Sujet de thèse proposé dans le cadre du projet ANR Fluti
Équipe Comportement et Calcul des Structures, Centre des Matériaux, Mines ParisTech,

Experimental and numerical analysis of sustained load cracking in Titanium

- *Partnership* : LMS Ecole Polytechnique, ICMPE
- *Duration* : Oct. 2011 to Oct. 2014
- *Key-words* : Titanium, toughness, sustained load cracking, hydrogen and oxygen influence, dynamic strain aging, numerical crack propagation
- *Funding* : ANR (French National Research Agency)

Abstract:

The influence of H and O on toughness and sustained load cracking (SLC) will be characterized. The influence of these impurities on the visco-plastic behaviour (yield stress, type and degree of hardening, strain rate sensitivity, activation volume) will also be investigated. Constitutive equations describing dynamic strain aging in relation with H and O contents and taking anisotropy into account will be formulated and identified. They will be used in finite element simulations of SLC taking into account H concentration at the crack tip and the impact of H on the local behaviour and damage process.

Main Objective:

Titanium alloys are widely used for aircraft or rocket engine manufacturing due to their high strength-to-weight ratio. They are also appreciated for steam turbines, naval and offshore applications as well as geothermal brine wells thanks to their resistance to corrosion. In the future, they could also be used for the first wall, blanket and magnetic coil structures of fusion reactors, for their good resistance to radiation damage and fast rate of residual radioactivity decay.

However, these alloys are prone to room-temperature creep and several associated phenomena which can be detrimental to structural integrity, such as creep-fatigue synergy (the "cold dwell effect" responsible for several in-service failures of aircraft engines during the past decades), sustained load cracking (mainly due to creep at the crack tip at low H content and to titanium hydrides precipitation and fracture at high H content) and absence of threshold for fatigue crack growth at high K_{max} (the "Marci effect", also associated with creep at the crack tip).

Titanium alloys always contain some residual solute impurities -among which oxygen- known to increase their yield stress through a reduction in the mobility of screw dislocations and hydrogen, which, in some circumstances, has an opposite effect (it triggers dislocations glide and softens the material) while in some other loading conditions, it also hardens the alloy. In the present practice, the H content is kept below an upper limit (around 150 weight ppm for alloys used in aeronautics) so as to avoid titanium hydrides precipitation, but no attempt to adjust the H content for optimum mechanical properties was made.

However, the amount of retained hydrogen in the range 0 to 150ppm has a large – but yet unexplained- influence on toughness, room-temperature creep (either enhanced or inhibited by H, depending on the alloy) as well as on the resistance to creep-fatigue, fatigue cracking at high K_{max} and sustained load cracking. When solute H enhances cold creep, sustained load cracking is triggered, while in the conditions for which it slows down creep, it also improves the resistance to SLC. There is an evident but yet unexplained correlation between the hydrogen content, the viscoplastic behaviour and the resistance to SLC. The aim of this project is to make the underlying mechanisms clear, so as to determine the optimum hydrogen content (as a function of the O content) to minimize cold creep, sustained load cracking and their consequences.

Task 1 – Experiments:

Tension and torsion tests at various loading rates or with loading rate jumps, as well as creep, loading-unloading-reloading and relaxation tests will be performed at LMS on each of the material batches, so as to investigate the anisotropy in the mechanical behaviour. Toughness and sustained load cracking tests followed by fractographic observations will be performed at CdM on CT specimens so as to determine the evolution in K_{IC} and the threshold stress intensity factor for SLC with the impurity content and detect possible modifications in fracture mechanisms (ductile voids, interfacial fracture or facetted fracture surfaces for example).

Task 2 – Models:

Macroscopic constitutive visco-plastic equations including the influence of H and O on DSA will be identified at CdM from experimental stress-strain curves for α Ti. A macroscopic model accounting for dynamic strain aging (DSA) will be improved including H and/or O concentrations. The constitutive equations include ageing terms in the yield function and in isotropic and kinematic hardenings. The creep arrest and the relaxation response of materials should then be accurately reproduced.

Task 3 – Simulations:

Finite element simulations of SLC in α titanium for various impurity content will be developed at CdM , assuming that the H distribution around the crack tip (in the interstitial lattice sites and trap sites) is in equilibrium with the local tress and plastic strain distributions (which seems reasonable for sustained load, considering the high diffusivity of hydrogen in titanium). The constitutive viscoplastic equations depending on the impurity level determined previously will be used in these simulations.
Firstly, a crack in a material showing DSA will be simulated in order to observe the strain localisation phenomena around the crack tip. In a second time, the diffusion of H in the calculated stress gradient will be estimated from a coupled mechanics-diffusion simulation. The H distribution will then be evaluated for each crack length. Finally, simulations of SLC will be performed including the obtained field of H concentration and adding cohesive zones in order to simulate the crack propagation in such conditions.

References:

[1] D.N. Williams, Effects of hydrogen in Ti alloy on subcritical crack growth under sustained load, Mat. Sci. Eng. 24, 1976, 53-63

[2] F. Mignot, V. Doquet, C. Sarrazin-Baudoux, Micromechanical investigation of the abnormal cracking of Ti6246 at high mean stress, , Journal of Mechanical Behaviour of Materials, 16 n°3, 2005, pp195-210
[3] S. Graff, S. Forest, JL. Strudel, C. Prioul, P. Pilvin, JL. Béchade, Strain localization phenomena associated with static and dynamic strain aging in notched specimens : experiments and finite element simulations, Mat. Sci. & Eng. A 387-389 (2004) 181-185
[4] S. Graff, S. Forest, JL. Strudel, C. Prioul, P. Pilvin, JL. Béchade, Finite element simulations of dynamic strain aging effects at V-notches and crack tips, Scripta Mat. 52 (2005) 1181-1186

To apply:
The candidate would ideally own a master related to Material Science or Numerical Simulation. A good background in Finite Elements theory and practice is required. The candidate must be proficient in English, shall talk C++ and preferably be used at working with a UNIX environment.

Applicants should supply the following :
- a detailed Cv

- a covering letter explaining the applicant's motivation for the position
- detailed exam results
- references

which must to arrive at Centre des Matériaux de l'Ecole des Mines de Paris, B.P. 87 – 91003 EVRY CEDEX, for the attention of recruitment department, and/or by e-mail : recrutement@mat.ensmp.fr