| ESRF | **Experiment title:** In-situ 2D strain mapping to study delayed hydride cracking in zirconium alloys | **Experiment number**: MA-283 |
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| **Beam line**: ID15A | **Date of experiment**: from: 11.04.2007 to: 16.04.2007 | **Date of report**: 12-07-2009 |
| **Shifts:** 15 | **Local contact(s)**: Matthew Peel | *Received at ESRF:* |


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**Report:**

The most common fission reactor type worldwide is the pressurized water reactor (PWR) which uses zirconium alloys as cladding material for nuclear fuel. One of the main drivers to improve the efficiency of current and future water-cooled reactors is to develop fuel assemblies that can operate under more severe fuel duty cycles. Zirconium alloys are used due to their good performance in the environment of a water-cooled reactor, and their low neutron absorption. During corrosion of the cladding material, hydrogen diffuses into the metal and forms hydrides due to the low solubility of hydrogen in zirconium (about 200 ppm at the service temperature of 320°C). Hydride formation leads to embrittlement of the cladding material, which limits the life time and the total amount of energy produced from a fuel assembly (note, it is not the fuel which limits the life time). Improved life predictions of fuel assemblies will require a detailed, mechanistic understanding of the so-called delayed hydride cracking (DHC), which is now seen as one of the most critical issues for developing advanced fuel assemblies. DHC is caused by hydrogen diffusion, precipitation and growth of hydrides. The process occurs at stress concentrations around cracks, notches and flaws found at the surface of the cladding material. The crack growth rate is determined by the rate the hydrides crack, which in turn is governed by the stress fields experienced by the hydrides in front of the crack tip and the diffusion rate of the hydrogen. Interestingly, the diffusion of hydrogen in the vicinity of a notch is affected by the hydrostatic tensile stress field. In addition, it has been shown that stresses will affect the solubility level of hydrogen in zirconium, which could result in early hydride formation in front of the crack tip [1]. Stress is also known to affect the type of hydrides (γ or δ) that is formed [2]. All these factors demonstrate that the development of a true mechanistic DHC model will depend on the possibility of in-situ mapping the strain/identifying the phase/detecting volume fraction variations of the hydrides in the vicinity of a notch/crack at elevated temperatures.

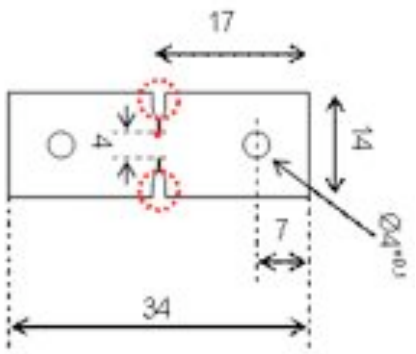


Figure 1: Sample geometry

In order to understand the role of hydrides during mechanical loading, in particularly around notches, loading experiments of double notched samples (Figure 1) were carried out on ID15A between room temperature and 400°C. Fine 2D strain maps were recorded using a 50 x 50 $\mu m^2$ beam size around one notch of the samples. While the strain of the Zr matrix was relatively easy to map, the zirconium hydride phase only allowed to map two very small diffraction peaks and the measued strain showed significant scatter. Nevertheless, some very interesting observation could be made, which are currently discussed in terms of how the mechanism of DHC might have to be redefined. Figure 2 shows strain maps of the zirconium matrix when the sample was loaded to 150 MPa. It can be seen that with increasing ZrH content the strain in the Zr matrix generally increases towards the notch. Work by Kerr et al [3] has suggested that the Young's modulus of Zr and ZrH is relatively similar. Consequently, the observations made here indicate that the hydrides do not carry significant load. However, a large peak shift was observed for the measured ZrH peak (Figure 3). This indicates, as recently demonstrated in [4], that the large peak shift observed for ZrH might be related to a phase transformatiuon strain. The finding of this work together with [4] have raised considerable interest in the nuclear industry as it could fundamentally change the view we understand DHC. Consequently, a new project is currently being set up, funded by the French Nuclear Safety Authority, to use synchrotron x-ray diffratcion to study hydrides in zirconium alloys.

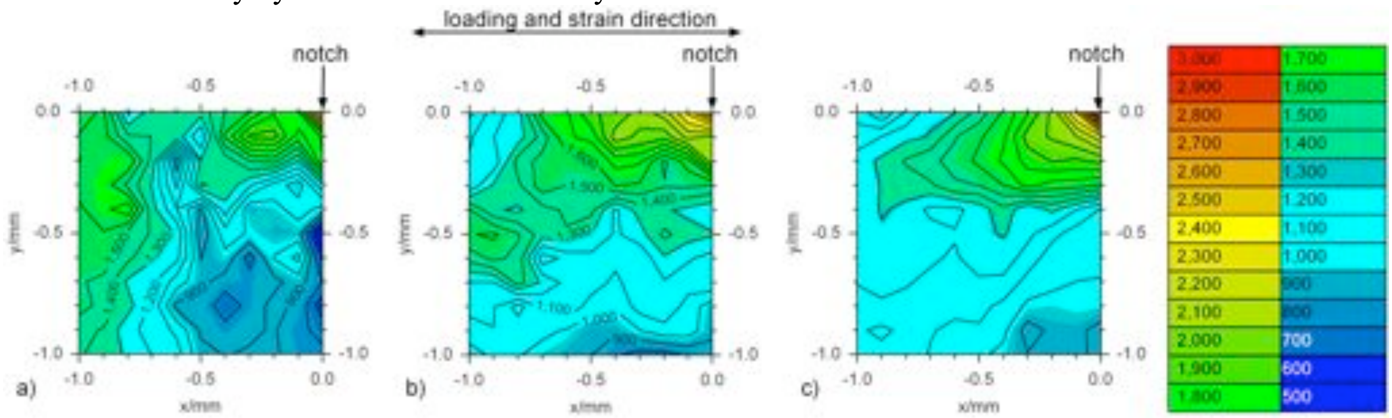


Figure 2: Zr matrix strain fields around the notch for a) sample with about 0 ppm hydrogen, b) 350 ppm hydrogen and c) 800 ppm hydrogen when the sample was loaded to 150 MPa. Note that the strain near the notch increases noticably with increasing hydrogen levels.

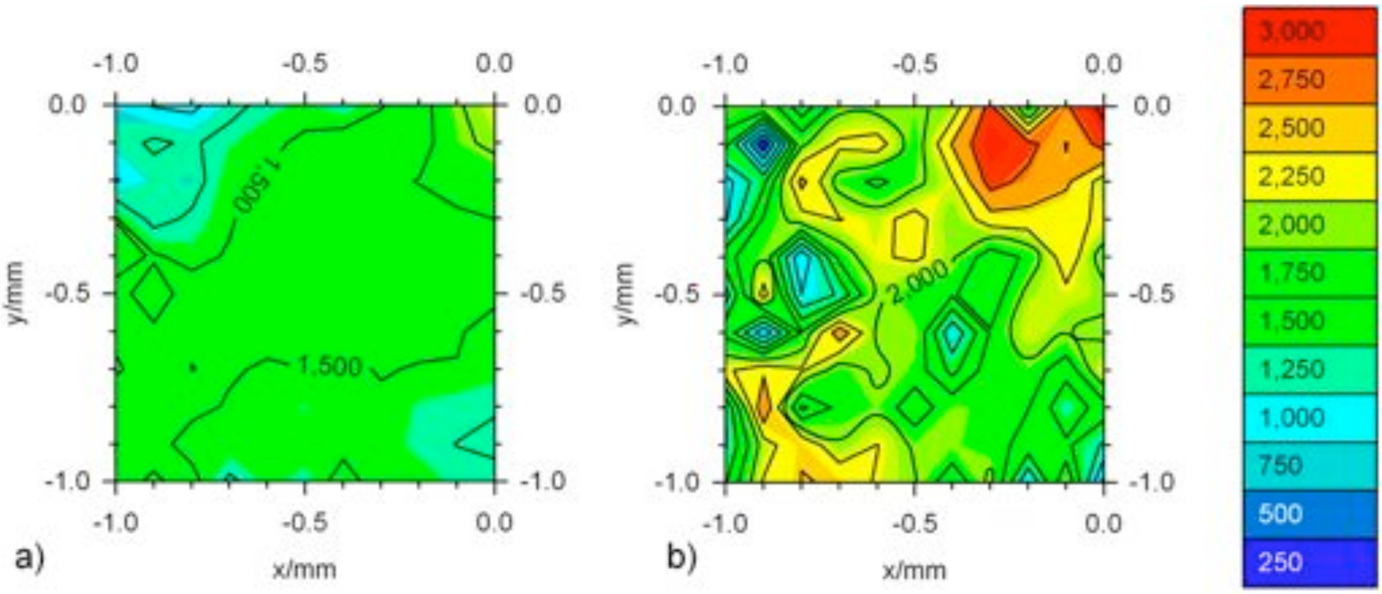


Figure 3. Comparing the strain field of the zirconium matrix (a) and of zirconium hydrides (b) tested at 400°C and loaded to 150 MPa. Note the very pronounced difference in apparent tensile strain observed in the hydrides that is not matched in the matrix even though the elastic properties of Zr and ZrH are supposed to be similar.

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1 R. Dutton et al., Metallurgical Transaction A, 8 (1977),.1553.

2 D.A. Meyn, Metallurgical Transaction, 3 (1972), 2302-2305.

3 M. Kerr, M.R. Daymond, R.A. Holt, J.D. Almer: Strain evolution of zirconium hydride embedded in a Zircaloy-2 matrix, Journal of Nuclear Materials, Volume 380, Issues 1-3, 15 October 2008, Pages 70-75

4 A. Steuwer, J.R. Santisteban, M. Preuss, M.J. Peel, T. Buslaps, M. Harada, Evidence of stress-induced hydrogen ordering in zirconium hydrides, Acta Materialia, Volume 57, Issue 1, January 2009, Pages 145-152.