Extended summary of the PhD thesis

Pop-in is a phenomenon of crack propagation instability observed during toughness tests on some materials. This phenomenon has been observed on the 6061-T6 aluminum alloy, which has been identified as an essential structural element of the core of the Jules Horowitz research reactor. This thesis was initiated to understand the origin of this phenomenon on 6061-T6 aluminum and to propose a physics-based modeling, usable for the exploitation and interpretation of toughness tests, especially in the irradiated state.

The different origins identified in the literature have been experimentally tested. Different aging times (4/8/12/16h) were applied to obtain different mechanical behaviors. Tensile tests with image correlation have shown that the observed pop-ins are not due to a PLC effect. Nor do they correspond to microstructural heterogeneity; they are not linked to different fracture mechanisms, because the rupture is typically ductile, whether a pop-in is involved or not (*Figure 2*). These mechanisms and the different microstructures were compared using several techniques (SEM, EBSD, EDS, Atom Probe Tomography, tomography, synchrotron laminography and nanolaminography). Pop-ins are therefore only the result of an acceleration of the ductile fracture.

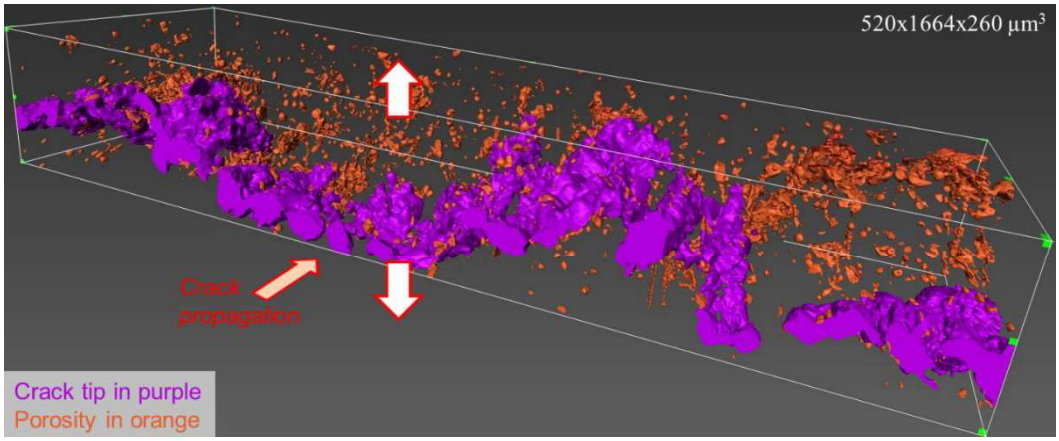

Figure 2 – Crack tip of a CT specimen with pop-in: the fracture is typically ductile. 3D reconstruction of a volume acquired by synchrotron radiation laminography (ESRF, Grenoble)

In fact, they are due to an interaction between two parameters: the reduced material crack growth toughness (i.e. the low tearing modulus), and the significant compliance of the test device (i.e. the low stiffness). In order to investigate this second parameter, an innovative setup has been designed to make the machine stiffness vary during toughness tests (*Figure 3*). Two analytical criteria, one based on the load-opening curve, the other on the J-integral, have been established, making it possible to reliably quantify the conditions for initiation and arrest of pop-in. This work was published in the journal Engineering Fracture Mechanics.

To take into account the central role of hardening for ductile propagation, a new stress-controlled nucleation criterion has been introduced into a single GTN model. This makes it possible to simulate and capture by finite elements the various *J-Δa* toughness curves by modifying only the elastoplastic law (*Figure 4*). This work, which provides a link between interdependent notions (macroscopic / microscopic, mechanical / microstructure, simulation / experiments), was published in the journal Acta Materialia.

By adding springs in the models and with an adapted control, the pop-ins are successfully simulated, and remain exploitable with the analytical criteria. The implementation of this model, combined with the use of a numerical piloting method to manage propagation instabilities by the finite element method, has allowed the successful simulation of experimentally observed pop-ins. These numerical pop-ins

remain usable with the analytical criteria, which provides a robust confirmation of their validity. In the future, we plan to publish this purely numerical work.

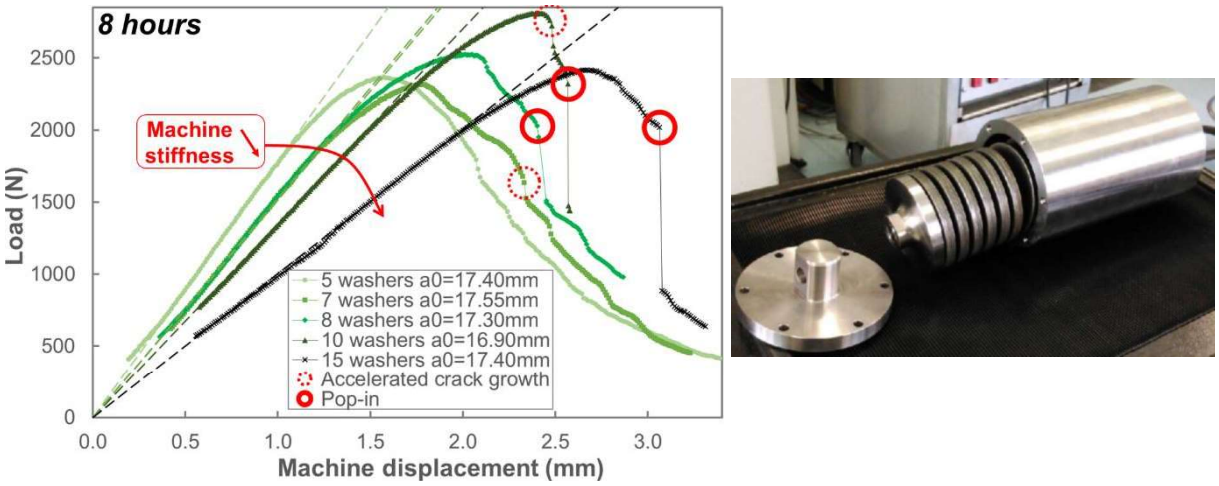

Figure 3 - Experimental curves obtained following toughness tests carried out with the innovative assembly using Belleville washers. The increase in the number of washers leads to a decrease in the stiffness of the machine, which causes the appearance of instabilities on a material that appeared stable during tests without assembly.

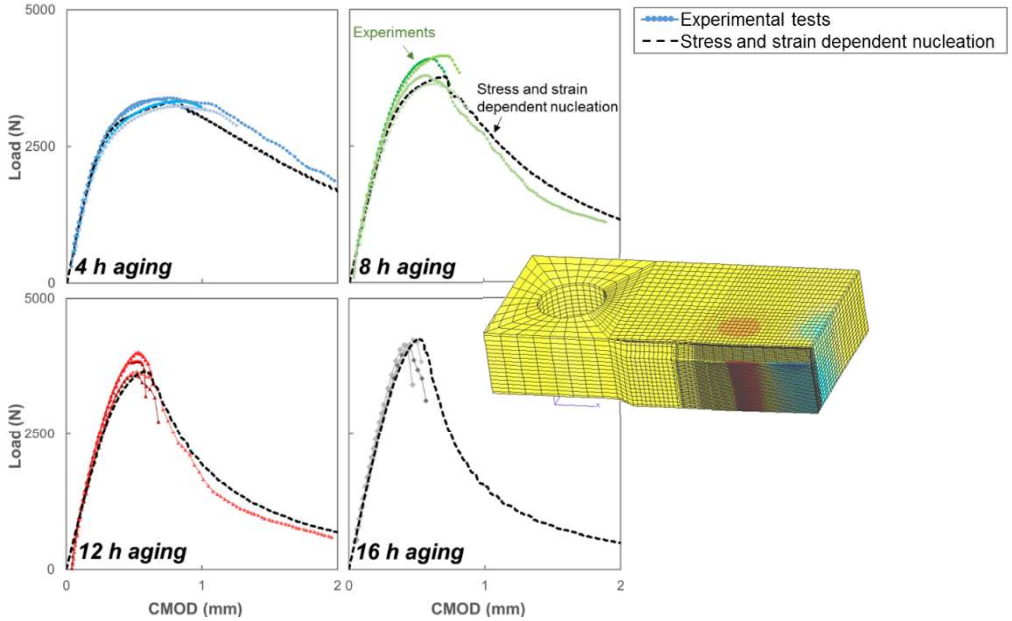

Figure 4 - Comparison of experimental and simulated toughness test curves for different aging times. The damage law, using a new stress germination criterion, is unique; only the elastoplastic law evolves from one ageing time to another.

Studies on irradiated specimens carried out in hot cells have shown that the increase in pop-ins with irradiation results from the decrease in the tearing modulus, itself due to hardening. As in the non-irradiated state, pop-ins thus appear solely because of the interaction between the tearing modulus and the test device stiffness, and not because of a range of industrial development not mastered. This complex test campaign, which was the ultimate goal of the thesis, and the resulting interpretations are the subject of a paper submitted to the Journal of Nuclear Materials.

This thesis answered important questions about the core of the Jules Horowitz reactor, particularly with regard to the behaviour of the material under irradiation in the presence of cracks. I continued this work by supervising an internship (which focused on the characterization of the hardening nano-precipitation

via the Atom Probe Tomography, whose results will soon be submitted to the journal Materials Science and Engineering), and today a PhD thesis (focused on the modeling of the toughness of the irradiated material).

Publications

S. Meddeb, **T. Petit**, V. Garric, K. Colas. Study of the hardening nanoprecipitation of an 6000 aluminum alloy using atom probe tomography. **Current writing.**

T. Petit, J. Besson, C. Ritter, T.F. Morgeneyer, Neutron irradiation effects on the mechanical properties, crack propagation instabilities and damage mechanisms of an aluminum alloy. **Current writing.**

S. Cicero, M. Lambrecht, H. Swan, P. Arffman, E. Altstadt, **T. Petit**, F. Obermeier, B. Arroyo, J.A. Álvarez, R. Lacalle. Fracture mechanics testing of irradiated RPV steels by means of sub-sized specimens: FRACTESUS project. Proceeding of 6th International Small Sample Test Techniques Conference SSTT2020 (2020).

T. Petit, J. Besson, C. Ritter, K. Colas, L. Helfen, T.F. Morgeneyer, Effect of hardening on toughness captured by stress-based damage nucleation in 6061 aluminum alloy, Acta Mater. 180 (2019) 349-365. doi.org/10.1016/j.actamat.2019.08.055

T. Petit, Comprehension and modeling of toughness tests with pop-in: application to 6061-T6 aluminum and effect of neutron irradiation, Thèse, MINES Paristech, 2018. http://www.theses.fr/s157382. **1st Jean Bourgeois Award 2019 of the French Nuclear Energy Society.**

T. Petit, C. Ritter, J. Besson, T.F. Morgeneyer, Impact of machine stiffness on "pop-in" crack propagation instabilities, Eng. Fract. Mech. 202 (2018) 405–422. doi.org/10.1016/j.engfracmech.2018.08.007. **3rd ZwickRoell Science Award 2018.**

T.O. Thornhill, **T. Petit**, R.J. Poole, D.J.C. Dennis, Vortex breakdown in swirling pipe flow of fluids with shear-dependent viscosity, Phys. Fluids. 30 (2018) 114107. doi.org/10.1063/1.5057409.

National and international conferences

S. Meddeb, **T. Petit**, V. Garric, K. Colas. Study of the hardening nanoprecipitation of an 6000 aluminum alloy using atom probe tomography. 17th International Conference on Aluminium Alloys ICAA17, Grenoble (France). October 2020.

T. Petit, J. Besson, C. Ritter, K. Colas, L. Helfen, T.F. Morgeneyer. 17th International Conference on Aluminium Alloys ICAA17, Grenoble (France). October 2020.

M. Shokeir**,** C. Ritter, J. Garnier, **T. Petit**, J. Besson. Influence of radiation damage on the fracture toughness of aluminum alloys – computational methods on the AA6061-T6. 17th International Conference on Aluminium Alloys ICAA17, Grenoble (France). October 2020.

T. Petit, J. Besson, C. Ritter, K. Colas, L. Helfen, T.F. Morgeneyer. Ténacité d'un alliage d'aluminium destiné au cœur pressurisé d'un réacteur nucléaire de recherche. Solutions innovantes pour les ESP applicables aux industries d'aujourd'hui et de demain ESOPE 2020, Paris (France). October 2020.

S. Cicero, M. Lambrecht, H. Swan, P. Arffman, E. Altstadt, **T. Petit**, F. Obermeier, B. Arroyo, J.A. Álvarez, R. Lacalle. Fracture mechanics testing of irradiated RPV steels by means of sub-sized specimens: FRACTESUS project. 6th International Small Sample Test Techniques Conference SSTT2020, Santander (Spain). September 2020.

T. Petit, J. Besson, C. Ritter, K. Colas, L. Helfen, T.F. Morgeneyer. Effect of hardening on toughness captured by stress-based damage nucleation in a Gurson-Tvergaard-Needleman model framework for a

6061 aluminium alloy. 14th World Congress in Computational Mechanics and ECCOMAS Congress WCCM14, Paris (France). July 2020.

S. Meddeb, **T. Petit**, V. Garric, K. Colas. Hardening of an aluminum 6061 alloy due to nanoprecipitation**.** European Atom Probe Tomography Workshop EAPT2019, Rouen (France). November 2019.

T. Petit, J. Besson, C. Ritter, K. Colas, L. Helfen, T.F. Morgeneyer. Effet du durcissement sur la ténacité : germination par la contrainte appliquée à un alliage d'aluminium 6061. Journées Annuelles de la Société Française de Métallurgie et de Matériaux JA SF2M 2019, Paris (France). October 2019.

T. Petit, C. Ritter, J. Besson, T.F. Morgeneyer. A new test machine to cause instabilities and fast cracks. ZwickRoell Science Award 2018, Shanghaï (China). June 2019.

T. Petit, J. Besson, C. Ritter, K. Colas, L. Helfen, T.F. Morgeneyer. Effect of hardening on toughness: stress-dependent nucleation in the case of 6061 aluminum alloy. 6th International Conference on Computational Modeling of Fracture and Failure of Materials and Structures CFRAC 2019, Braunschweig (Germany). June 2019.

T. Petit, C. Ritter, J. Besson, T.F. Morgeneyer. Instabilités de propagation de fissure sur un alliage Al-Mg-Si. Matériaux 2018, Strasbourg (France). November 2018.

T. Petit, T.F. Morgeneyer, C. Ritter, J. Besson. Pop-in instabilities in a 6061 aluminum alloy. 55th Annual Technical Meeting of the Society of Engineering Science SES 2018, Madrid (Spain). October 2018.

T. Petit, C. Ritter, J. Besson, T.F. Morgeneyer. Impact of machine stiffness and heat treatments on crack propagation instabilities in an Al-Mg-Si alloy. 22nd European Conference on Fracture ECF22, Belgrade (Serbia). August 2018.

T. Petit, C. Ritter, J. Besson, T.F. Morgeneyer. Instabilités de propagation de fissure sur un alliage Al-Mg-Si. Séminaire du Centre des Matériaux « Alliages d'aluminium : microstructures et propriétés mécanique », Evry (France). June 2018.

T. Petit, C. Ritter, J. Besson, T.F. Morgeneyer. Impact of machine stiffness and heat treatments on crack propagation instabilities in an Al-Mg-Si alloy. 16th European Mechanics of Materials Conference EMMC16, Nantes (France). March 2018.

T. Petit, C. Ritter, J. Besson, T.F. Morgeneyer. Impact of heat treatments of an Al-Mg-Si alloy on instabilities during crack propagation in fracture toughness tests. 14th International Conference On Fracture ICF14, Rhodes (Greece). June 2017.

Awards

1st Jean Bourgeois Award 2019 of the French Nuclear Energy Society. Paris (France). Awards a PhD thesis already defended. June 2019.

3rd ZwickRoell Science Award 2018, ZwickRoell Academia Day. Shanghai (China). Awards an article "in which material tests have played a major role, in order to recognize outstanding scientific efforts" (200 candidates, 17 countries). June 2019.

1st Award 2017 of the Doctoral Student Days of the Saclay Nuclear Activities Direction, CEA. Paris (France). Awards the best poster (50 candidates). May 2017.

1st Award 2017 of the Doctoral Student Day of the Nuclear Materials Department, CEA. Paris (France). Awards the best poster (25 candidates). March 2017.

Chloé Varenne internship supervision, internship awarded with 2nd place at the 2017 Materials Award of the SF2M West Section. 2017.

Supervision

PhD Thesis:

Fracture toughness and thin products: DHC (delayed hydride cracking) during transport of fuel rod claddings. MINES ParisTech, from October 2020 to September 2023.

Mohamed Shokeir, Modelling of the irradiation effects on fracture toughness of precipitation hardened aluminum alloys. MINES ParisTech, from October 2019 to September 2022.

Master 2 level internships:

Study of adaptation, convergence and mesh stability for modeling damage in the irradiated state. Polytechnic School, from April to July 2020.

Pierrick François, Miniaturization of toughness specimens. University of Technology of Compiègne, from February to August 2020.

Freddy Salliot, Fracture toughness and thin products: DHC (delayed hydride cracking) during transport of fuel rod claddings. ISAE-ENSMA Poitiers, from March to September 2020.

Fanny Audisio and Blanca Belzunegui Gabilondo, Generation of abacuses for optimizing the determination of the brittle-ductile transition temperature shift of a steel. Centrale Supélec, from November 2019 to March 2020.

Sami Meddeb, Study of the hardening nano-precipitation of an aluminium alloy by Atom Probe Tomography. Grenoble INP – PHELMA, from February to August 2019.

Mohamed Shokeir, Modelling of the irradiation effects on fracture toughness of precipitation hardened aluminum alloys. École Nationale Supérieure d'Arts et Métiers, from February to August 2019.

Aurélie Vessaire, Feasibility and representativeness of a new method for determining the toughness of zirconium cladding: "pipe-ring" specimens. École Nationale Supérieure d'Arts et Métiers & Master MAGIS, from February to July 2019.

Laurie Perlangeli, Modeling of mini-CT toughness specimens for the study of the ductile-brittle transition of 16MND5 steel. University of Technology of Troyes, from February to July 2019.

Chloé Varenne, Study of the influence of heat treatments on the microstructure and mechanical properties of an aluminium alloy. National graduate school of engineering of Caen, from February to July 2017. 2nd place at the 2017 Materials Award of the SF2M West Section.

Classes

Practical and Numerical Work:

- Paris 6 University / Pierre et Marie Curie / UPMC, Licence 3 Mécanique / Mécanique du solide : 24 h (2020)