Development of a Toughness Testing Technique, for Zircaloy Cladding, using an Internal Conical Mandrel (ICM)

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ABSTRACT : *An understanding of fuel rod cladding characteristics, that determine the limiting stress level for crack initiation and propagation, is a fundamental requirement for the design and development of water reactor clad materials. Conventional mechanical tests used at present to evaluate fracture properties are of limited use. The reason is that the fracture toughness procedure, meeting ASTM standards, is adapted for thick flat-plate materials that differ significantly from fuel cladding geometry (0.57 mm thick). Therefore, results that can be related to clad structure and performance need to be obtained by appropriately characterised tests outside the purview of current ASTM standards. The Internal Conical Mandrel (ICM) test is designed to simulate the effect of fuel pellet diametrical increase on a clad with an existing crack. It consists in forcing a cone, having a tapered increase in diameter, inside the Zircaloy cladding with an initial axial notch or pre-cracked notch. The purpose of this test is to quantify the crack initiation and propagation criteria. The experimental system has been designed and is operating in our laboratory. The axial load measured during the test can only be indicative of the crack progress, and cannot be used for a quantitative evaluation of toughness due to friction coefficient. From a fracture mechanics point of view, these considerations make the evaluation of toughness using the Rice's integral (J) very difficult to achieve. In order to overcome these problems and evaluate the J integral, a finite element simulation of crack behavior (or characteristics) during this test is used.*

INTRODUCTION

Zircaloy cladding is the tube containing nuclear fuel in Pressurised Water Reactor (PWR), and it is the first wall barrier against contamination of the primary coolant water. Thermo-mechanical loading of the cladding is due to thermal gradient and to fuel pellet diametrical increase during either normal or incidental operations. In all these configurations, the structural integrity of the cladding must be ensured, or, at least failure of the cladding due to crack propagation has to be within acceptable safety limits. The conventional dimensions of the cladding are an outer diameter of 9.5 mm and a typical thickness of 0.57 mm. It is worth to say that conventional fracture toughness testing techniques such as those recommended in standards (e.g. NF-A03-183, ISO 12135 and ASTM E-1820) are not suitable for the cladding because of geometry and loading mode restrictions. Furthermore, the crack-tip constraint is very low and probably is near to plane stress rather than plane strain condition [1]. Therefore, all the toughness measurement techniques developed have to address not only the material but also the geometry and the loading mode.

Different toughness test techniques, such as PLT [2], VEC [3], X-Specimen [4], have already been developed but they do not meet the problem faced by the nuclear industry from the considerations of the loading mode and crack propagation possibilities. These were the reasons for the development of Internal Conical Mandrel (ICM) test [5].

ICM TEST PRINCIPLE

An overview of the ICM testing device is given in Figure 1. The inserting cone rod is composed of three parts : (a) a cylindrical part at the bottom with its diameter matching the inner tube diameter, (b) a large diameter (12 mm) cylindrical part at the top, and (c) a conical part joining the two cylindrical parts (a) and (b) which applies the load. The cone usually has an angle of 4° (but 6 or 2° were also tested).

The ICM specimen geometry had the following characteristics :

- Tube height : 100 mm (adaptable between 20 and 120 mm),
- Notches : 2,
- Initial notch + crack length : 5 + 2 mm,
- Fatigue pre-cracking was performed using a specific loading tool for working in the tension-opening mode on the two sides. The stress ratio (R) was maintained equal to 0.1 during this pre-cracking stage. The maximum load was selected in order to be lower than the loss of linearity for a monotonic loading (less than 200 N). A crack length of 2 mm was obtained in about 10 kcycles.
- U-Notch radius (opposite to the pre-cracked side) : 0.5 mm.

The bottom of the test piece is simply supported. A $MoSi_2$ lubricant was used and the conical mandrel was forced by compression into the cladding. No elastic buckling could occur because of the support provided by the matching part of the mandrel. The test is performed at a constant displacement rate of 1.5 mm/min. An axial load versus displacement curve is recorded. In addition video images, of the tube and in particular of the crack tip loading, were also acquired during the test. An example of the video image is shown in Figure 2, for the test T12912 performed at room temperature.

DATA ANALYSIS AND FINITE ELEMENT SIMULATION

In Figure 3, the flow diagram proposed for data analysis is shown. The data collected comprise the following : axial load, cone displacement, crack propagation and CTOA. The axial load measured is not directly related to the applied load because of friction. It should be mentioned that a conventional (from fracture mechanics point of view) load-line displacement curve is not generated. Only CTOA and crack propagation available from the video record are used in the experimental analysis. From Finite Element (FE) numerical simulation, we can get the imposed cone displacement, an axial load (without friction), a CTOA and a Rice integral (J) evaluation. Such FE J computations have also been performed for PLT geometry [6].

The FE simulation is performed with Castem 2000, which is a FE code developed at CEA. Due to plane symmetry along the axis, only the half tube is meshed with 3D solid elements. A total of 1214 non-linear CUB20 elements, which lead to 7138 nodes, and 2 elements for the tube thickness are considered. The displacement is imposed at the bottom of the tube in the Z (axial) direction. The cone is not really implemented in the FE simulation ; Instead the corresponding deformation is performed using specially imposed displacement relations. This simplifies the problem of FE formulation because there is no contact problem, which in turn implies that friction is not an issue. Elastic-plastic mechanical behaviour at 20°C, for the material, is extracted from tensile test results on the same cladding material. The plasticity criterion is assumed to be isotropic, Von Mises, as a first approach.

The validation of the FE computation of J (G-Θ formulation) is achieved by a comparison with a similar case reported in a J handbook. This reference case is an *"Axial Throughwall Crack"* given in an EPRI handbook on ductile fracture [7]. Figure 4 shows such a comparison between J calculated using Castem 2000 and that from the reference solution given in the EPRI Handbook [7]. The agreement is very good but not perfect. This is attributed to the fact that only a flow stress was used in the EPRI formulation and not the whole stress-strain formulation expected for the plastic behaviour of the material.

TEST RESULTS ON SR ZY-4 AT ROOM TEMPERATURE

The material used here is a Zircaloy-4 cladding in Cold Worked Stress Relieved (CWSR) condition. All the three tests reported here (T12908, T12909 and T12912) were performed at room temperature. The load versus cone displacement curve is shown in Figure 5. The experimental curve is displaced relative to the curve obtained from FE simulation. This is due to

the fact that friction is not taken into account in the FE simulation. In Figure 5, the diametrical increase ($\Delta D/D_0$%) at the crack-tip (right hand ordinate) is also shown. This curve clearly indicates that a moderate diametrical increase, here less than 0.30%, is enough in order to get a propagating crack. The observation that this value decreases for cone displacements larger than 10 mm, coincides with the finding that the crack-tip is ahead of the bottom of the cone for long crack propagations (subsequent to crack initiation).
Figure 6 shows the Crack Tip Opening Angle (CTOA) versus cone displacement curves, both the experimental data and those from FE simulation. The agreement between these two sets of curves indicates that we obtained a good description of the experiment using the FE simulation. It is a validation step. The ordinate, on the right side in the figure, shows the crack propagation for the three tests performed at room temperature. A crack propagation of 17 mm was measured during test T12908 before the test was interrupted. In fact, with ICM very long crack propagation can be achieved, if required, depending on the initial geometry. During preliminary testing, we have obtained a 50 mm crack propagation without any problem. The only drawback is that the crack direction is free to deviate from the vertical and can become non-visible for the video system.
Figure 7 shows, the left ordinate, the computed J integral for different rings of elements (4, 6 and 8) around the crack tip. The computed values are not as stable as those reported for the reference case in the EPRI handbook. This is probably due to the fact that the boundary conditions are evolving more abruptly in our ICM case than in the case of the pressurised tube. Nevertheless, the results obtained for 8^{th} ring of elements can be considered as stable from J computation point of view. The crack propagation values are shown on the right ordinate in the figure (note the scale magnification compared to Figure 6). These results (measured crack propagation and the computed J integral using FE) are then used to determine a J value for a crack propagation of 0.2 mm. This value of 0.2 mm crack propagation is in accordance with the convention followed in toughness testing standards such as ISO 12135 or ASTM E-1820. It must also be mentioned that in the current video configuration, it will be difficult to accurately measure lower extents of crack propagation. The $J_{0.2}$ obtained for the three tests (T12808, T12809 and T12812) performed at room temperature is found to be within 30 to 40 kJ/m^2.
In order to express these $J_{0.2}$ values in toughness terms (K in MPa$\sqrt{m}$ units), the following plane stress relation was used [1] :

$$K_J^{PStress} = \sqrt{E \cdot J} \tag{1}$$

where E is the Young's modulus, and is taken as 95.352 GPa at room temperature for Zircaloy-4.

The calculated ($K_{J0.2}$) values range from 53.5 to 61.8 MPa$\sqrt{m}$. These toughness values compare well with the lower bound values in the range 60 and 100 MPa$\sqrt{m}$, reported in the literature [2-4]REF for Zircaloy-4 at room temperature.

CONCLUSIONS & FUTURE WORK

Internal Conical Mandrel (ICM) test is a novel technique showing a good potential for application to toughness measurements on fuel cladding, because :

- it can be easily performed on a tensile-compression machine,
- it can be performed directly on thin walled tube (cladding),
- the crack tip loading is circumferential, and the imposed displacement corresponds to mode I (C-L) simulating the fuel pellet diametrical increase,
- long crack propagations can be studied (up to 50 mm or more),
- it can easily be implemented in a hot cell.

The first results obtained on pre-cracked CWSR Zircaloy-4 cladding at room temperature exhibit :

- a low toughness of $J_{0.2}$= 40 kJ/m^2 or $K_{J0.2}$= 61.8 MPa$\sqrt{m}$,
- the commonly reported values in the literature, for CWSR Zy-4 at 20°C ,using other techniques vary from 60 to 100 MPa$\sqrt{m}$.

On-going developments have shown that :

- crack propagation and CTOA can be measured during the test using image analysis ; crack initiation corresponding to a conventional increment of 0.2 mm can be identified ; and finally a critical value of CTOA for crack initiation can be easily experimentally determined.
- the Finite Element simulation for the determination of $J_{0.2}$ can be validated in two steps.

Future developments will address the interpretation of results from this test at 300°C, and the development of a methodology to derive the whole fracture résistance curve (J-Δa).

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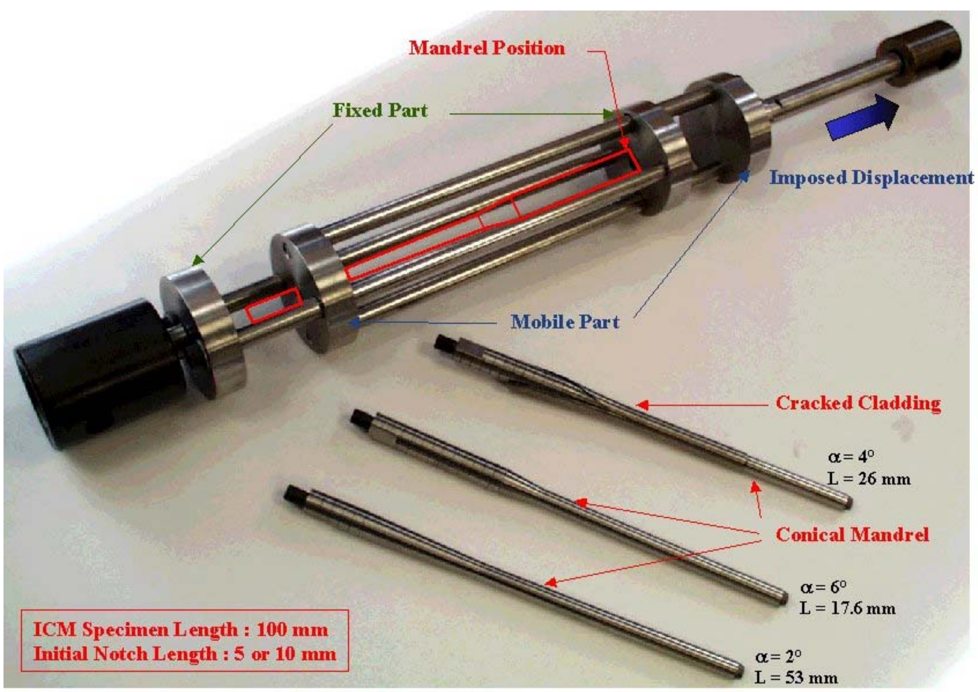

Figure 1 : *ICM Testing Device.*

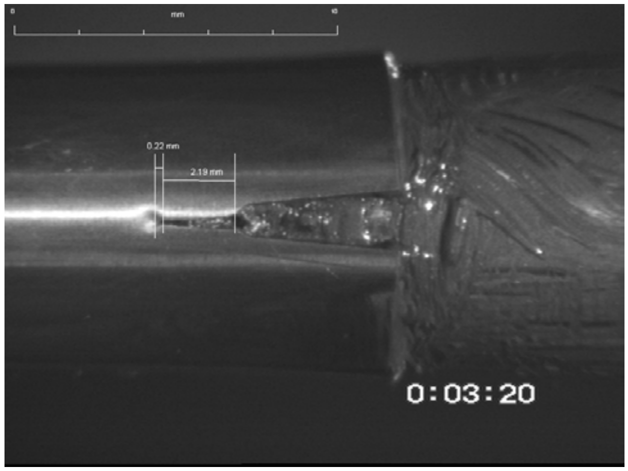

Figure 2 : *View of ICM Test T12912 for Δa= 0.22 mm.*

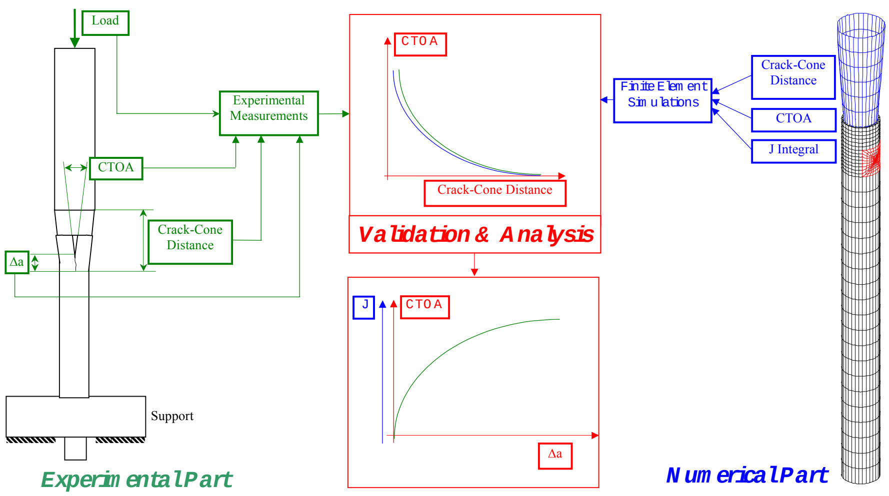

Figure 3 : *Analysis Flow Diagram.*

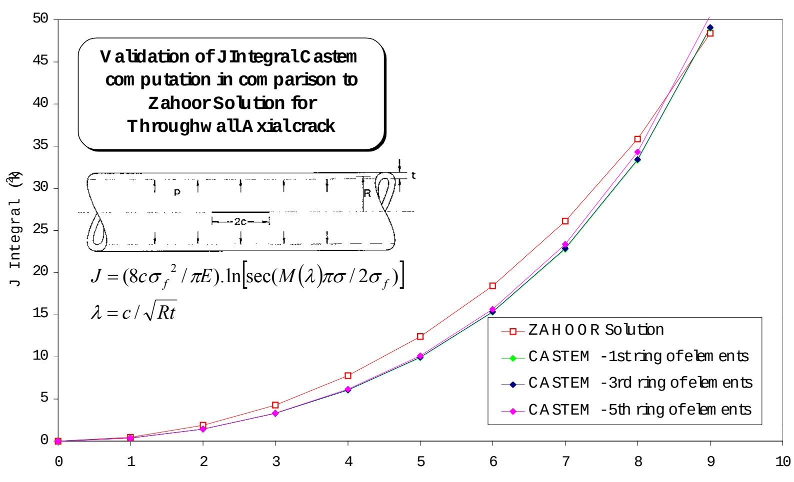

Figure 4 : *Validation of J integral computation with EPRI Handbook [7].*

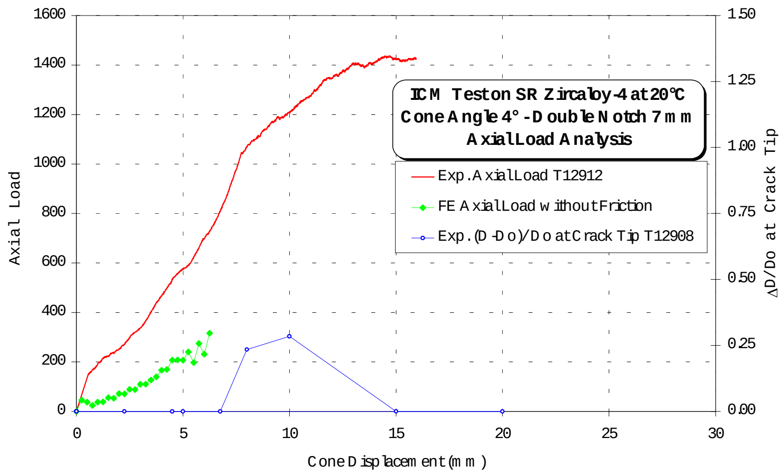

Figure 5 : *Loading Diagram for an ICM test at room temperature.*

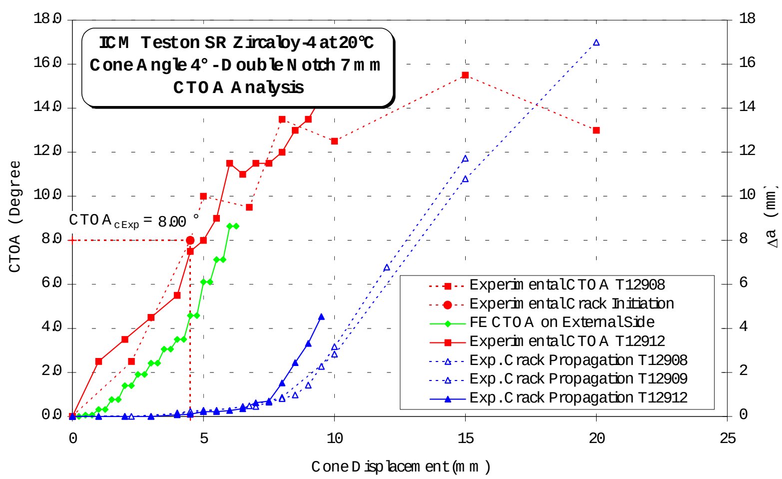

Figure 6 : *CTOA & Δa versus cone displacement.*

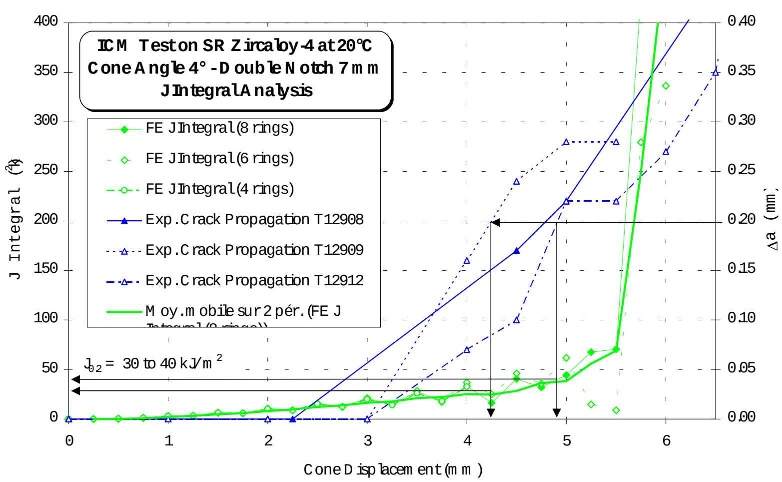

Figure 7 : *Determination of J integral for a crack propagation of 0.2 mm.*