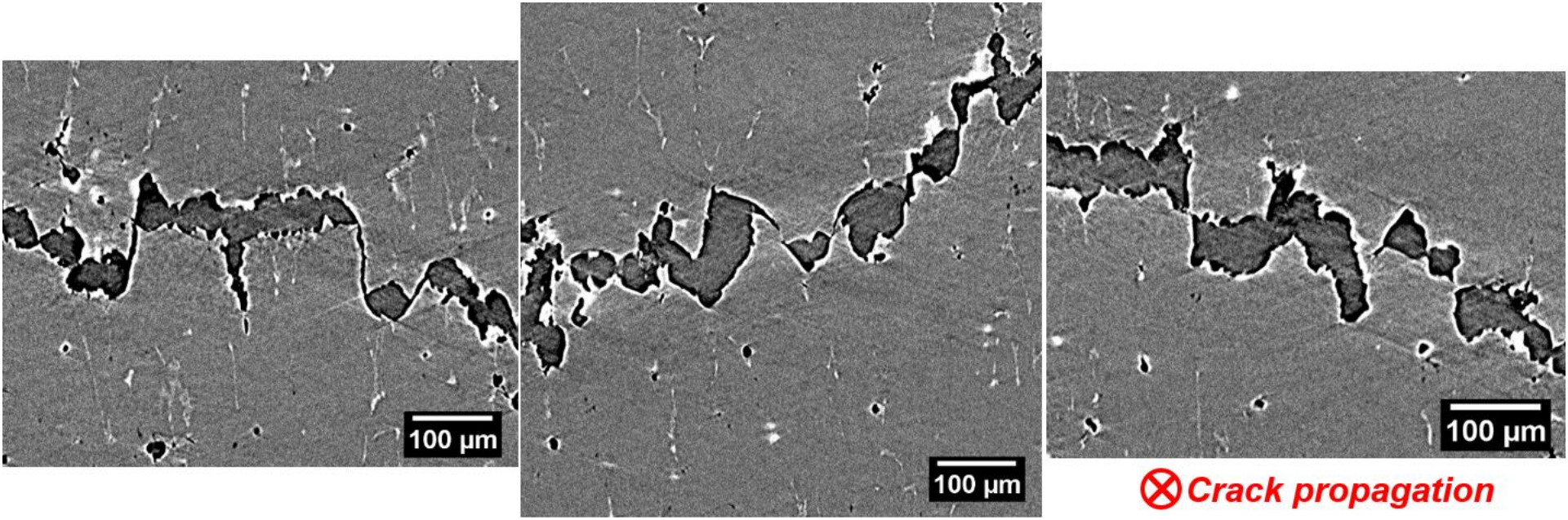
Aging time (h)

4	8	12	16

Strength ↗



Atom Probe Tomography


100 µm
100 µm
100 µm
Crack propagation

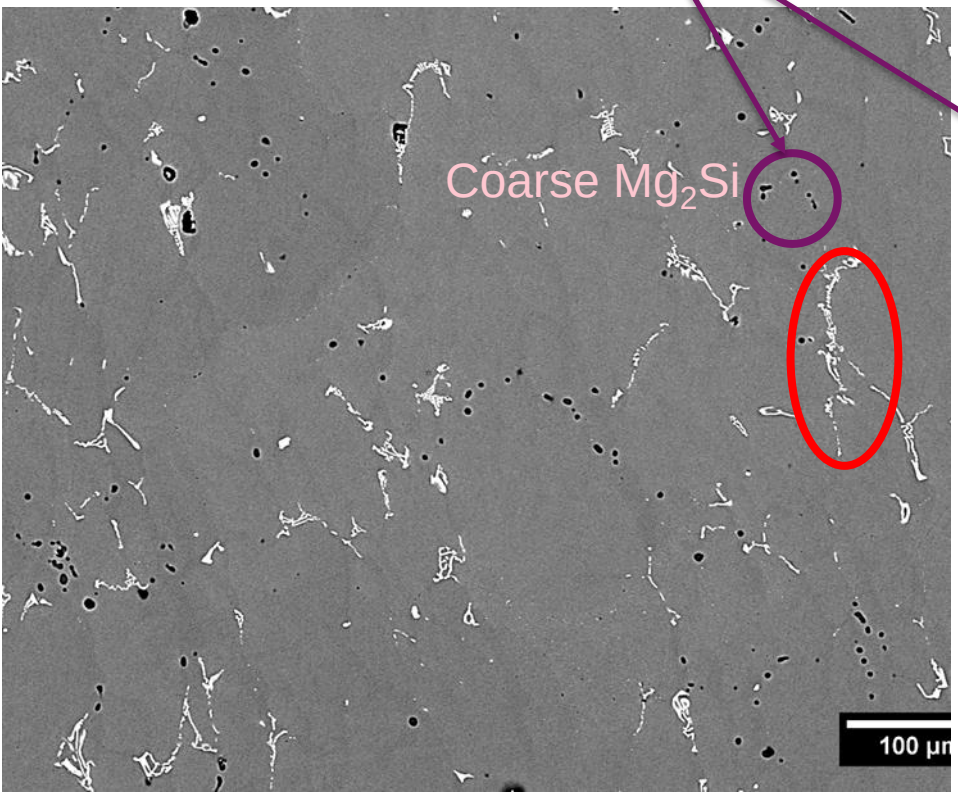
Impurity Resistance to grain growth

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

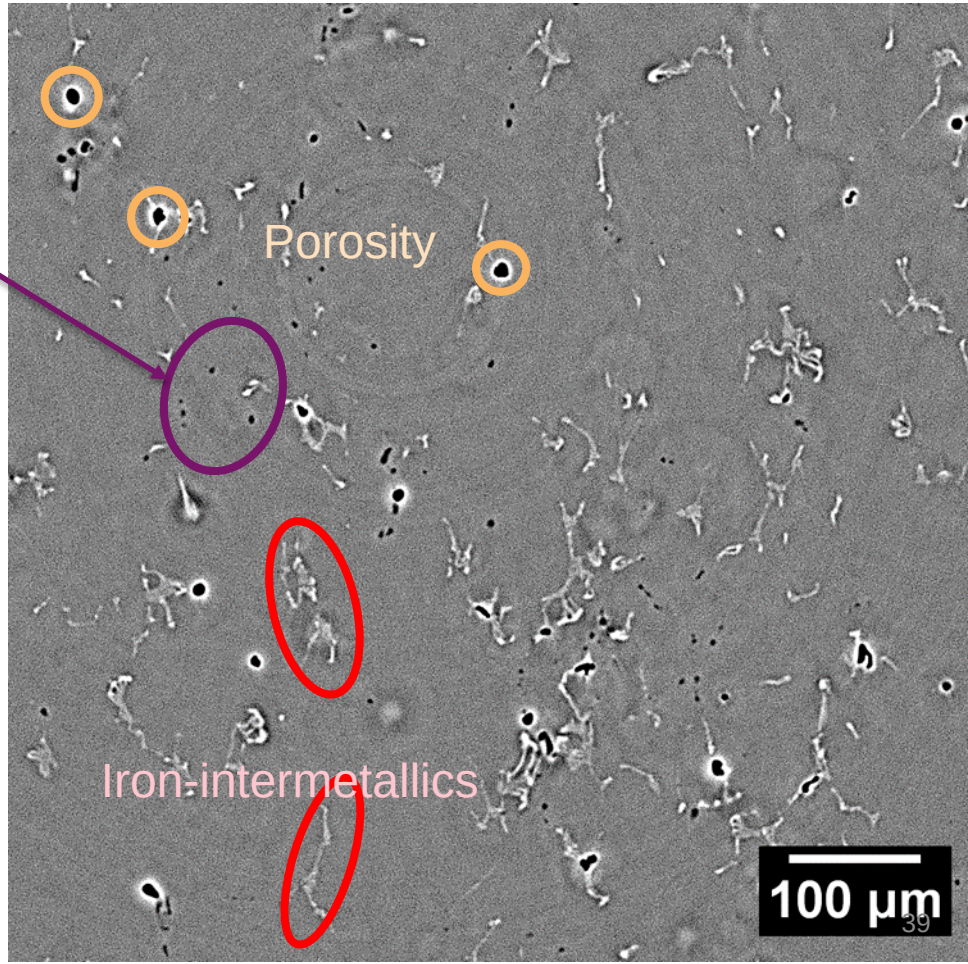
Norme NF EN 573-1

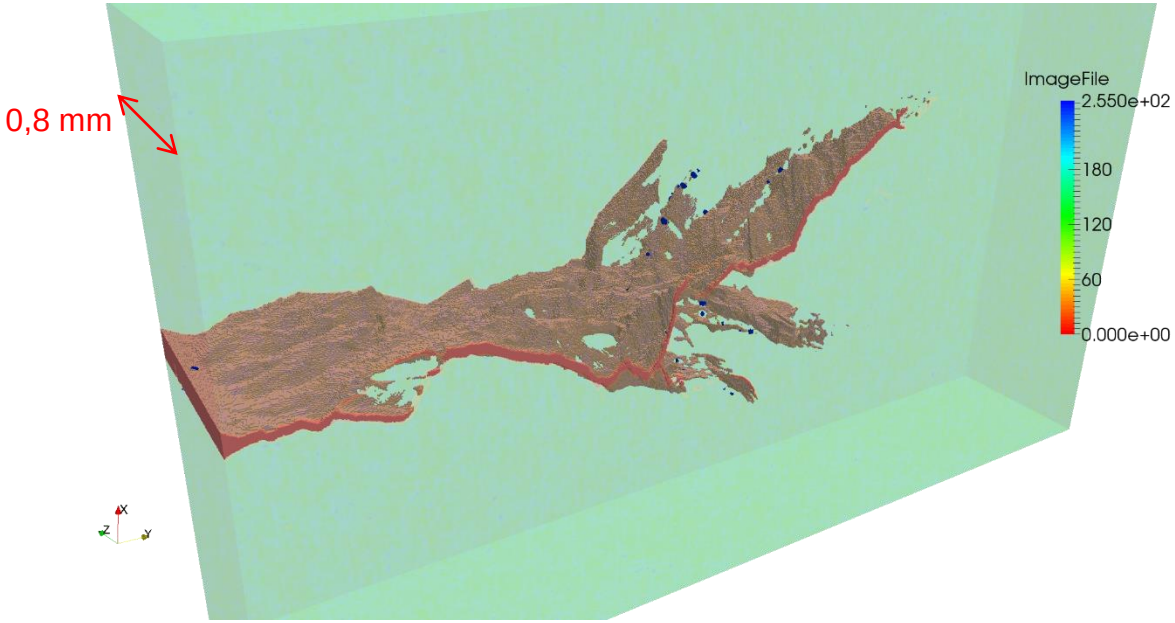
+++ Structural hardening (during ageing)
--- Clusters of coarse precipitates (during quench)

SEM

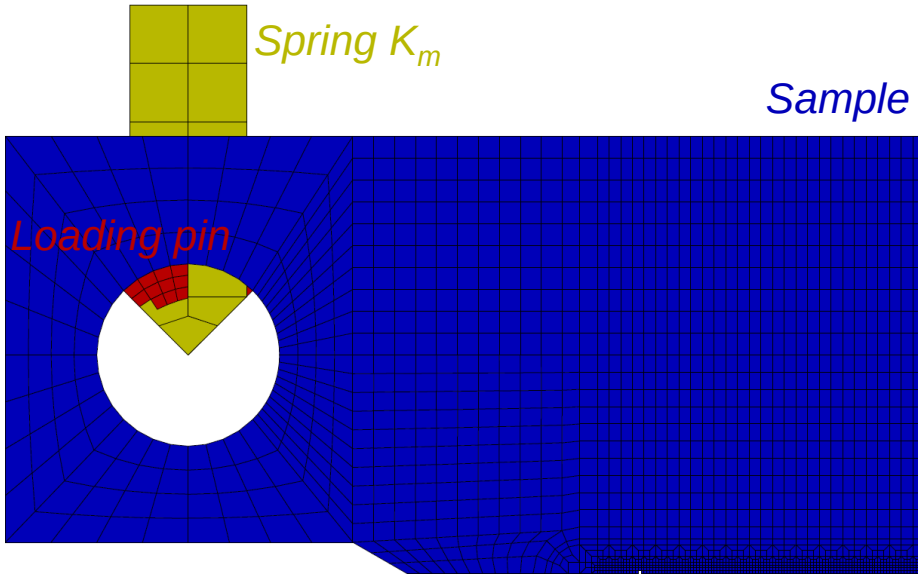


Synchrotron laminography

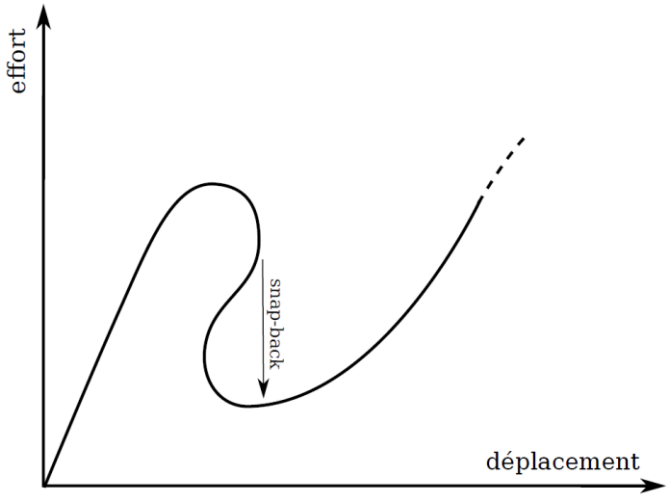


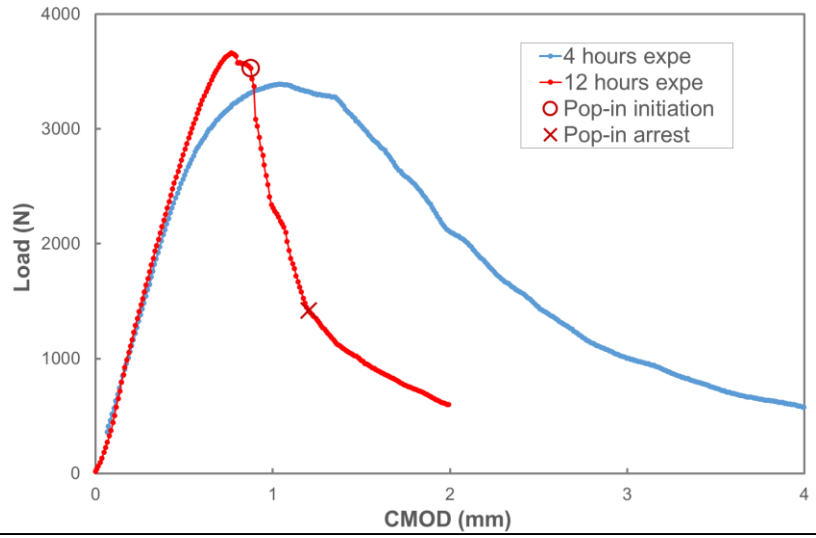

0,8 mm
ImageFile
2.550e+02
180
120
60
0.000e+00

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

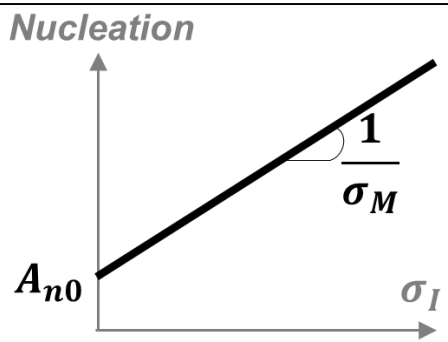


- Pilotage en longueur d'arc : méthode incrémentale de Riks
- Principe : ajouter aux équations d'équilibre une équation imposant la longueur du vecteur incrémental dans le plan charge/déplacement -> le chargement appliqué devient une variable additionnelle du problème





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

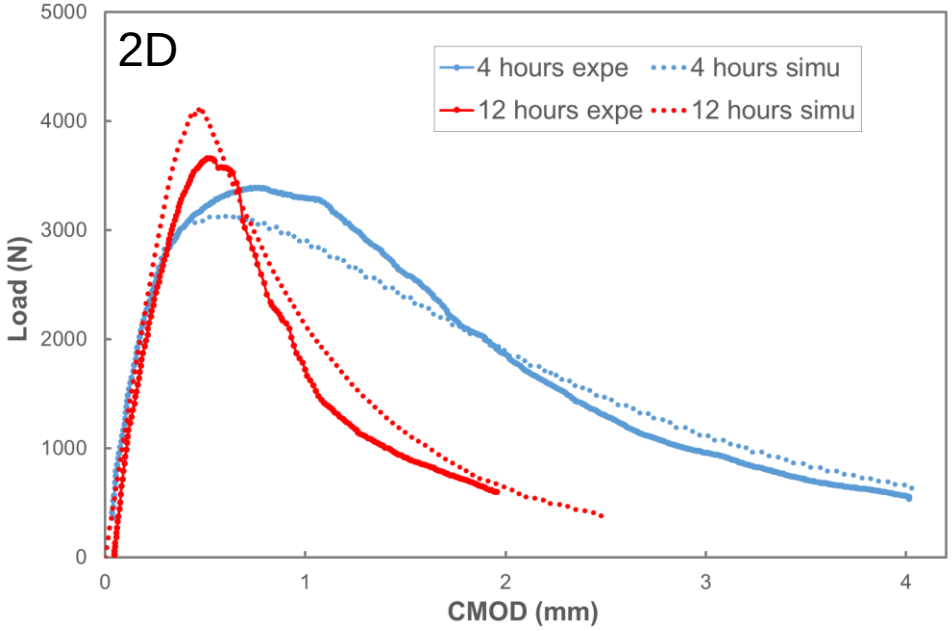


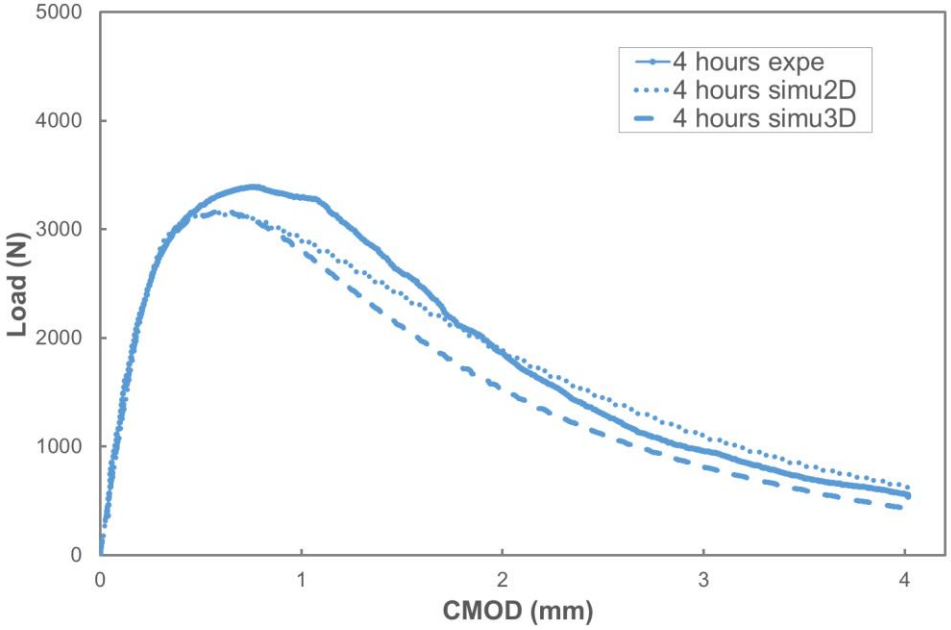
- Paramètres d'optimisation :
  - q_1 (Tvergaard). Potentiel plastique : $\phi(\sigma_{eq},\sigma_m,\bar{\sigma},f) = \left(\frac{\sigma_{eq}}{\bar{\sigma}}\right)^2 + 2q_1 f\cosh\left(\frac{3q_2\sigma_m}{2\bar{\sigma}}\right) - (1+q_3 f)^2 = 0$
  - A_{n0}
  - σ_M
  - *fact* (facteur géométrique permettant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

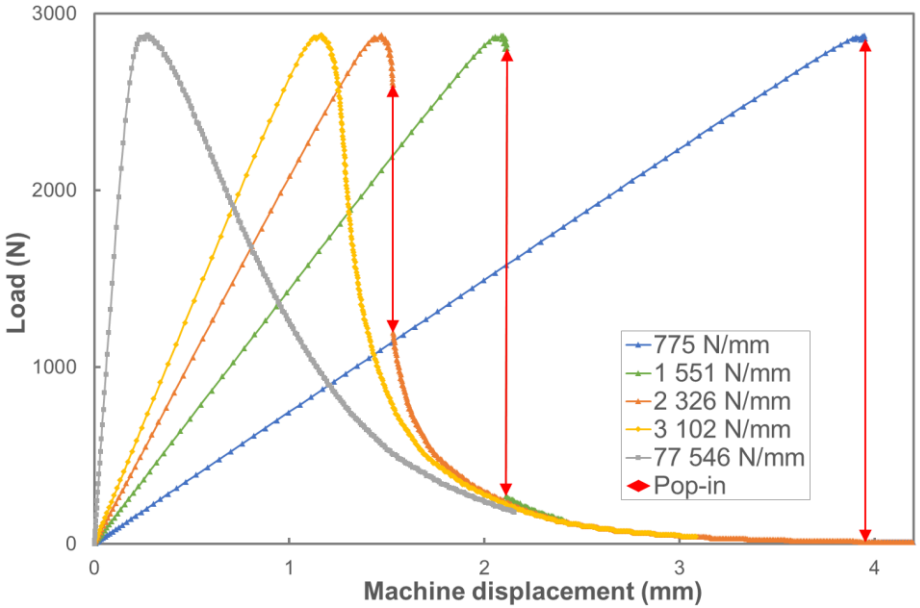
- Zebulon
- Eléments quadrangles (8 noeuds) linéaires à intégration sélective
- Comparaison 2D déf planes – 3D validée

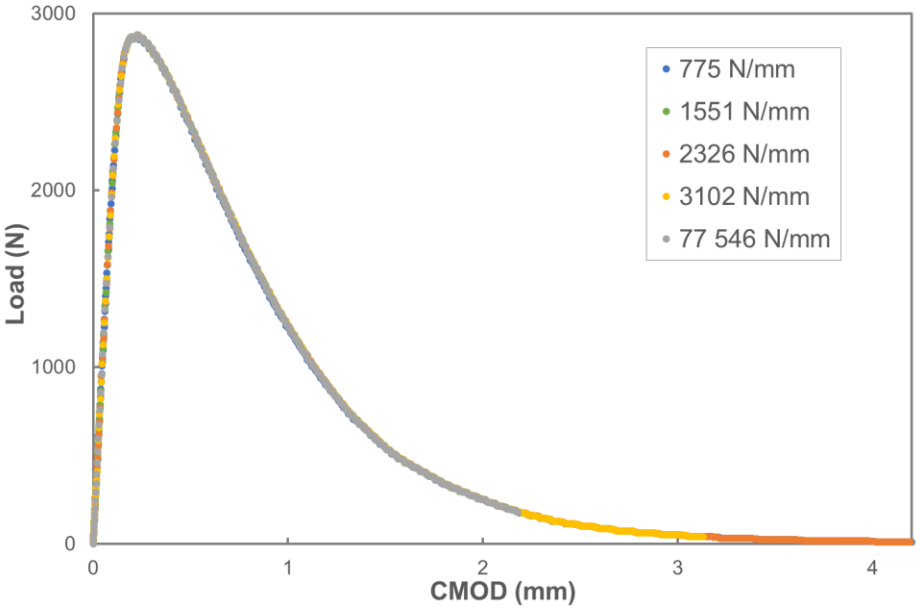
- Différents traitements thermiques :
  - **Loi élastoplastiques** (Voce) **différentes**
  - **Lois d'endommagement** (Gurson et nucléation par les contraintes) **identiques**

- Après optimisation des paramètres :






3000
2000
1000
0
Load (N)
0
1
2
3
4
Machine displacement (mm)
775 N/mm
1 551 N/mm
2 326 N/mm
3 102 N/mm
77 546 N/mm
Pop-in


3000
2000
1000
0
Load (N)
0
1
2
3
4
CMOD (mm)
775 N/mm
1551 N/mm
2326 N/mm
3102 N/mm
77 546 N/mm