Induction Heating on Dynamic Tensile Tests in CEA Saclay

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Abstract

The LCMI (Laboratory for characterization of irradiated materials), located in CEA from Saclay, is in charge of the mechanical tests on irradiated materials. The dynamic tensile testing machine, in a hot cell equipped with two remote handlings, has been first improved in 1995, to fulfill the French safety programs on Reactivity Initiated Accident (RIA). One objective of this machine is to obtain mechanical property data on current Zircaloy cladding types needed to quantify the cladding's response under RIA or LOCA transient loading and thermal conditions. For the RIA, this means testing at strain rates up to 5 s^{-1} and heating rates up to 200°C.s^{-1}, while for Loss Of Coolant Accidents (LOCA) testing at strain rates of 10^{-3} s^{-1} and heating rates of 20°C.s^{-1} would be appropriate.

The tensile samples are machined with a spark erosion machine, directly from pieces of cladding previously defueled. Two kinds of samples can be machined in the cladding:

- Axial samples in order to test axial mechanical characteristics
- Ring samples in order to test transverse mechanical characteristics, more representative of RIA conditions

On one hand, the axial tensile tests were performed using the Joule effect, and heating rates up to about 500°C.s^{-1} were obtained. This enabled us to perform the axial tests in a satisfactory manner.

On the other hand, the tensile ring tests were first performed in a vertical furnace with a heating rate about 0.2°C.s^{-1} and a thermal stability about 1°C. For temperatures above 480°C, the mechanical characteristics showed a sharp drop which could be attributed to irradiation defect annealing. Therefore we have recently developed an induction heating system to reach heating rates high enough (200°C.s^{-1}) to prevent any significant annealing before performing the ring tensile tests. To apply a uniaxial tangential tension, two matching half-cylinders are inserted inside the ring and are pulled apart.

The main objective of this paper is to present this system that can be telemanipulated and achieve heating rates up to 200°C.s^{-1} while taking into account the requirement for air-cooled coils in the hot cell. The same interface is used for induction heating equipment and Joule effect (current system), in order to control the specimen temperature synchronously with the load/extension, collecting data from all transducers connected including load/displacement.

Keywords: Induction heating, tensile ring test, irradiation defect annealing

1. Introduction

Economic considerations have promoted the use of high burnup fuel in nuclear power plants. However, the behaviour of the high burnup UO_2 and MOX must be assessed: one of the requirements is that high burnup fuel does not lead to core degradation during a design basis reactivity initiated accident (RIA), i.e. in a pressurized water reactor (PWR) a rod control cluster accident leading to fast power increase (in a few ms). In this framework, the RIA CABRI REP-Na programme [i] has been run jointly by IPSN and EDF in order to analyse the high burnup fuel behaviour under RIA transients and to validate the use of the current safety criterion. To support these studies, the CEA runs the PROMETRA (which stands for "Transient Mechanical Properties") programme [i] which is devoted to the assessment of the mechanical properties of Zircaloy-4 cladding under thermomechanical conditions representative of the first phase of an RIA. Constitutive laws of irradiated Zircaloy-4 cladding, taking into account irradiation hardening, hydriding, waterside oxidation and spalling, are derived and implemented in the SCANAIR code [i] in order to simulate more accurately fuel behaviour during accidents.

In an RIA, the sudden increase in reactor power deposits a large amount of energy into the fuel. The resulting thermal expansion of the fuel pellets, possibly reinforced by fission gas swelling, first loads rapidly the cladding into the plastic regime. In a second phase, plenum pressure driven clad ballooning may occur, depending on conditions in the coolant channel. But, in this paper, we will focus on the first stage of the accident, which is dominated by the Pellet Clad Mechanical Interaction (PCMI).

This phase is characterised by high heating rates (~10^3 °C.s^{-1}) and high strain rates (~1 s^{-1}). The typical temperatures reached are between 280 and 600°C. The cladding is submitted to hoop and axial strain, with a σ_z/σ_θ ratio ranging between 0.5 (pure gas pressure) and 1 (PCMI). The samples tested originated from cold work stress relieved Zircaloy-4 claddings, irradiated up to five cycles in a PWR and taken from different grid spans, in order to observe the influence of corrosion (oxide, hydride and possibly spalling). First, uniaxial tensile tests have been performed and the results have been published elsewhere [ii]. Then, ring tests on machined tubing have been realized [iii] in order to measure the relevant mechanical properties (such as yield strength, ultimate tensile strength, uniform elongation, stress-strain curve,...). These tests were complemented by an iterative finite element analysis (FEA) to estimate constitutive laws in spite of the heterogeneous stress and strain fields encountered during these hoop tests [iv]. However, there was concern about the significance of values obtained at temperatures higher than 480°C, due to the potential annealing of irradiation defects: the samples were heated with a conventional furnace with slow heating rates (~0.2 °C.s^{-1}) and consequently, annealing, redistribution of hydrides and even recrystallization for the higher temperatures could be expected. Therefore, we have decided to develop a fast heating technique (200 °C.s^{-1}) to minimise the impact of annealing.

2. Rapid Heating Tests

2.1. Experimental techniques

The materials stem from grid spans 2 to 6 of irradiated Zircaloy-4 cladding with tin contents of 1.5% (former standard) and 1.3% (present standard). The oxide thickness of these claddings has been determined using Eddy current measurements. The samples are machined with a ram spark erosion machine which requires the prior mechanical removal of the oxide layer. For these tests, the samples were rings machined from tubes with an external diameter of about 9.5 mm and a thickness of about 0.6 mm. The rings have a 5 mm current width with two gauge lengths of 3 mm length and 2 mm width (gauge length to width ratio equal to 1.5). The rings are placed around two half cylinder (double-D) inserts which are attached to the cross heads and pulled apart inside the rings as shown in Figure 1.

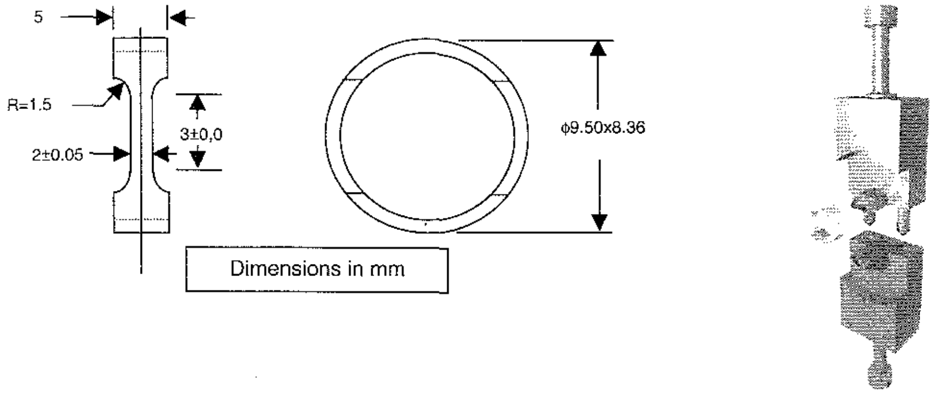

Figure 1 Ring specimen geometry and 3D view of the mandrel and ring test sample

The fixtures are placed on a servo hydraulic tensile testing machine equipped with load and displacement sensors. In opposition to the tests performed earlier [iii], the samples are heated up rapidly with an induction coil as shown in Figure 2. The induction coil is air cooled. Outside the hot cell, an air to water heat exchanger (included in the oscillator) is used (as illustrated on figure 3).

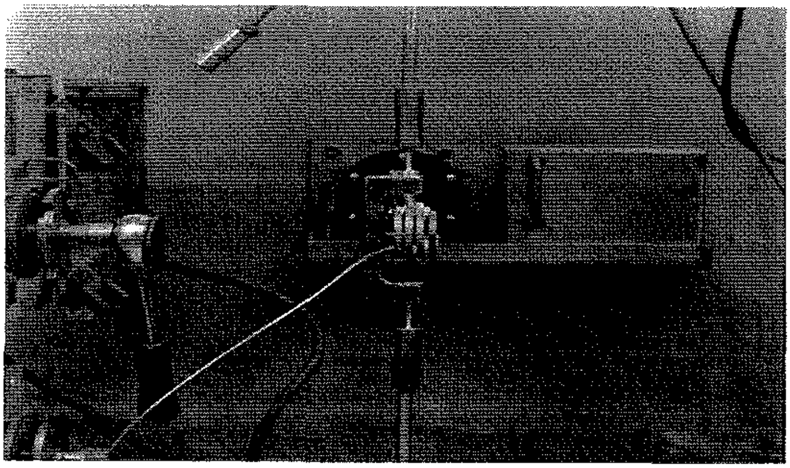

Figure 2 Rapid heating device

The performances of the device are described in table 1. The test starts with the dynamic heating of the sample at the required temperature ramp rate. Thermal dilation is compensated by load regulation. Then, immediately after the target temperature is reached (T_1), the control becomes a strain control and the tensile test starts (T_n). The tests were performed with a strain rate of 5 s^{-1} with a heating rate of 200 °C.s^{-1} *followed by a short stabilisation time : typically about 7-10 s elapsed between the start of the heating ramp* and the completion of the test. Figure 4 illustrates the sequence.

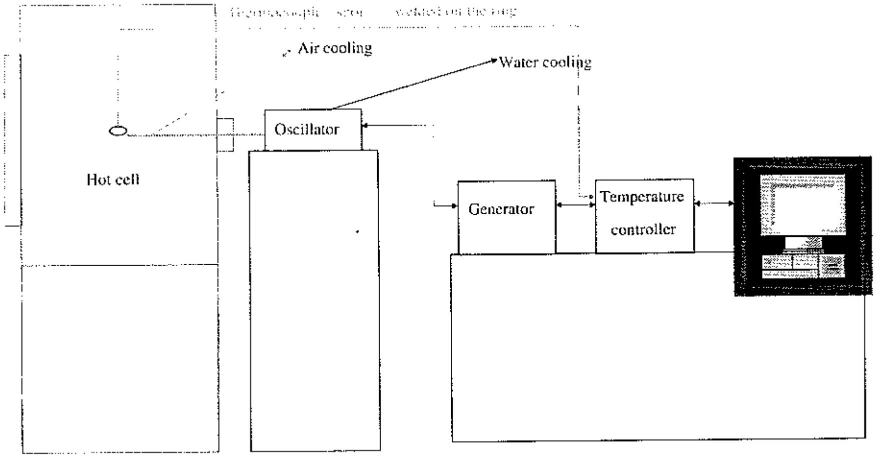

Figure 3 Principle of the device

The load versus displacement curve yields the engineering parameters: 0.2YS (yield strength), UTS (ultimate tensile strength), UE (uniform elongation). The total elongation is not very significant in that case: when the necking of the specimen starts, the section on the gauge length is no longer uniform and some bending occurs.

Individual measurements (thickness, outer diameter) are performed on each sample before testing in order to determine the conventional stress.

Table 1 Performances of the dynamical tensile test device

Tensile machine load and position controlled		
	Actuator displacement velocity	0<velocity<500 mm/s
	Load cell capacity	5 kN
	Displacement transducer	+/- 50 mm
Heating by vertical furnace		
	Temperature ramp rate	0.5 °C/s
	Maximum temperature	750°C
	Precision	+/-2°C (TC in contact with the sample)
	Stability in temperature	+/-1°C
Heating by Joule Effect (50Hz)		
	Temperature ramp rate	500°C/s
	Maximal temperature	1250°C
	Precision	+/-2°C (TC in contact with the sample)
Heating by induction system		
	Temperature ramp rate	200°C/s
	Maximal temperature	900°C
	Precision	+/-2°C (TC in contact with the sample)
Computer: acquisition and control		

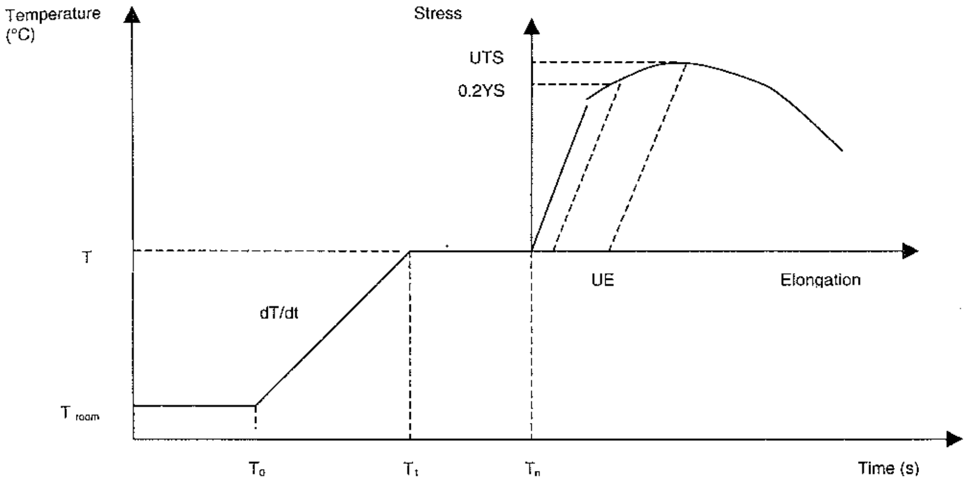

Figure 4 Sequence of test

The most recent development on this device is the induction heating system and was finalized outside the hot cell. The heating rate obtained is 200 °C.s^{-1} (to be compared to 0.2 °C.s^{-1} obtained with a conventional furnace) and temperatures up to 900°C can be reached. The inductor coil is located around the mandrel.

We optimised the initial radial gap between the sample and the inserts to reduce the bending on the gauge length during the increase of temperature: this gap is reduced for example from 35 microns at room temperature to 10 microns at 600°C. For each sample, the gauge lengths are centred to apply the load on them.

The material of the pull–rods with inserts has been chosen in order to have a good mechanical behaviour at high temperature, to have a dilation similar to that of the sample and to be easy to machine. Inconel proved to be the best compromise.

In order to protect this coil during the test, the range of displacement of the jack is limited to 5 mm. The temperature is regulated using a K-type thermocouple (0.5 mm diameter) spot welded in the middle of one of the gauge lengths. Prior to the introduction in hot cell, the temperature measured by the thermocouple has been validated by measurements with a monochromatic pyrometer from 375 to 900°C, in order to answer some concerns about inertia of the thermocouples and their possible coupling with the induction coil. A good agreement between the temperatures given by the two devices was obtained. Therefore, the measurement of temperature in hot cell is performed with the thermocouple.

The test matrix is given in Table 2.

Table 2 Test matrix giving temperature ranges (in °C) covered for slow heating rates [iii] and fast heating rates.

Heating rate	Oxidation of the cladding (ZrO_2 thickness)				
°C.s^{-1}	Unirradiated	<30µm	30 to 60	60 to 100	>100µm
0.2	20-600	280-600	280-600	280-600	280-480
200		480-600	480-600		

3. Results

Figures 5 and 6 show the hoop ultimate tensile strength and the uniform elongation plotted versus the temperature for the tests carried out with a slow heating rate [iii] and the results obtained with the rapid heating technique. These figures show that for the tests at 480°C, there are no differences between the results obtained with the two heating techniques. This suggests that no significant annealing takes place during the heating ramp to 480°C and that the results obtained with a conventional furnace are valid up to this temperature. For the tests at 600°C, important differences between the mechanical properties obtained with conventional heating and induction heating are observed. As expected, the ultimate tensile strength increases and the uniform elongation decreases, which shows the necessity of using induction techniques for temperatures higher than 480°C. This is due to the fact that the time allowed to reach the target temperature and proceed to the test (<10 s) is insufficient to allow significant microstructural changes to occur.

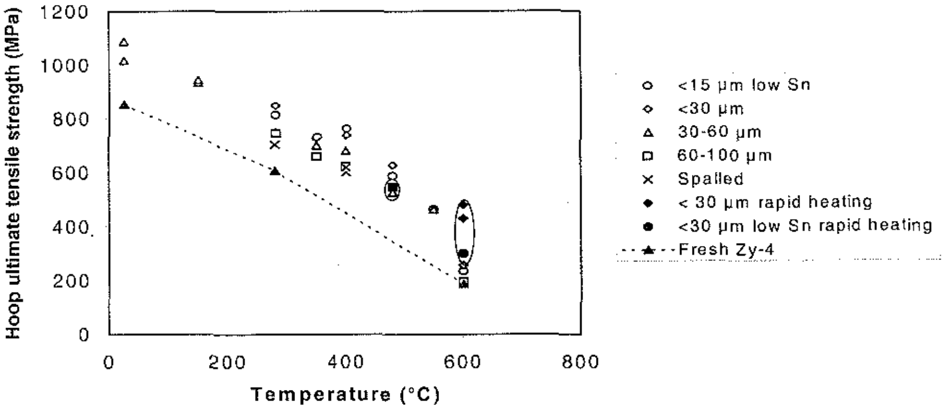

Figure 5 Hoop ultimate tensile strength versus temperature

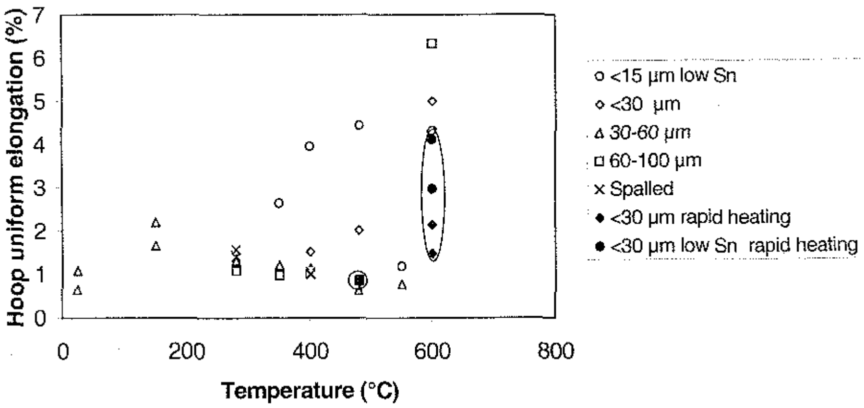

Figure 6 Uniform elongation versus temperature

4. Conclusions

High strain rate mechanical tests are needed in support of the RIA studies led by EDF and IPSN. Up to now, the PROMETRA program has yielded important data on transient mechanical properties of irradiated Zircaloy-4 cladding, and the influence of waterside corrosion up to 480°C. In this work, we have developed and implemented in hot cell a rapid heating device which enables us to perform tests up to 900°C with a heating rate of 200 °C.s^{-1}. The comparison of the results obtained with both types of heating have shown the necessity to use the induction heating for temperatures higher than 480°C.

5. References

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[i] . PAPIN J., BALOURDET M., LEMOINE F., FRIZONNET J.M., SCHMITZ F.,"French Studies on High-Burnup Fuel Transient Behavior Under RIA Conditions", Nuclear Safety 37(4) (1996) pp. 289-327.

[ii] . BALOURDET M., and BERNAUDAT C., "Tensile Properties of Irradiated Zircaloy 4 Cladding Submitted to fast transient loading", Proceedings of the CSNI Specialist Meeting on Transient Behavior of High Burnup Fuel, Cadarache, France, September 12-14 1995, pp. 417-431

[iii] . BALOURDET M., BERNAUDAT C., BASINI V., and HOURDEQUIN N., "The PROMETRA Programme : Assessment of Mechanical Properties of Zircaloy 4 Fuel Properties During an RIA", Transactions of the 15th International Conference on Structural Mechanics in Reactor Technology (SMiRT-15) Seoul, Korea, August 15-20, 1999, pp. II-485-492.

[iv] . YVON P., SAINTE CATHERINE C., DUGUAY C., CARASSOU S., HOURDEQUIN N., CAZALIS B., BERNAUDAT C., "Development of new techniques to assess the mechanical behaviour of Zircaloy-4 during an RIA", Paper presented at the AIEA Technical Committee Meeting on "Fuel Behaviour under transient and LOCA conditions", Halden, Norway, September 10-14 2001