DEVELOPMENT OF THE FRACTURE TOUGHNESS METHODOLOGY FOR THE SMALL TUBES USED IN THE GENERATION IV REACTORS

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The paper represents a part of research carried out at the RATEN ICN Pitesti in the framework of development methodologies to obtain the material properties of the candidate materials used in the generation IV reactors. In this respect, it is important to obtain the material properties of structural elements, such as thin wall tubes and small diameters, which are used as nuclear fuel cladding. The paper is focused to obtain a specific analytical geometrical function need inside of the fracture toughness methodology. The results obtained from the mechanical tests are in good agreement with those from scientific literature.

Keywords: ODS alloy, generation IV reactors, PLT method, fracture toughness.

1. Introduction

Generation IV systems have a precise and practical response to the clean and safe nuclear energy demand for modern society being fully satisfied with the requirements of sustainable development [1]. For the safety reasons and economy in operation it is necessary to maintain the structural integrity of the components. During operation the components undergo an aging process generated by the thermal and pressure changes and the interaction between the structural materials and the coolant.

Choosing lead as a cooling agent in the Generation IV systems brings an improvement in safety in operation, given to the high boiling temperature of lead (1745^{o}C). However, under certain high temperature conditions, lead has a corrosive effect on structural materials. That is why it is very important to choose the appropriate structural materials for making the components of the reactor and it is also very important to control the purity of the lead.

The determination of material properties for the structural components is based on well-established procedures and standards following theoretical and

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experimental studies, occupying a central place in the research-development area on the evaluation of structural integrity. However, there is still room for the improvement of the current standardized testing methods as well as the need to develop new not yet standardized methods, to deal with the acquisition of properties of interest for concrete cases. In this respect, it is important to obtain the material properties of structural elements, such as thin wall tubes and small diameters, which are used as nuclear fuel cladding. Regarding this aspect, the aim of the paper is to determine the fracture toughness of the ODS steels (oxide dispersion-strengthened alloy) generation IV material, the candidate material for the development of fuel elements.

2. Experimental method

Tubes with thin walls and small diameter are widely used in nuclear power and are found in the case of heat exchangers tubes, steam generator tubes and fuel cladding tubes [2].

There are two situations that restrict the application of fracture mechanics for testing the thin wall tubes. The first refers to the tube geometry, which does not meet the requirements of ASTM standards for sample configuration. The second situation concerns the difficulties of testing the samples that preserve the original geometry of the tubes from which they were cut.

In view of these considerations and in order to ensure the structural integrity of the components in operating installations it was necessary to know their resistance to crack propagation, which led to the necessity of introducing a new method of evaluation of material properties of thin-walled tubes [3]. The new method was introduced by Grigoriev [3,4], [5] and is called Pin-Loading Tension Test (PLT).

Determination of the fracture mechanics parameters by this method requires the existence of a crack or a very sharp artificial mechanical notch. Also the tension is applied at one end of the sample (Fig. 1.).

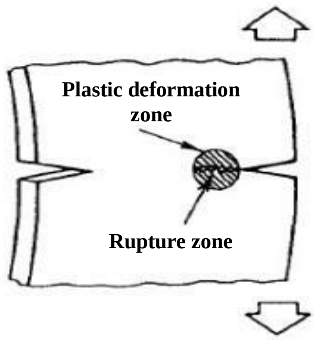

Fig. 1. Specimen deformation by PLT test

Fig. 2 shows the main characteristics of the PLT experimental arrangement. The fixture consists of two halves, which, when placed together, formed a cylindrical holder, A. The diameter of the holder allows it to be inserted into the specimen while maintaining a small gap. The fixture halves are loaded in tension through pins at position B and rotated around a pin, C, at the ends of the cylindrical holder providing similarity to the loading of a compact toughness specimen, but on two cracks. Very important is to line up the pre-cracked notches with the intersection of the two halves of the fixture.

a b

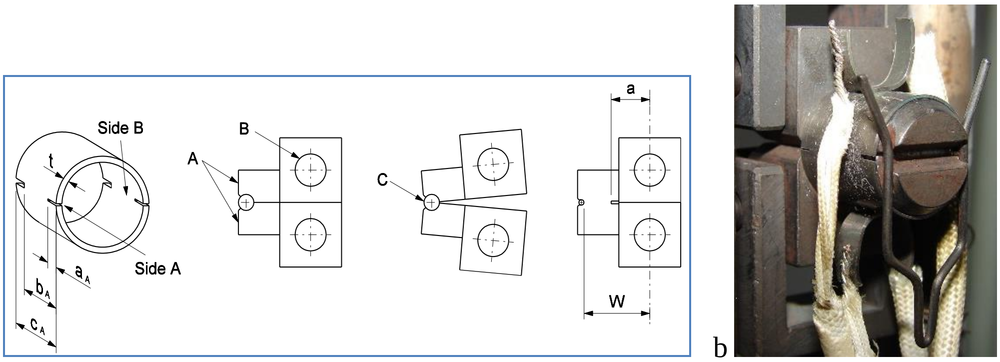

Fig.2. Schematic diagram of the PLT specimen (a), fixture and specimen-fixture assembly (b)

According to the strain energy approach, the strain energy release rate, *G*, is a measure of energy available for an increment of area of the crack extension, *dA*, and for the specimen with edge crack *a*, and is expressed as:

$$G = \frac{P^2}{2} \cdot \frac{dC}{dA} = \frac{P^2}{2B} \cdot \frac{dC}{da} \tag{1}$$

where *P* is load applied to the specimen, B is the thickness, and *C* is the specimen compliance.

The strain energy release can be expressed also as:

$$G = \frac{K_I^{\;2}}{E} = \left(\frac{P}{B}\right)^2 \cdot \frac{1}{WE'} \cdot f^2\left(\frac{a}{W}\right) \tag{2}$$

where *K* is the stress intensity factor, *W* is distance between the load-line and the crack tip, and *E* is Young's modulus ($E'=E$ for plane stress and $E'=E/(1-\upsilon^2)$ for plane strain). The PLT specimen fabricated from the thin walled tubing contains two edges-notches at the edge of specimen. $E'=E$ due to the small thickness of the specimen. In the specimen there are two cracks edge so $B=2t$ and the geometry function is:

$$f\left(\frac{a}{W}\right)=\left[t\cdot E\cdot\frac{dC}{d\left(\frac{a}{W}\right)}\right]^{\frac{1}{2}} \tag{3}$$

Note that the required geometry functions for evaluation of the stress intensity factor for such setup should be evaluated before testing for defined tube geometry and dimensions. The evaluation steps for the apparent K_{IC} from PLT tests are summarized in Fig. 3.

Step 1: Compliance determination

$$C_i=\frac{\Delta x}{\Delta P}\Rightarrow C=f_1\left(\frac{a}{W}\right)\Rightarrow\frac{dC}{d\left(\frac{a}{W}\right)}=f_2\left(\frac{a}{W}\right)$$

Step 2: Geometric function determination

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

Step 3: Fracture toughness

$$K_I=\left[\frac{P}{2t\sqrt{W}}\right]\cdot f\left(\frac{a}{W}\right)\Rightarrow K_{IC}=\left[\frac{P_C}{2t\sqrt{W}}\right]\cdot f\left(\frac{a}{W}\right)$$

Fig.3: The K_{IC} evaluation steps from PLT tests.

w = distance between the load application point and the technological crack tip;
t = wall thickness of the tube;
P_Q = the specific applied load following ASTM rule;
$f(a/W)$ = geometric function

The PLT type samples have been obtained by mechanical machining processes including cutting and milling (Fig. 4). At the two ends of each sample two diametrically opposed cracks are machined. The cracks on the left side of the images have a depth of 2mm and a width of 0.5mm, their role being technological. The cracks on the right of the image are those for testing, and from this end it will start crack propagation and the sample fracture. The dimensions of these cracks are variable in depth in the range 1.5mm to 5mm. The width is kept constant - about 0.15mm.

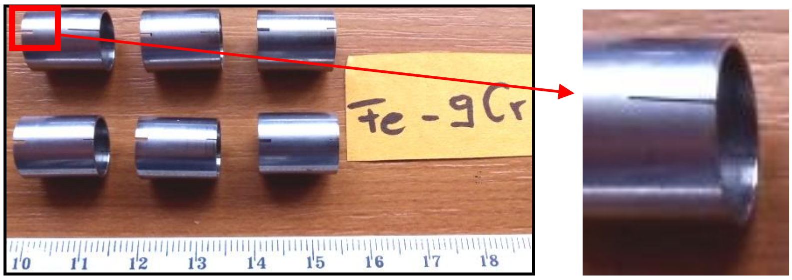

Fig. 4: PLT specimens

3. Results and discussions

3.1. Compliance determination

Determination of geometric function requires the achievement of compliance measurements. Three mechanical tests were performed at room temperature on ODS specimens (Oxide Dispersion Strengthened alloys) with different crack lengths (1,5mm; 3mm and 5mm) to determine compliance of the experimental arrangement. With the experimental curve available, the compliance for each sample was calculated on the linear part of each curve:

For 1,5 mm crack length (Fig. 5):

$$C_{1.5} = \frac{\Delta x}{\Delta P} = \frac{0.54mm}{1000N} = 0.54 \cdot 10^{-3}\frac{mm}{N} = 0.54 \cdot 10^{-6}\frac{m}{N} \quad (4)$$

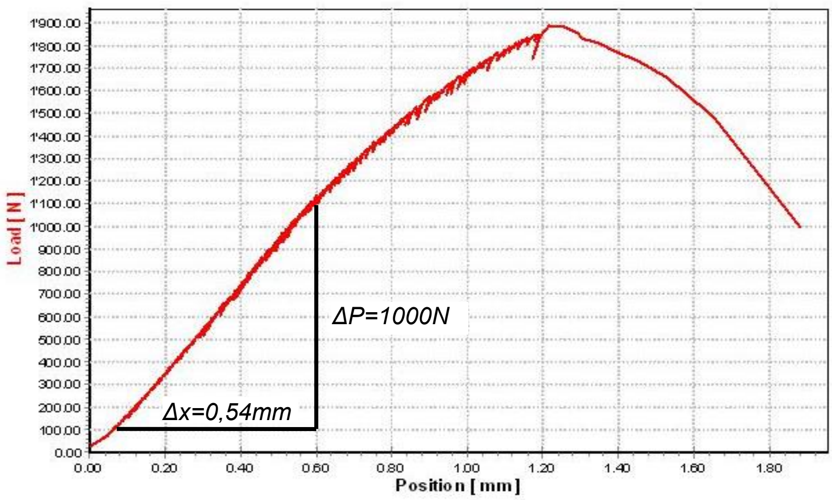

Fig. 5. Determination of Compliance for the Fe-9Cr ODS sample - 1.5mm

For 3 mm crack length (Fig. 6):

$$C_3 = \frac{\Delta x}{\Delta P} = \frac{0.48mm}{750N} = 0.64 \cdot 10^{-3}\frac{mm}{N} = 0.64 \cdot 10^{-6}\frac{m}{N} \quad (5)$$

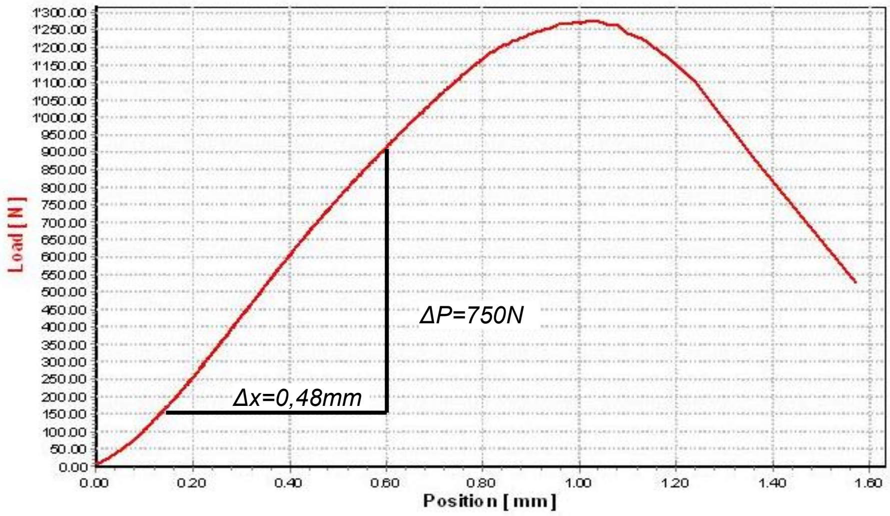

Fig. 6. Determination of Compliance for the Fe-9Cr ODS sample - 3mm

For 5mm crack length (Fig. 7):

$$C_5 = \frac{\Delta x}{\Delta P} = \frac{0.40mm}{350N} = 1.14 \cdot 10^{-3}\frac{mm}{N} = 1.14 \cdot 10^{-6}\frac{m}{N} \quad (6)$$

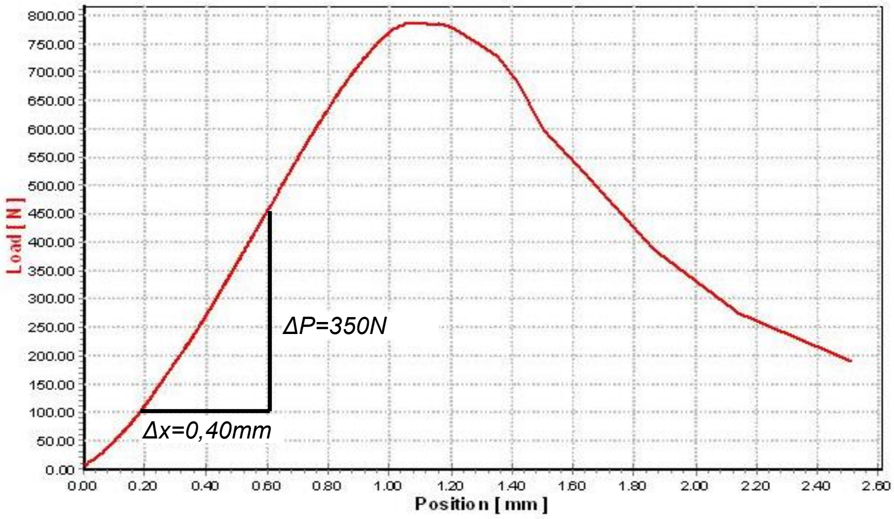

Fig. 7. Determination of Compliance for the Fe-9Cr ODS sample - 5mm

For the exponential fit of compliance, it is necessary to know the compliance parameters ($C_{1,5}$, C_3, C_5) and *a/W*. So we have:

$$\left[\frac{a}{W}\right]=\left[\frac{a_1}{W};\frac{a_2}{W};\frac{a_3}{W}\right] \quad (7)$$

Where:

$$\begin{cases} a_1 = a_{01} + b \\ a_2 = a_{02} + b \\ a_3 = a_{03} + b \end{cases} \; but \; \begin{cases} a_{01} = 1.5mm \\ a_{02} = 3mm \\ a_{03} = 5mm \end{cases} \; and \;\; b = 7{,}5mm \Rightarrow \begin{cases} a_1 = 9mm \\ a_2 = 10.5mm \\ a_3 = 12.5mm \end{cases} \quad (8)$$

Taking into account the relation (8) and W=*18.5* mm the relation (7) has the result:

$$\left[\frac{a}{W}\right] = \left[\frac{9}{18.5};\frac{10.5}{18.5};\frac{12.5}{18.5}\right] = [0.4865; 0.5675; 0.6757] \quad (9)$$

In order to avoid negative values of predictions an exponential fitting is performed on the values of compliance and characteristics of artificial cracks (a/w) rel. (9):

$$C\left(\frac{a}{W}\right) = 1.661 \cdot 10^{-7} \cdot \exp\left(2.648 \cdot x\right) \quad (10)$$

To obtain the polynomial of compliance, a polynomial fitting is performed after a polynomial of the sixth degree (Fig. 8). Thus, we obtain the relationship:

$$C\left(\frac{a}{W}\right) = 10^{-6}\left[0.3105\left(\frac{a}{W}\right)^6 - 0.2238\left(\frac{a}{W}\right)^5 + 0.6729\left(\frac{a}{W}\right)^4 + 0.3671\left(\frac{a}{W}\right)^3 + 0.6174\left(\frac{a}{W}\right)^2 + 0.4357\left(\frac{a}{W}\right) + 0.1663\right] \quad (11)$$

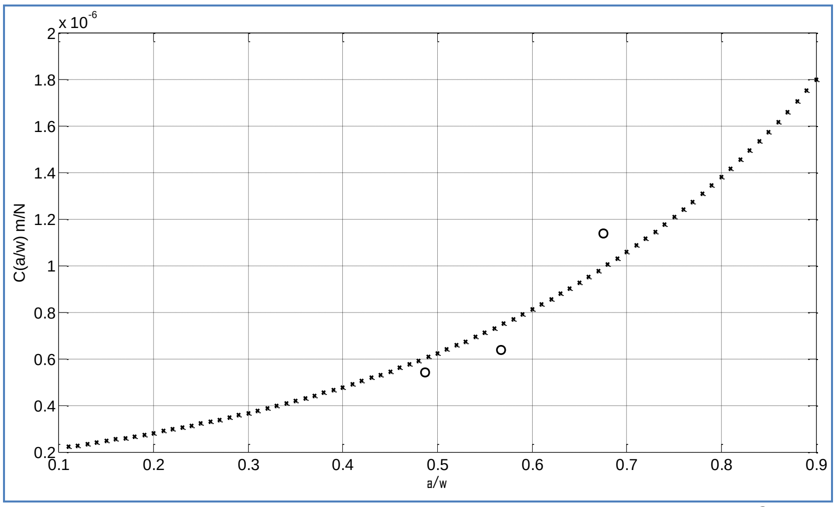

Fig. 8. Polynomial Fitting of Compliance for Fe-9Cr ODS specimen (R^2=0.95)

Further, the derivative of compliance is calculated and has the relationship:

$$\frac{dC}{d\left(\frac{a}{W}\right)} = f_2\left(\frac{a}{W}\right) = 10^{-6}\left[\left(\frac{a}{W}\right)^5 - 1.119\left(\frac{a}{W}\right)^4 + 2.6916\left(\frac{a}{W}\right)^3 + 1.1013\left(\frac{a}{W}\right)^2 + \right.$$
$$\left. +1.2348\left(\frac{a}{W}\right) + 0.4357\right] \quad (12)$$

3.2. Geometric function determination

The geometric function is given by the relationship:

$$f\left(\frac{a}{W}\right) = \left[t \cdot E \cdot f_2\left(\frac{a}{W}\right)\right]^{\frac{1}{2}} \quad (13)$$

Where:

t= 0.6mm; E=200 GPa– the value of Young's modulus is provided in the literature [6]

Further, the relationship (13) is fitted to a fifth-degree polynomial:

$$f\left(\frac{a}{W}\right) = 0.7946\left(\frac{a}{W}\right)^5 - 0.2936\left(\frac{a}{W}\right)^4 + 4.0012\left(\frac{a}{W}\right)^3 + 5.8040\left(\frac{a}{W}\right)^2 +$$
$$9.7427\left(\frac{a}{W}\right) + 7.2554 \quad (14)$$

3.3. Fracture toughness determination

The calculation of the fracture toughness, K_{IC}, is performed with:

$$K_{IC} = \left[\frac{P_Q}{2t\sqrt{W}}\right] \cdot f\left(\frac{a}{W}\right) \quad (15)$$

Here the value for parameters *a*, *t* and *W* are known. The P_Q load value, however, is obtained by analyzing the experimental curves for the samples subjected to the test itself as recommended in the ASTM standards (Fig. 9 – Fig. 11) [7].

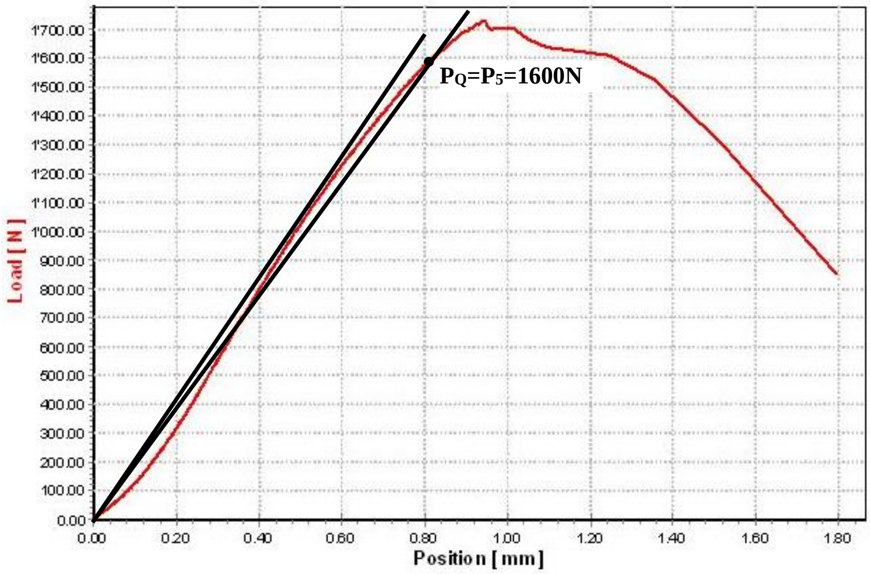

Fig. 9. Determination of P_Q load value for Fe-9Cr ODS - test1

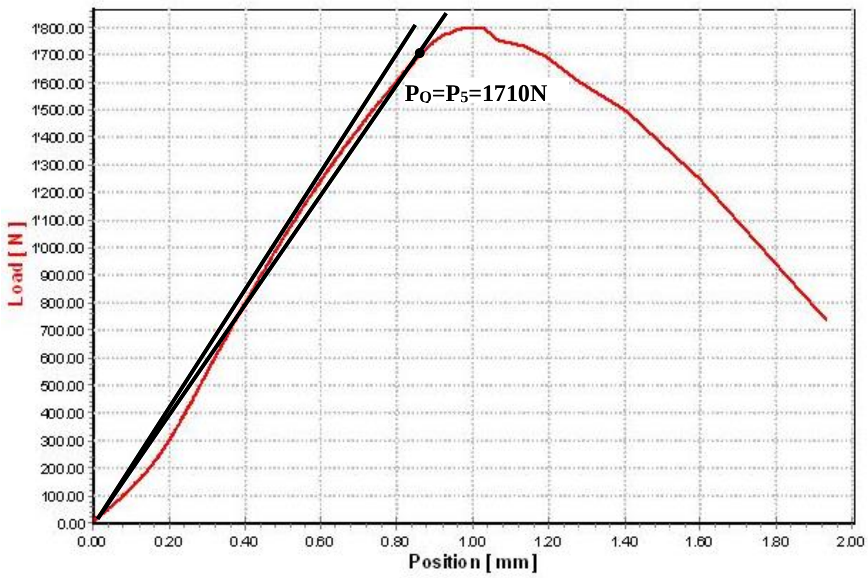

Fig. 10. Determination of P_Q load value for Fe-9Cr ODS – test2

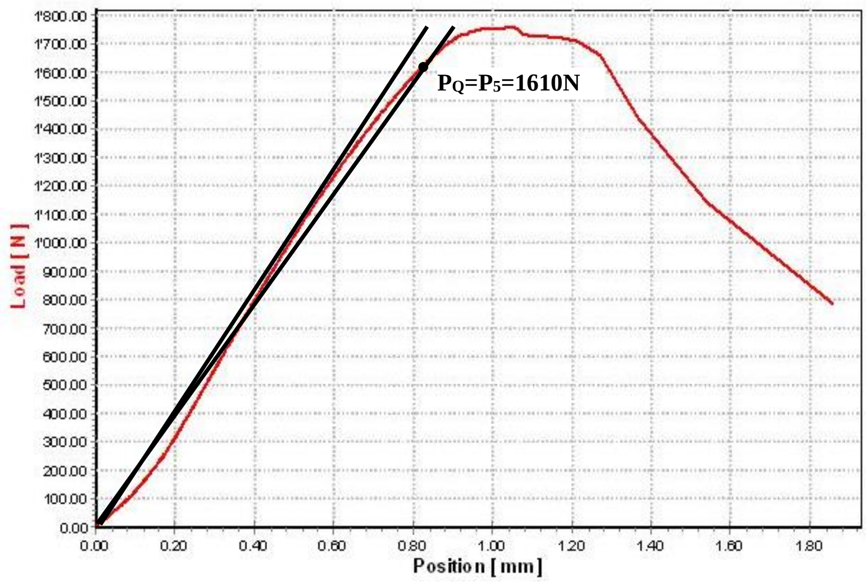

Fig. 11. Determination of P_Q load value for Fe-9Cr ODS – test3

As a result of the analysis made on the basis of the experimental curves, the values of the P_Q loads corresponding to the 3 samples tested were obtained. These values allow (Equation 15) to determine the fracture toughness K_{IC} values in the axial direction of the small tubes. The results obtained are presented in Table 1.

Table 1.

Experimental results for Fe-9Cr ODS material

Sample	Load P_Q (N)	Tenacity K_{IC} (MPa.m$^{1/2}$)
test1 (Fig. 9.)	1600	135.6
test2 (Fig. 10.)	1710	144.9
test3 (Fig. 11.)	1610	136.5

The average K_{IC} fracture toughness obtained from the tests in this paper is approximately of 140 MPa·m$^{1/}$2 in good agreement with previous literature results [6,8].

6. Conclusions

The paper scope is placed in the research-development area on the evaluation of structural integrity of tubes with thin walls and small diameter that are widely used in nuclear power (in the case of heat exchangers tubes, steam generator tubes, and fuel cladding tubes).

In order to know the resistance to the crack propagation in thin walled small radius tubes a new method of evaluation of material properties is proposed and the method is called Pin-Loading Tension Test (acronym PLT).

The paper describes the steps methodology to obtain the axial fracture toughness of ODS tubes with small radius:

- In the first step the compliance of the experimental arrangement (tube specimen with artificial cracks and characteristic loading) is calculated;
- In a second step an exponential fitting is performed on the values of compliance and characteristics of artificial cracks (a/w), in order to avoid negative values of predictions;
- In a third step the 6^{th} polynomial fittings is performed on the values given by exponential function for the specific (a/w) values;
- Finally the geometric function is obtained following the described methodology;
- The P_Q load value is obtained by analyzing the experimental curves for the samples subjected to the test itself as recommended in the ASTM standards;
- By processing the above results, it is possible to determine the fracture toughness K_{IC} values in the axial direction of the ODS small tubes;
- The average K_{IC} fracture toughness obtained from the tests in this paper is approximately of 140 $MPa{\cdot}m^{1/2}$ in good agreement with results from literature.

The paper proposes new but not yet standardized method which deals with the assessment of K_{IC} fracture toughness for tubes with thin walls and small diameter used as components for the generation IV reactors.

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