DEVELOPMENT OF A NON-STANDARDIZED PIN-LOADING TEST METHOD TO OBTAIN THE FRACTURE MECHANICS PARAMETERS OF ZIRCALOY-4 CLADDING TUBE

ALEXANDRU NIŢU, VASILE RADU, VIOREL IONESCU, DENISA TOMA, LIVIA STOICA, ALEXANDRA JINGA, MIRELA MATEI, AMALIA POPA, GRAŢIELA BĂDULESCU

Institute for Nuclear Research (RATEN ICN) Piteşti, Romania
e-mail: alexandru.nitu@nuclear.ro

Abstract

Zirconium alloys are widely used as fuel tubes and other core components of light water reactors, as well as pressurized heavy water reactors (PHWR). To ensure the structural integrity of the fuel element for a longer period in the reactor, the principles of fracture mechanics can be applied to evaluate the fitness-for-purpose concept of these fuel elements. The main objective of the work was the development of the Pin-Loading Test (PLT) experimental testing methodology for obtaining the fracture mechanics parameters in the case of zircaloy-4 tubes. The experimental data were processed in the MATLAB programming environment, to calculate the K_{IC} toughness for the fuel cladding material, in the axial direction of the tube. Future determination of the mechanical properties of the Accident Tolerant Fuel - ATF fuel element tubes was considered. PLT-type tests are non-standardized tests but are used in the literature for thin tubes of small diameters.

Keywords: *ATF fuel, PLT method, Fracture mechanics, Zircaloy-4 cladding*

Introduction

Zirconium alloys are widely used as fuel tubes and other core components of light water reactors, such as boiling water reactors (BWR), pressurized water reactors (PWR), as well as reactors with pressurized heavy water (PHWR). High mechanical strength, strong ductility, a very low neutron absorption cross-section, and exceptional corrosion resistance are some of these alloys' advantageous characteristics.

It is important to ensure the structural integrity of these fuel tubes during various operational transients as well as accident scenarios. To ensure the structural integrity of the fuel element for a longer period in the reactor, the principles of fracture mechanics can be applied to evaluate the fitness-for-purpose concept of these fuel elements.

Fracture mechanics introduces the concept of toughness in engineering design. Fracture toughness relates the strength of a structure to the size of the dominant crack contained in that structure. Consequently, one of the essential elements in the analysis based on fracture mechanics is determination of the crack size and stress intensity factor at the crack tip [1].

Geometric and compliance functions in linear-elastic fracture mechanics (LEFM) have been extensively studied for use in determining these critical values. The geometric function is used to determine the stress intensity factor in a relatively simple stress state (eg., an uniform stress), while the compliance function is used to determine the crack length.

Experimental work

Two situations restrict the application of fracture mechanics concepts in testing thin-walled tubes [2]. The first situation refers to the geometry of the tubes, which does not meet the requirements of the ASTM standards for the configuration of the samples and the applied load. For example, specimens for tensile tests could be obtained from previously straightened tube sections, but the straightening process introduces several uncertainties in results regarding the change in the material microstructure and the redistribution of internal stresses.

The second situation relates to the difficulties of testing samples that retain the original geometry of the tubes from which they were cut. Taking the whole tensile test as an example, there are difficulties in reproducing the actual tensioning conditions of ring-type tensile specimens [3, 4].

Having these considerations, to ensure the structural integrity of the components working in the installations, it was necessary to know their resistance to crack propagation, which led to the need to introduce a new method for evaluating the material properties of thin-walled tubes [5]. The new method was introduced by Grigoriev [6] and is called the Pin-Loading Tension Test - PLT.

This approach requires the specimen to have a crack or a very sharp artificial mechanical defect to determine the fracture mechanics parameters. Also, the mechanical stress is done at one end of the sample, unlike an uniaxial test on the same type of sample, in which case the mechanical load is applied to the central axis of the sample. The advantage is the fact that the force required deforming the sample and the elastic deformation of the clamping system is smaller than in the case of uniaxial stress, so the elongation of the sample is greater, and sufficient data are recorded for the characterization of the material (Fig. 1).

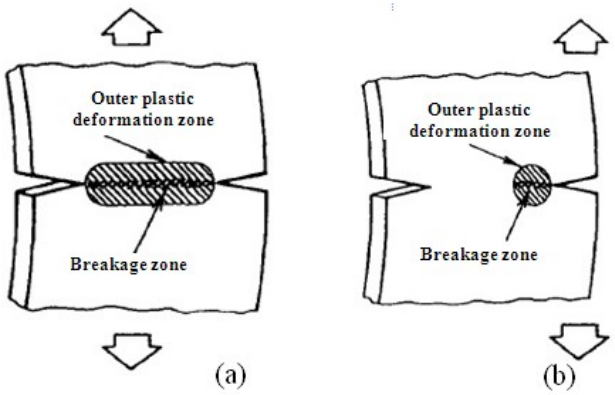


Fig. 1. Deformation of the sample by stress:
a) uniaxial, b) Pin-Loading Tension-type

The material used in the experimental program of this work was the Zircaloy 4 alloy used in the manufacture of fuel elements for Generation III reactors of CANDU type.

By using mechanical processing procedures that included cutting and milling, PLT-type samples were obtained (see Fig. 2.). Two diametrically opposite slits are made at the two ends of each sample. The dimensions of these slits are variable in terms of depth, starting from 1.5mm to 5mm. The width is kept constant – approximately 0.15mm.

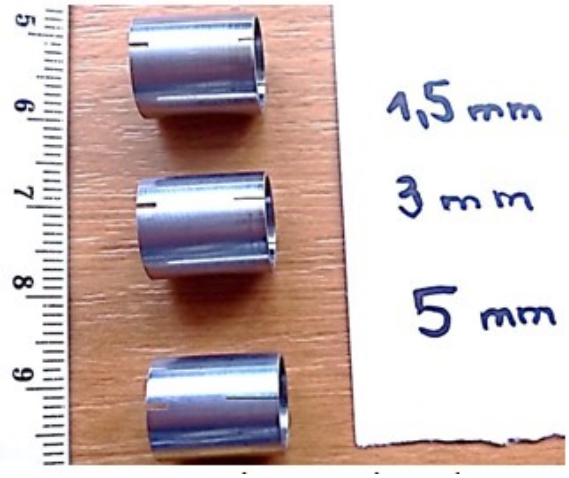


Fig. 2. PLT samples. Material: Zircaloy-4

For mechanical testing, two sets of samples were made. The first set comprises three samples with different test slot lengths (1.5mm, 3mm, and 5mm). These samples are used to measure material compliance. The second set includes three samples with the same length of the test slits – 1.5mm and are used for the actual tests. The results obtained in their case are used to calculate the KIC toughness of the material.

The clamping system is composed of two cylinder halves (see Fig. 3) with the possibility of fixing at one end in the traction rods of the mechanical testing machine. At the other end, the clamping system has a conical geometry with a channel on which safety is mounted to allow the insertion and fixation of the PLT samples.

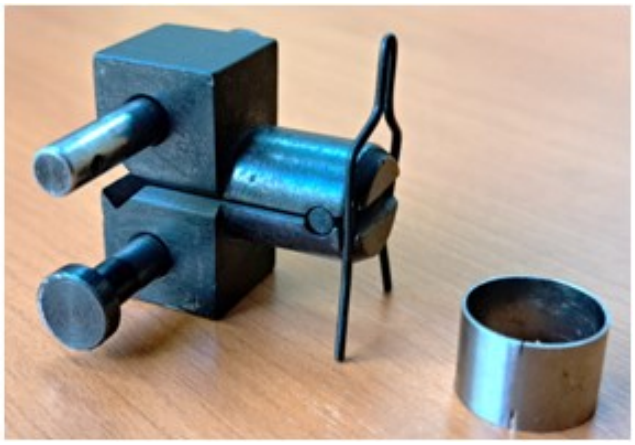


Fig. 3. Clamping system for PLT samples

Results and discussion

Determination of compliance

To determine the compliance of the Zircaloy-4 alloy, it was necessary to carry out mechanical tensile tests on specimens with different mechanical crack lengths (1.5mm, 3mm, and 5mm). The compliance calculation was performed for each sample using the force-displacement curves obtained after testing. Fig. 4 presents an example for sample Zy-4 – 1.5mm.

$$C_{1,5}=\frac{\Delta x}{\Delta P}=\frac{0.7\ mm}{1000\ N}=0.7\cdot 10^{-3}\frac{mm}{N}=0.7\cdot 10^{-6}\ m/N \quad (1)$$

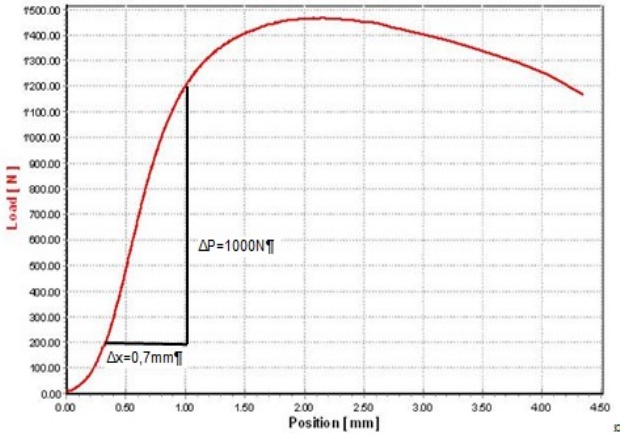


Fig. 4. Determination of compliance for Zy-4 sample – 1.5mm

For the exponential fit of the compliance, it is necessary to know the compliance parameters (C1.5, C3, C5) and a/W. Thus we have:

$$\left[\frac{a}{W}\right]=\left[\frac{a_1}{W},\frac{a_2}{W},\frac{a_3}{W}\right] \quad (2)$$

where:

$$\begin{cases} a_1=a_{01}+b \\ a_2=a_{02}+b \\ a_3=a_{03}+b \end{cases} \quad with \quad \begin{cases} a_{01}=1.5mm \\ a_{02}=3\ mm \\ a_{03}=5\ mm \end{cases} \quad (3)$$

$$and\ b=8mm \Rightarrow \begin{cases} a_1=9.5mm \\ a_2=11\ mm \\ a_3=13\ mm \end{cases}$$

Considering relation (3) and W = 16.42mm, relation (2) becomes:

$$\left[\frac{a}{W}\right]=\left[\frac{9.5}{16.42},\frac{11}{16.42},\frac{13}{16.42}\right]=[0.5785;0.6699;0.7917] \quad (4)$$

Next, an exponential fit is made (see Fig. 5) according to a function of the form $f(x)=a\cdot e^{b\cdot x}$, obtaining the exponential form of the compliance function:

$$C\left(\frac{a}{W}\right)=1.09\cdot 10^{-7}\cdot e^{3.346\cdot x} \quad (5)$$

where $x=a/W$ and was chosen in the range 0.5785 – 0.7917 from the relation (4).

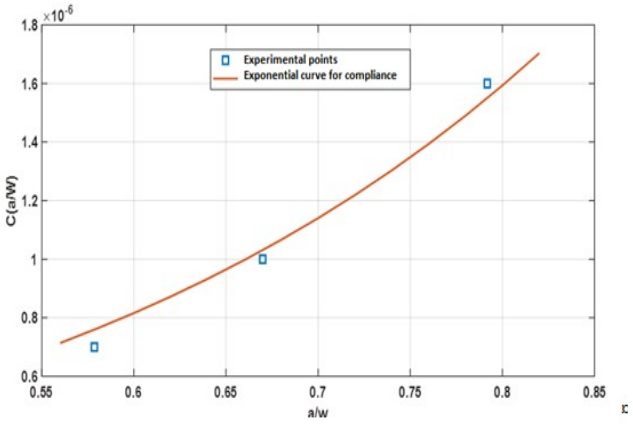


Fig. 5. Exponential fitting curve for $C(a/W)$

Polynomial compliance will be obtained by a polynomial fitting after a polynomial of degree 6. Thus we have:

$$C\left(\frac{a}{W}\right)=10^{-5}\left[0.2165\cdot\left(\frac{a}{W}\right)^6-0.5073\cdot\left(\frac{a}{W}\right)^5+0.7809\cdot\left(\frac{a}{W}\right)^4-0.4732\cdot\left(\frac{a}{W}\right)^3+0.2969\cdot\left(\frac{a}{W}\right)^2-0.0191\cdot\left(\frac{a}{W}\right)+0.0165\right] \quad (6)$$

Next, the compliance derivative is calculated:

$$\frac{dC}{d\left(\frac{a}{W}\right)}=f_2\left(\frac{a}{W}\right)=\left[1.2985\cdot 10^{-5}\cdot\left(\frac{a}{W}\right)^5-2.5365\cdot 10^{-5}\cdot\left(\frac{a}{W}\right)^4+3.1236\cdot 10^{-5}\cdot\left(\frac{a}{W}\right)^3-1.4196\cdot 10^{-5}\cdot\left(\frac{a}{W}\right)^2+5.938\cdot 10^{-6}\cdot\left(\frac{a}{W}\right)-1.91\cdot 10^{-7}\right] \quad (7)$$

Determination of geometric function

The geometric function is given by the relation:

$$f\left(\frac{a}{W}\right)=\left[t\cdot E\cdot f_2\left(\frac{a}{W}\right)\right]^{\frac{1}{2}} \quad (8)$$

where: t = 0.4mm; E = 970 GPa –Young's modulus value is provided in the literature [6].

Performing the fitting by a polynomial of degree 5, we obtain the final form of the geometric function:

$$f\left(\frac{a}{W}\right)=\left[1.4468\cdot\left(\frac{a}{W}\right)^5-1.1309\cdot\left(\frac{a}{W}\right)^4+5.5731\cdot\left(\frac{a}{W}\right)^3-3.6920\cdot\left(\frac{a}{W}\right)^2+6.8097\cdot\left(\frac{a}{W}\right)-3.7083\right] \quad (9)$$

Determination of K_{IC} toughness

K_{IC} toughness can be calculated by using the relationship:

$$K_{IC}=\frac{P_Q}{2t\sqrt{W}}\cdot f\left(\frac{a}{W}\right) \quad (10)$$

where a, t, and W factor values are known (a = 1.5mm, t = 0.4mm, W = 18.5mm). P_Q load values for the tested samples are, however, obtained by analyzing the experimental curves resulting from the actual test according to the recommendations of the ASTM standards (see Fig. 6.) [7].

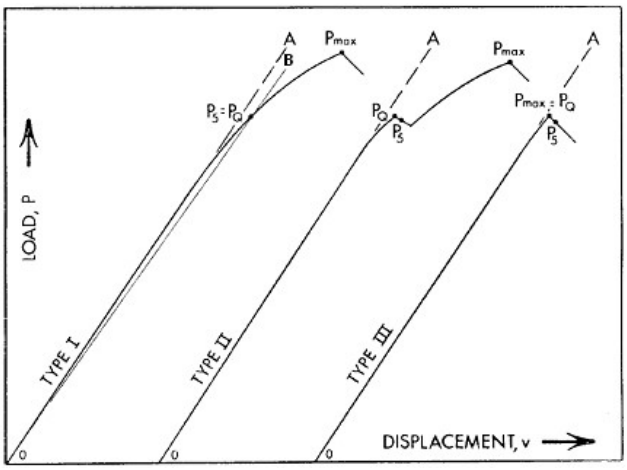


Fig. 6. Main types of experimental load-displacement curves

Fig. 7 shows how to determine the point corresponding to the P_5 load for one of the test samples.

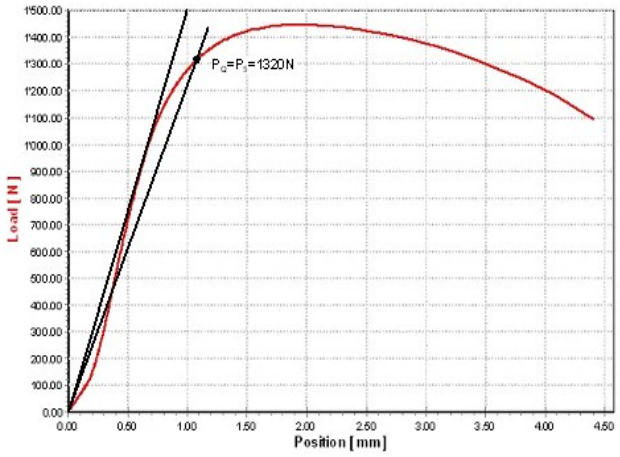


Fig. 7. Determination of P_Q load value

Following the analyses made based on the experimental curves, the P_Q load values corresponding to the three tested samples were obtained. These values were entered into relation (10) to determine the K_{IC} toughness values.

The results obtained are presented in Table 1. The average value of the zircaloy-4 sheath toughness, K_{IC}, obtained from the tests in this study is 123 $MPa \cdot \sqrt{m}$.

Table 1. Experimental results for material Zy-4

Sample	P_Q (N)	Geometric function $f(a/W)$	Toughness K_{IC} $\left(MPa \cdot \sqrt{m}\right)$
test1	1320	9.9506	128.13
test2	1275	9.9506	123.76
test3	1225	9.9506	118.92

Conclusions

The study highlighted the importance of the pin-loaded test method as an essential test method for ensuring the structural integrity of the components operating in the active zone of the nuclear reactor, namely the fuel channel. The entire documentation activity is integrated into the current context of the development of new types of accident-tolerant nuclear fuels, an issue treated with interest also within RATEN ICN.

The development of an experimental testing methodology of the Pin-Loading Test type was possible considering the experience accumulated in the RATEN ICN's mechanical testing laboratory regarding the PLT tests. Thus, the equipment used and the specially developed specimen fixing systems were presented.

The experimental data acquired by the software of the testing facility were processed by using the MATLAB programming and numerical calculation platform, to calculate the K_{IC} toughness for the fuel pellet capping material - Zircaloy-4 alloy.

In the first step, the compliance of the Zircaloy-4 material was determined. The compliance calculation required performing mechanical stress tests on samples with different artificial defects having depths of 1.5mm, 3mm, and 5mm, respectively. Through an exponential fitting followed by a polynomial fitting after a polynomial of the degree 6, the compliance function was obtained. The derivative of this function allowed the calculation of a geometric function. also called a geometric correction factor. This factor is an important parameter in the K_{IC} toughness calculation.

The average toughness value for the Zircaloy-4 tube, K_{IC}, obtained after performing the tests was 123 $MPa \cdot \sqrt{m}$.

The results of the study will be used for future work on development and characterization of ATF-type sheaths.

References

[1] Kanninen, M., Popelar, C. (1985) ″Advanced fracture mechanics″, *Oxford Engineering Science series*, Oxford University Press.

[2] Samal, M.K., Sanyal, G. (2012) ″A load-separation technique to evaluate crack growth and fracture resistance behaviour of thin-walled axially cracked tubular specimens″, Proceed. IMechE, Vol. 226, Part C: *Journal of Mechanical Engineering Science*.

[3] Grigoriev, V., Josefsson, B., Lind, A., Rosborg, B. (1995) ″A pin-loading tension test for evaluation of thin-walled tubular materials″, *Scr. Metall. Mater*., Vol. 33(1), pp.109–114.

[4] Grigoriev, V., Josefsson, B., Rosborg, B. (1996) ″Fracture toughness of zircaloy cladding tubes″, Proceed. 11th Int. Symposium on Zirconium in nuclear industry, (Eds. E. R. Bradely and G. P. Sabol), ASTM STP 1295, pp. 431–447 (American Soc. for Testing and Materials, Pennsylvania).

[5] Sanyal, G., Samal, M.K., Chakravartty, J.K., Ray, K.K., Suri, A.K., Banerjee, S. (2011) ″Prediction of J–R curves of thin-walled fuel pin specimens in a PLT setup″, *Engineering Fracture Mechanics*, Vol. 78 (6), pp.1029–1043.

[6] Grigoriev, V., Jakobsson, R. (2000) ″Application of the Pin-Loading Tension Test to Measurements of Delayed Hydride Cracking Velocity in Zircaloy Cladding″, SKI Report 00:57, Studsvik Nuclear AB, Sweden.

[7] ASTM International (2011) ″ASTM E399-22- Standard test method for plane-strain fracture toughness of metallic materials″