Application of the Load Separation Method to Measure the Fracture Toughness of Zr-2.5Nb

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1. Introduction

To clarify a tendency of the fracture toughness as a function of the crack-tip constraint Q for Zr-2.5Nb pressure tube material, it is necessary to analyse full possible change of the value Q from 0 to –1. In this case, it is attractive to use nonstandard configuration of specimen to simulate dependence of the fracture toughness versus Q changed from 0 to –1. The procedure of calculating the fracture toughness and crack extension can be based on the load separation method and allows experimental estimation of the J-integral for the cracked nonstandard specimen. To verify this procedure, the curved CT specimens of Zr-2.5Nb material were tested.

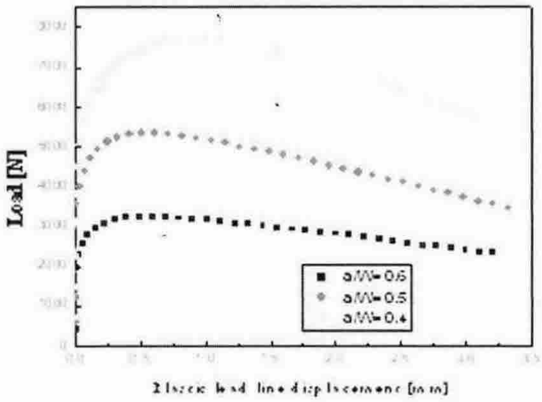

Figure 1. Typical load – load line displacement curves for the CT specimens of Zr-2.5Nb pressure tube material at room temperature.

2. Methods and Results

All tests are conducted using a single specimen technique and the separation method which allowed monitoring the specimen crack length and the applied J-integral during the course of the test.

2.1 The η-factor Estimation for the CT Specimen of Zr-2.5Nb material

The *J*-integral can be calculated as the sum of elastic and plastic components

$$J = J_e + J_p = \frac{K^2}{E'} + \eta \frac{A_{pl}}{B(W-a)}, \quad (1)$$

Here, B is specimen thickness; A_{pl} is plastic area under the load P versus load-line plastic displacement v_{pl} curve, a is crack length, W is width of the specimen; η is plastic correction factors, K is the stress intensity factor, E' is effective Young's modulus.

To calculate the η-factor, Sharobeam and Landes [1] introduced the separation parameter $S_{ij}\left(\frac{b_i}{W}\right)$ in the form

$$S_{ij}\left(\frac{b_i}{W}\right)\bigg|_{v=const} = \frac{P_i}{P_j}\bigg|_{v=const}, \quad (2)$$

where $b_i = W - a_i$ is ligament length.

The separation parameter (1) can be calculated using the load versus load-line displacement records of the CT specimen with different crack lengths (Fig. 1).

It was suggested [2] that for a given material in the separation region ($S_{ij}\left(\frac{bi}{W}\right) = const$) the $S_{ij}\left(\frac{b_i}{W}\right)$ parameter (Eq. (2)) as a function of remaining ligament b_i determined at constant displacement can be fitted with a power law, i.e.

$$S_{ij}\left(\frac{b_i}{W}\right)\bigg|_{v} = A_m\left(\frac{b_i}{W}\right)^{\eta}, \quad (3)$$

where A_m is constant with $b_j = const$ as a reference ligament.

Calculations were carried out for the curved CT specimen of Zr-2.5Nb material with W=17 mm, B=4.2 mm and a/W=0.5 using S_{ij}=1.66 at b/W=0.5. Second used point has the separation parameter S_{ij}=1 for the reference specimen at b/W=0.4 (a/W=0.6). The slope of a log-log plot of S_{ij} versus b/W for the specimen with a/W=0.5 and 0.6 is the η-factor in Eq. (1) which equals to 2.25. The ASTM Standard equation gives η=2.26.

2.2 Calculation of Growing Crack Length

For growing crack, S_{pb} parameter can be defined as the load ratio between two specimens, one with a growing crack a_p and the other with a fixed notch length a_b, at constant plastic displacement [2, 3]

$$S_{pb} = \left.\frac{P_p\left(a_p, v_{pl}\right)}{P_b\left(a_b, v_{pl}\right)}\right|_{v_{pl}=const} = \left.\left(\frac{a_p}{a_b}\right)^m\right|_{v_{pl}=const}, \quad (4)$$

Equation (4) is a relationship between the crack length and the separation parameter, and rearranging it, it is possible to obtain an expression for the growing crack length as

$$a_p = a_b\left(\left.S_{pb}\right|_{v_{pl}=const}\right)^{1/m}, \quad (5)$$

where $\left.S_{pb}\right|_{v_{pl}}$ is determined by Eq. (4) as the load ratio for given v_{pl} values. As a result, crack length can be estimated for each point of the load displacement record if "*m*" parameter is known.

To determine the "*m*" exponent, the points of the load versus load line displacement record for which the crack length is known must be used. These calibration points are those corresponding to the initial and final crack lengths where the S_{pb} parameter can be determined from the load displacement record according to Eq. (4). The first part of the $S_{pb} - v_{pl}$ curve, where the S_{pb} is constant corresponds to the initial crack length and the last point of the load displacement record to the final crack length, both of which can be measured on the crack surface of the broken specimen. A third point is introduced by the boundary conditions imposed to Eq. (4). When the fatigue pre-cracked specimen during the test achieves the same crack length as the blunt notched specimen, both are bearing the same load and the S_{pb} parameter is equal to one, that is,

$$S_{pb} = \left.\frac{P_p}{P_b}\right|_{v_{pl}} = \left(\frac{a_p}{a_b}\right)^m = 1, \quad (6)$$

This condition is particularly useful in those test cases when it is not possible to determine the load displacement point that corresponds to the specimen final crack length, as for example in dynamic tear type tests. For these cases, the "*m*" parameter can be obtained more confidently using the initial crack length and the theoretical calibration point stemming from the boundary condition.

Taking logarithms to both sides of Eq. (5), results,

$$log\left(S_{pb}\right) = m\, log\left(\frac{a_p}{a_b}\right), \quad (7)$$

With the calibration points defined above, the "*m*" parameter is readily obtained using a linear regression through them.

2.3 The J-R curve of Zr-2.5Nb material

The *J-R* curve of Zr-2.5Nb pressure tube material constructed from the crack length measured by the S_{pb} method is shown in Fig. 2. The notched CT specimen with *a/W*=0.6 and notch tip radius 0.5 mm was employed as a reference specimen. Good agreement was found between the result obtained by the load separation method and the DCPD method.

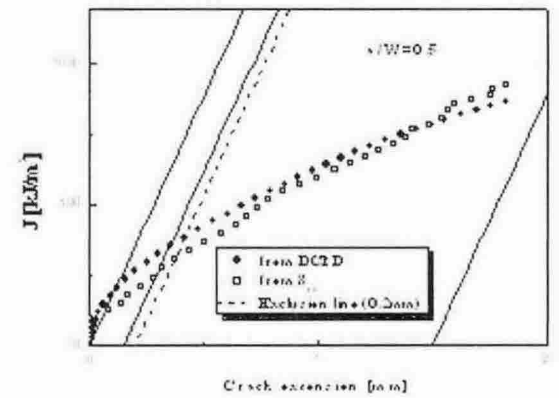

Figure 2. *J-R* curve of the CT specimen of Zr-2.5Nb pressure tube material.

3. Conclusion

The procedure of calculation of the fracture toughness and estimate of growing crack length is based on the load separation method, which has been described in this paper. The fracture toughness of Zr-2.5Nb pressure tube material estimated by the load separation method is consistent with one measured by the DCPD method. The method can be recommended to measure the fracture toughness of nonstandard specimen of Zr-2.5Nb pressure tube material.

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