NEW FRACTURE MECHANICS METHOD FOR THE ODS STEEL TESTING

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Abstract

The paper presents a part of the contribution of RATEN ICN to the achievement of the European FP7 MatISSE Project objectives. In this context, the experimental work was carried out by RATEN ICN Pitesti and focused on the mechanical properties characterization for the Generation IV Oxide Dispersion Strengthened (ODS) steel cladding tubes, in order to evaluate the microstructural anisotropy impact on the fracture mechanics properties. To ensure the structural integrity of components which are on use in nuclear installations, it was necessary to know their resistance to the initiation and propagation of crack. Because of their dimensions it is a quite demanding task to prepare the standard fracture mechanics specimens for classical ASTM test. All this led to the need of introducing a new method for assessing the fracture material properties of tubes with thin walls called Pin-Loading Test (PLT). The paper highlights the improvement of the PLT experimental test methodology, and the results processing to obtain the KIC toughness on the thin-walled tubes with small diameter.

Keywords: *ODS steels, Fracture mechanics, K_{IC} toughness, PLT testing*

Introduction

The thin-walled tubes with small diameter are used on a large scale in nuclear power plants. More often, these tubes are used as heat exchanger tubes, steam generator tubes and nuclear cladding tubes [1]. The operating conditions of these tubes are severe due to high temperatures and mechanical stresses combined with the effects of radiation on the material properties. The cracking behaviour of thin-walled tubes is an important feature for the structural integrity during operation.

Given these considerations, to ensure the structural integrity of components which are on use in nuclear installations, it was necessary to know their resistance to the initiation and propagation of crack. Because of their dimensions it is a quite demanding task to prepare the standard fracture mechanics specimens for classical ASTM test. All this led to the need of introducing a new method for assessing the fracture material properties of tubes with thin walls [2].

The new method is called Pin-Loading Test (PLT) [3, 4]. The PLT-type mechanical tests are non-standard mechanical tests which are under development, and they are preferred in situations where the standardized tests are not enough accurate to study the behaviour of the structural components. This type of tests was applied on specific samples prepared from ODS steel.

Experimental work carried out by RATEN ICN Pitesti focusing on the mechanical properties characterization for the Generation IV ODS (Oxide Dispersion Strengthened) steel cladding tubes that is an innovative material, in order to evaluate the microstructural anisotropy impact on the mechanical.

The paper highlights the PLT experimental test methodology, obtaining of the geometric function necessary tool for determining K_{IC} toughness and results processing.

Experimental method

Determination of the fracture mechanics parameters by the Pin-Loading Test method requires the existence of specimen with a crack (a very sharp artificial mechanical defect).

In the case of PLT method, tension is applied at one end of the specimen, compared to the loading in a tensile test, where the loading in applied on the whole cross-section, as shown in Figure 1. The advantage is that the tension required for the deformation of the specimen and the elastic deformation of the gripping system are lower than that in the uniaxial tensile test. Therefore, the elongation of the specimen is larger and the recorded data is enough to characterize the material.

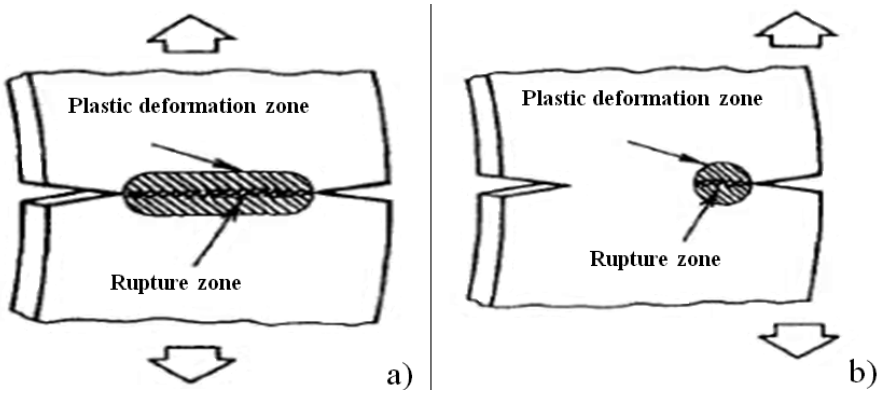


Fig. 1. Specimen deformation by: a) uniaxial tensile test, b) PLT test

Figure 2 shows the main characteristics of the PLT experimental arrangement. The fixture consist 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. Care is taken to line up the pre-cracked notches with the intersection of the two halves of the fixture.

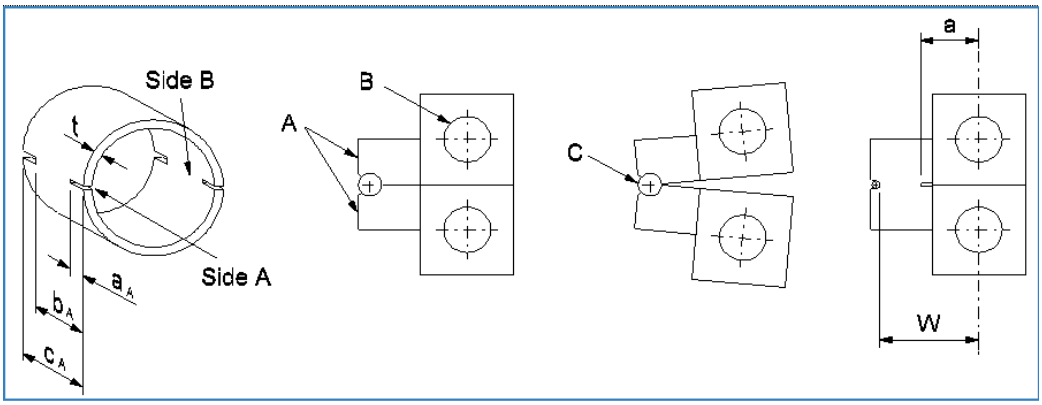


Fig. 2. Fig.2: Schematic diagram of the PLT specimen, fixture and specimen-fixture assembly

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 be 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 the distance between the load-line and the crack tip, and *E* is Young's modulus (*E'=E* for plane stress and *E'=E/(1-υ2)* 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 crack edges, so *B=2t* and the geometry function is:

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

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 Figure 3.

$$C_i = \frac{\Delta x}{\Delta P} \Rightarrow C = f_1\left(\frac{a}{W}\right) \Rightarrow \frac{dC}{d\left(\frac{a}{W}\right)} = f_2\left(\frac{a}{W}\right) \Rightarrow f\left(\frac{a}{W}\right) = \left[t \cdot E \cdot f_2\left(\frac{a}{W}\right)\right]^{\frac{1}{2}}$$

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

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 specimens were obtained by machining processes that included cutting, milling and electro-erosion. Figure 4(a) shows the sketch of PLT specimen. The specimen gripping system is presented in Figure 4(b) and Figure 5.

Details on the manufactured specimens can be seen in Figure 5. At each end of the specimen two diametrically opposed clefts were applied. The clefts from the bottom part of the specimen have a depth of 2 mm and a width of 0.5 mm. The clefts from the top of the specimen are very important because the fracture initiates from these clefts and is propagating until becomes fracture of the specimen. The depths of these clefts vary from 1.5 mm to 5 mm. Their width is kept constant, i.e., about 0.15 mm.

Two sets of specimens were tested for each material. The first set includes three specimens with different lengths of test clefts (1.5 mm, 3 mm and 5 mm). These specimens are used to measure the compliance. The second set comprises of three specimens with the same length of test clefts, i.e., 1.5 mm and are used for the PLT tests. The results obtained for the PLT tests are used to calculate the apparent toughness K_{IC} of the material.

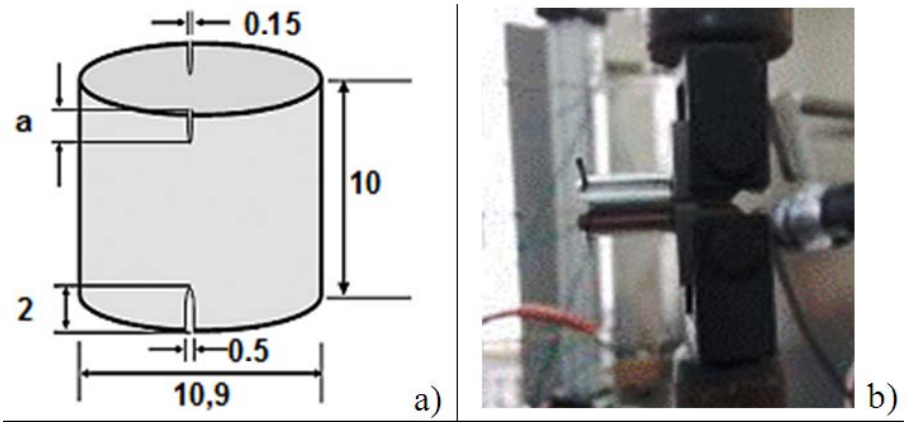


Fig. 4. PLT specimen: (a) sketch of the PLT specimen, (b) instrumented PLT specimen for potential drop

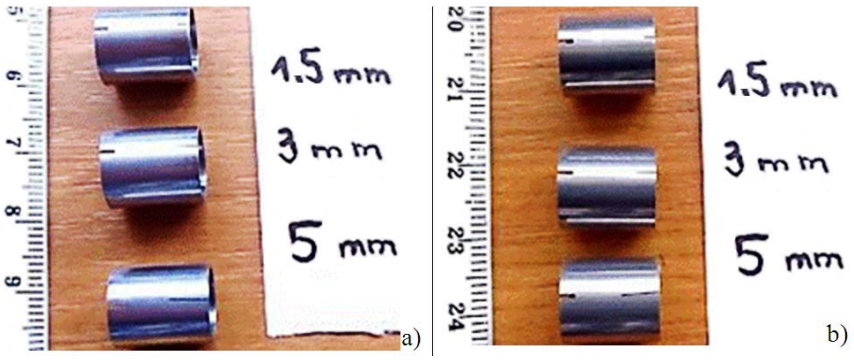


Fig. 5. PLT specimens: a) Fe-9Cr ODS; b) Fe-14Cr ODS

Results and discussion

As shown above in Figure 3, the fracture toughness determination is subject to the determination of P_Q and $f(a/W)$. The geometric function is obtained from measurements of compliance.

Compliance calculations

Fe-14Cr ODS – 1.5 mm (see Figure 6):

$$C_{1.5} = \frac{\Delta x}{\Delta P} = \frac{0.48mm}{850N} = 0.56 \cdot 10^{-3} \frac{mm}{N} = 0.56 \cdot 10^{-6} \frac{m}{N} \quad (4)$$

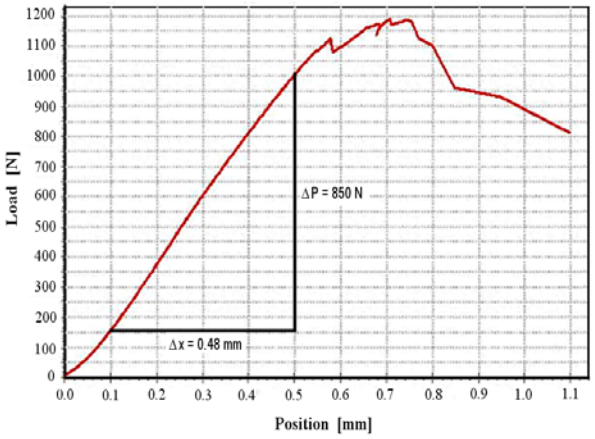


Fig. 6. Compliance calculation for Fe-14Cr ODS (1.5 mm sample)

Fe-14Cr ODS – 3 mm (see Figure 7):

$$C_3 = \frac{\Delta x}{\Delta P} = \frac{0.32mm}{475N} = 0.67 \cdot 10^{-3} \frac{mm}{N} = 0.67 \cdot 10^{-6} \frac{m}{N} \quad (5)$$

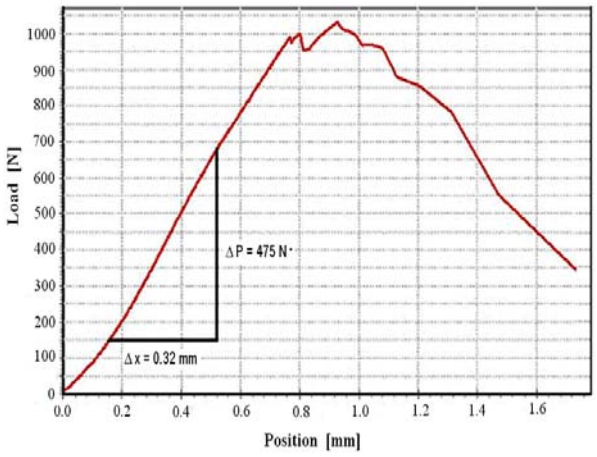


Fig. 7. Compliance calculation for Fe-14Cr ODS (3 mm sample)

Fe-14Cr ODS – 5 mm (see Figure 8):

$$C_5 = \frac{\Delta x}{\Delta P} = \frac{0.28mm}{210N} = 1.33 \cdot 10^{-3} \frac{mm}{N} = 1.33 \cdot 10^{-6} \frac{m}{N} \quad (6)$$

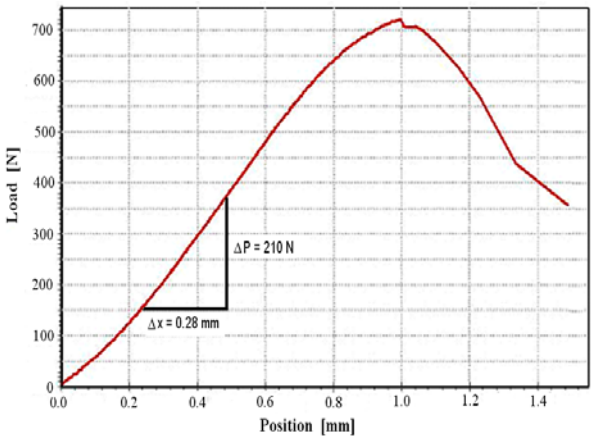


Fig. 8. Compliance calculation for Fe-14Cr ODS (5 mm sample)

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:

$$\begin{cases} a_1 = a_{01} + b \\ a_2 = a_{02} + b \\ a_3 = a_{03} + b \end{cases}, \text{ with } \begin{cases} a_{01} = 1.5mm \\ a_{02} = 3mm \\ a_{03} = 5mm \end{cases} \text{ and } b=7.5mm$$

$$\Rightarrow \begin{cases} a_1 = 9mm \\ a_2 = 10.5mm \\ a_3 = 12.5mm \end{cases} \quad (8)$$

Considering the relationship (8) and $W=18.5$ mm, the relationship (7) becomes:

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

By a polynomial fitting after a polynomial of degree 6, the polynomial of compliance is obtained (shown in Figure 9):

$$C\left(\frac{a}{w}\right) = 10^{-5}\left[0.0507 \cdot \left(\frac{a}{w}\right)^6 - 0.0438 \cdot \left(\frac{a}{w}\right)^5 + 0.1014 \cdot \left(\frac{a}{w}\right)^4 + \right.$$
$$\left. + 0.0376 \cdot \left(\frac{a}{w}\right)^3 + 0.0728 \cdot \left(\frac{a}{w}\right)^2 + 0.0465 \cdot \left(\frac{a}{w}\right) + 0.0167\right] \quad (10)$$

Further, the derivative of compliance is calculated and the following relationship is obtained:

$$\frac{dC}{d(a/W)} = f_2\left(\frac{a}{W}\right) = 10^{-6}\left[3.042 \cdot \left(\frac{a}{w}\right)^5 - 2.19 \cdot \left(\frac{a}{w}\right)^4 + 4.056 \cdot \left(\frac{a}{w}\right)^3 + \right.$$
$$\left. + 1.128 \cdot \left(\frac{a}{w}\right)^2 + 1.456 \cdot \left(\frac{a}{w}\right) + 0.465\right] \quad (11)$$

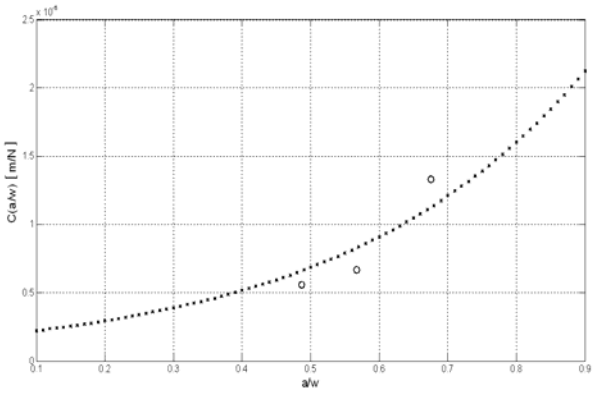


Fig. 9. Polynomial fitting of the compliance for the Fe14Cr ODS samples

Geometric function determination

Geometric function is given by:

$$f\left(\frac{a}{W}\right)=\left[t\cdot E\cdot f_2\left(\frac{a}{W}\right)\right]^{\frac{1}{2}} \tag{12}$$

where: t = 0.6 mm; E = 200 GPa –Young modulus (value from literature [5]).

By a polynomial fitting after a polynomial of degree 6, the relationship (12) becomes:

$$f\left(\frac{a}{W}\right)=11.2641\cdot\left(\frac{a}{W}\right)^5-0.8016\cdot\left(\frac{a}{W}\right)^4+5.53\cdot\left(\frac{a}{W}\right)^3+ \\ +6.5655\cdot\left(\frac{a}{W}\right)^2+10.8499\cdot\left(\frac{a}{W}\right)+7.5110 \tag{13}$$

K_{IC} toughness calculation

K_{IC} toughness is calculated using the relationship:

$$K_{IC}=\left[\frac{P_Q}{2t\sqrt{W}}\right]\cdot f\left(\frac{a}{W}\right) \tag{14}$$

The values of a, t and W factors are known. The P_Q load value can be obtained by analysing the experimental tensile tests curves according to the ASTM [6].

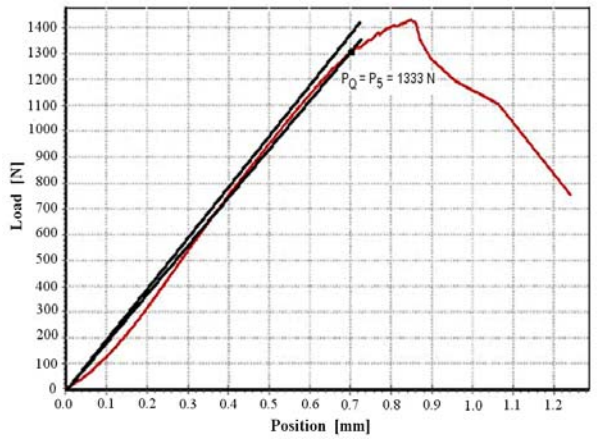


Fig. 10. The P_Q load calculation for Fe-14Cr ODS – test1

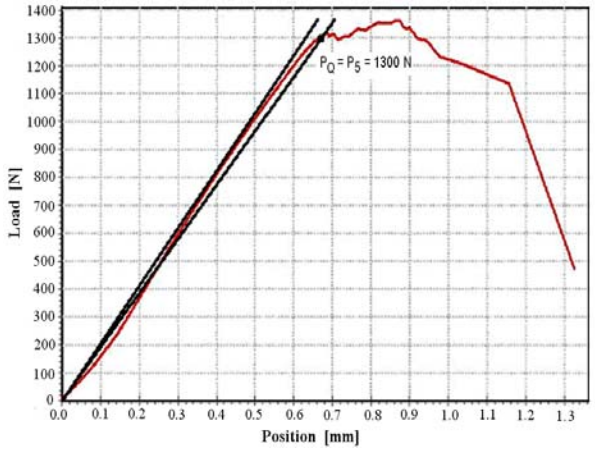


Fig. 11. The P_Q load calculation for Fe-14Cr ODS – test2

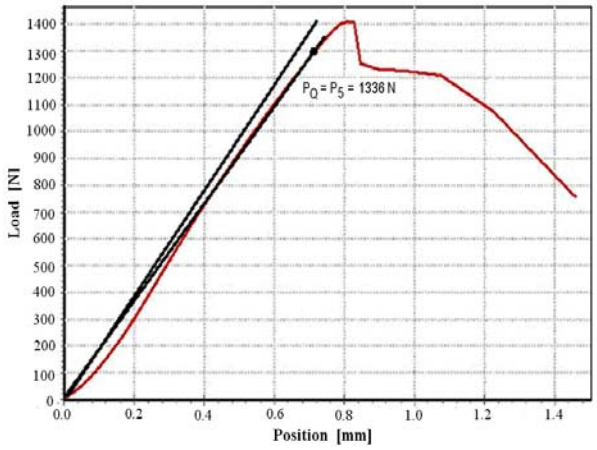


Fig. 12. The P_Q load calculation for Fe-14Cr ODS – test3

Analysing the experimental curves, the PQ load values corresponding to the three tested samples were obtained, and are shown in Figures 10, 11 and 12.

These values were inserted in Eq. (14) to determine the K_{IC} toughness. The results obtained are presented in the table below.

Table 1. Experimental results for Fe-14Cr ODS

Sample code	**P_Q Load [N]**	**K_{IC} toughness [MPa·m$^{1/2}$]**
Test 1	1333	122.2
Test 2	1330	121.9
Test 3	1336	122.5

Mean K_{IC} toughness obtained from tests of this work is 122 MPa·m$^{1/2}$, which represents a good value considering the recommendations made in the MATISSE Project meetings, namely that the toughness value must be placed within the range 80 – 180 MPa·m$^{1/2}$.

Conclusions

The experimental activity was carried out within the MatISSE Project framework and consisted in the ODS steel tubes characterization by means of mechanical tests.

The paper's objective was to initiate the testing activity to determine the mechanical properties of the candidate structural materials for the Generation IV reactors.

The pin-loading test samples were made in accordance with the MatISSE Project partners' recommendations.

In the first stage, the geometric function was determined by testing a set of samples which include three specimens with different lengths of test clefts (1.5 mm, 3 mm and 5 mm, respectively). This function was then included in the calculation for the K_{IC} toughness determination.

Mean K_{IC} toughness value (122 MPa·m$^{1/2}$) was in good agreement with the MatISSE Project recommendations (80 – 180 MPa·m$^{1/2}$).

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