Iodine induced stress corrosion cracking and axial creep: 2 new cladding testing facilities at Leci laboratory

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Abstract

Extension and refurbishment of the CEA Saclay Leci hot laboratory initiated 10 years ago is now considered as completed. The present paper describes two new cladding testing facilities available at Leci.

Iodine induced stress corrosion cracking of zirconium alloys fuel claddings may develop during power transient due to pellet-cladding interaction (PCI). This phenomenon was studied in the previous CEA installation using iodine atmosphere internal pressure creep tests on defuelled samples. The new facility allows tests to be performed in two modes: i) driving on the pressure with the ability to do complex loading creep tests, ii) driving on the hoop strain thanks to the diameter laser measurement, which allows relaxation tests to be achieved and consequently to be more representative of the loading imposed by the pellet on the cladding during PCI. Inert atmosphere can also be used in order to determine mechanical properties of irradiated claddings or hydrides re-orientation conditions.

Axial creep: Two electro-mechanical tensile machines have been set up to test several geometries of irradiated materials: tubular and flat specimens or bars. Variable gauge length extensometers with ceramic rods have been adapted to handling with telemanipulators and are used for both creep and relaxation tests up to 800°C.

Keywords

Iodine, stress corrosion cracking, pellet, cladding, mechanical test, creep, relaxation

1 Introduction

Extension and refurbishment of the CEA Saclay Leci hot laboratory initiated 10 years ago is now considered as completed. Nineteen new lead cells are equipped with new testing facilities dedicated to characterization of irradiated materials like fuel claddings, pressure vessels steels or inner parts of nuclear reactors. Another paper of the present conference [1] deals with one of the new testing facilities of the Leci laboratory: Raman spectroscopy. The present paper focuses on two other new cladding testing facilities available at Leci. On the one hand: Iodine induced stress corrosion cracking testing facility and on the other hand: Axial creep and relaxation testing facility.

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2 Iodine induced stress corrosion cracking (I-SCC) testing facility

2.1 Context

In pressurized water reactors (PWRs), the low thermal conductivity of the uranium oxide gives rise to an important temperature difference between the fuel pellet centre and its outer diameter. This radial temperature gradient leads to the hour-glass shape and to the cracking of the fuel pellet. Contact between fuel fragment and cladding initiates at the inter-pellets level. This situation is often referred to as pellet cladding interaction (PCI). Also, during heating induced by power transients, iodine as other fissile products stored in the pellet can be released. Under PCI conditions, I-SCC then results from the synergic effect of (i) the stress and strain imposed on the cladding by fuel thermal expansions during power transients and (ii) corrosion by iodine released from the fuel pellet.
I-SCC of irradiated claddings was studied in the previous CEA facility using iodine atmosphere internal pressure creep tests on defuelled samples [2]. However, mechanical loading of the cladding during power transients is more likely to be an imposed displacement condition than an imposed load condition. To reproduce such imposed deformation loading, a new facility was therefore developed with an on-line diameter measurement and the ability to drive the pressure following the diameter measure.

2.2 General description

A view of the new I-SCC facility is showed on Figure 1. Cladding sample, connected to the argon pressure input, is located in a three zones resistive furnace. Maximal temperature and internal argon pressure are 500°C and 1000 bars respectively. Temperature of the sample is measured using a type K thermocouple, which is clipped in the middle of the cladding sample. Pressure is measured by a sensor. External diameter of the cladding is measured by a scanning laser device, thanks to dedicated windows machined in the furnace. Both diameter and pressure values are transmitted to the controlling computer. Internal pressure is imposed by a regulator that is driven by the computer using either the sample pressure value or the sample diameter value. This allows us to run on this machine several kinds of tests:

- Constant strain rate tests
- Constant pressurization rate tests
- Creep tests (constant pressure)
- Relaxation tests (constant diametrical strain)
- Multi-phases tests driving on the diameter or on the pressure

Temperature evolution with time is programmed through the computer and temperature regulators independently from the pressure, which allows complex tests to be run such as hydrides re-orientation tests for fuel transportation and storage studies. Tests duration range is from several minutes to several weeks.

2.3 Testing procedure

Inner and outer diameters of the cladding are first measured in order to be able to convert pressure into hoop stress. Cladding sample is then equipped with a Swagelok end plug and union (Figure 2). Depending on the type of test to be run, a profilometry (laser scanning external diameter measure every half millimeter along the sample) can be made. A given mass of iodine pills are introduced in the sample just before the test. The sample is then connected to argon pressure input and introduced from the top in the three zones resistive furnace. Testing parameters are then entered in the driving software on the computer and the test is launched. After the test, sample is cooled down and removed from the furnace and data are saved. Depending on the aim of the study, post-test profilometry and/or scanning electron microscope (SEM) observation can be done after cleaning of the sample.

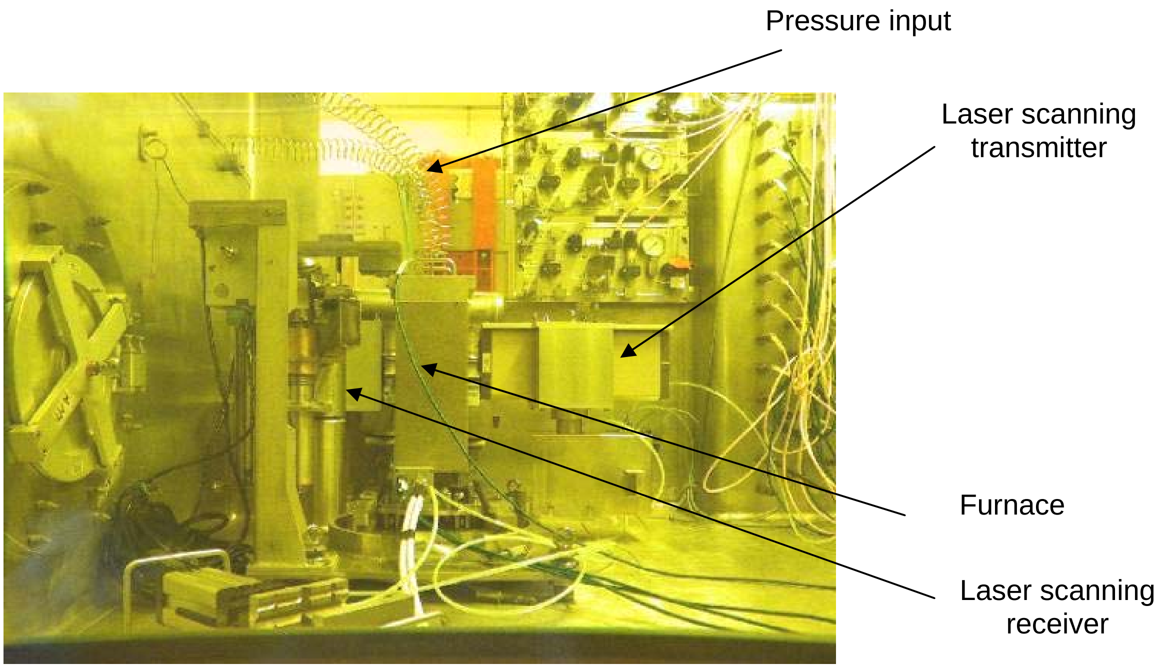

Figure 1: View of the I-SCC testing facility

Figure 2 : I-SCC specimen **(**90mm in length), left picture: de-fuelled cladding tube and Swagelok union and end plug, right picture: de-fuelled cladding tube with connected Swagelok union and end plug

2.4 Results

Strain rate is known to play an important role in mechanical behavior of Zircaloy claddings: around 350°C flow stress increases with strain rate. Strain rate plays even a more important role in I-SCC sensitivity because stress corrosion cracking is a diffusion controlled phenomenon. The new facility allows this strain rate effect to be studied straightforward by running constant strain rate tests driving the pressure on the diametrical strain. Figure 3 and Figure 4 show the post-test observations made after such a constant strain rate test on an un-irradiated Zircaloy-4 cladding sample. Iodine mass was 1.5 mg.cm^{-2}, temperature was 350°C and strain rate 10^{-5} s^{-1}. Through-thickness cracking was detected after 1.8% diametrical strain. SEM pictures in Figure 4 show that crack propagation is transgranular brittle at the beginning and transgranular ductile at the end.

Figure 3 : Picture of a 90mm I-SCC cladding specimen in un-irradiated recristallized Zircaloy-4 showing through thickness cracking after testing at 350°C and 10^{-5} s^{-1} constant strain rate

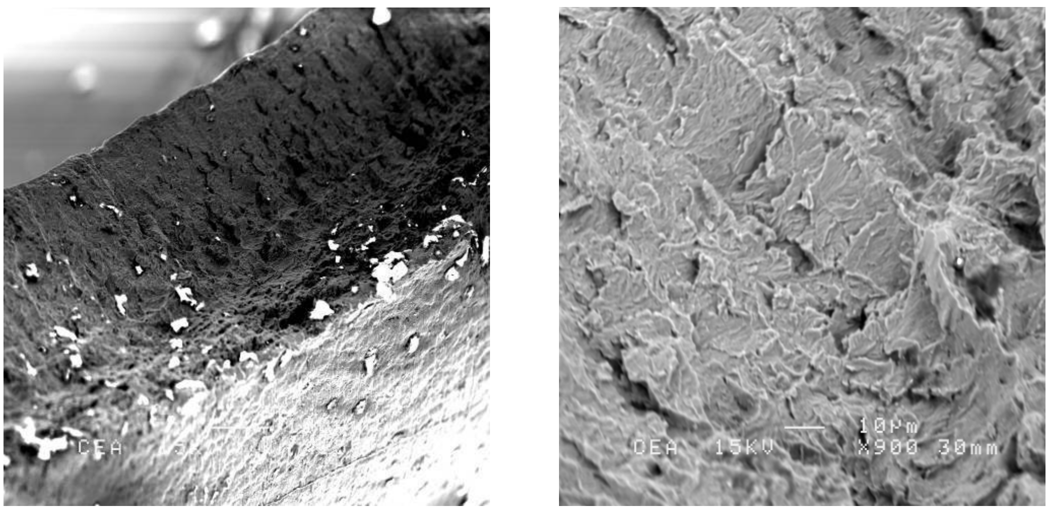

Figure 4 : Scanning electron micrography of a through thickness I-SCC crack in recristallized Zircaloy-4 un-irradiated cladding after testing at 350°C and 10^{-5} s^{-1} constant strain rate

3 Axial creep and relaxation testing facility

3.1 Context

Metallic in-core structural parts and fuel cladding are subjected to both neutron irradiation and thermo-mechanical constraints. As they play an important role in nuclear safety, mechanical properties of such irradiated materials at service temperature and above are required. PWRs claddings are mainly loaded with either internal or external pressure, however, during PCI (cf. § 1), complex loading of the cladding by the fuel pellet may happen. In order to obtain pertinent data to identify the anisotropic constitutive laws of the irradiated cladding, axial or combination of axial and pressure loadings are needed. The new axial creep and relaxation facility was designed to reach this goal.

Axial creep testing consists in applying a constant load on a specimen and measuring its progressive elongation with time whereas axial relaxation testing consists in measuring the progressive decrease of the load needed to keep the elongation constant with time. Creep is consequently representative of imposed load conditions whereas relaxation is representative of imposed displacement conditions. Both creep and relaxation tests are performed at constant temperature. Tests last usually from several days to several weeks.

3.2 General description

The new axial creep and relaxation facility consists in two identical DMG electro-mechanical tensile machines with 50kN capacity, two Pyrox three zones resistive furnaces with an achievable temperature from ambient to 800°C, 4 Maytec extensometers with LVDT sensors and zircon rods connected to the specimen (2 axial extensometers for elongation measurements and two diametrical extensometers for reduction in section measurements) and two independent DMG driving and login systems with dedicated softwares. Figure 5 represents a schematic view of a machine and Figure 6 shows a picture taken from the inside of the cell before its closing.

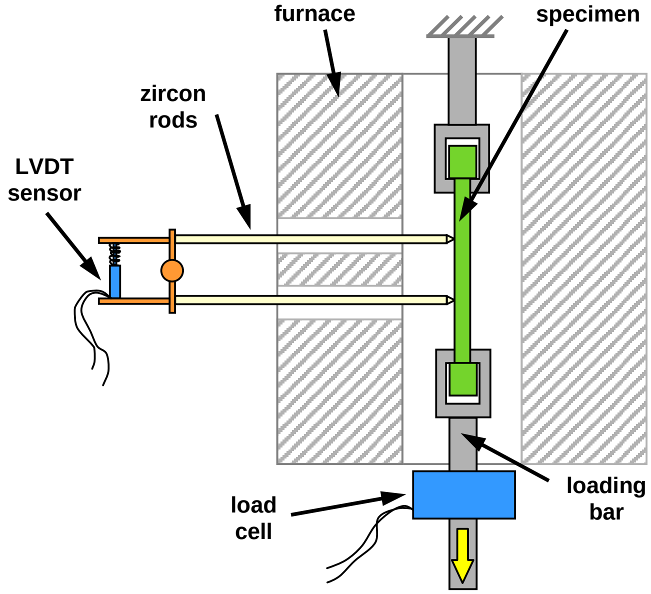

Figure 5 : Schematic view of the axial creep and relaxation testing facility

Figure 6 : View of one of the two machines from inside of the cell, notice the diametrical and the axial extensometers in the blue aluminum boxes and the zircon rods passing through a slot machined in the furnace

3.3 Testing procedure

Specimens' dimensions are accurately measured before testing using mechanical or optic devices. Specimens can be de-fuelled claddings samples with welded end plugs as illustrated in Figure 7 or flat usual dog bone tensile specimens or bars, depending on the material to be tested. As the axial extensometers have variable gauge length, various specimen lengths can be tested. In order to record the temperature during heating and testing, a type K thermocouple is connected to the gauge length of each specimen. Specimens are then inserted in the connecting parts of the loading bars. Before closing the furnaces, the zircon rods of the axial extensometers are gently moved forward until they reach the gauge length of the specimens. Diametrical extensometers are then also moved forward through the slot machined in the furnaces. Testing program is then launched on the controlling computers.

Figure 7 : Cladding specimen with laser beam welded end-plugs for axial creep testing

3.4 Results

Axial creep test on a laser beam welded un-irradiated zirconium alloy cladding during 10 days at 400°C and 110.5 MPa are presented in Figure 8. Argon flow was used in the furnace to minimize oxidation of the specimen.

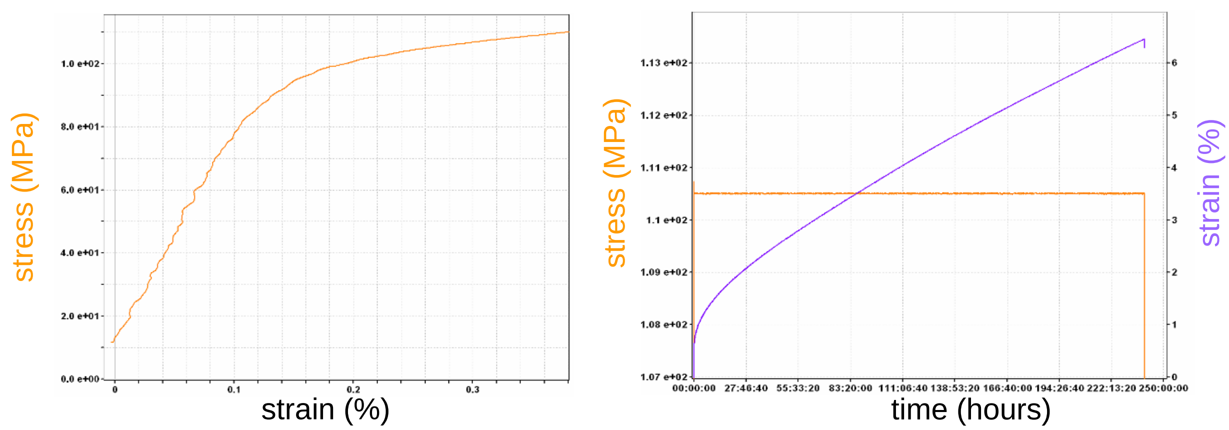

Figure 8 : Left: axial stress-strain curve during loading of the axial creep test, right: axial creep curve at 400°C and 110.5 MPa for an un-irradiated laser welded cladding specimen tested during 10 days

4 Conclusion

I-SCC and axial creep and relaxation facilities are accurate but also flexible machines. Driving on the load but also on the strain is possible with both of these facilities. Moreover, various specimen geometries can be tested.

5 References

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