On Application of *J-Q* Theory for Different Specimen Geometries of Zr-2.5Nb Pressure Tube Material

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Abstract

The effect of specimen geometry on the fracture toughness of unirradiated and irradiated Zr-2.5Nb pressure tube material has been analyzed. The *Q*-parameter has been employed to characterize the geometry dependent crack-tip constraint of Zr-2.5Nb pressure tube material. The effect of specimen geometry on the crack-tip constraint parameter *Q* and the fracture toughness has been discussed. The fracture toughness scaling model has been developed to transfer standard CT fracture toughness data to burst test specimens.

1. Introduction

In general case, the transferability of specimen fracture toughness data to an engineering component is an unresolved issue that currently receives a lot of attention among scientists. The influence of crack-tip constraint or stress triaxiality on ductile fracture has been emphasized recently in explaining the geometry dependent of the fracture toughness of specimens and structures.

To transfer specimen fracture toughness data to an engineering component, it is necessary to employ the crack-tip constraint approach, which could reflect the difference in the fracture toughness of specimens and components. Most of approaches involve the introduction of a second parameter to characterize the crack-tip constraint conditions (e.g. [1-3]). These approaches are based on an analysis of the existing stress field ahead of the crack tip in the specimen. O'Dowd and Shih introduced the *Q*-parameter to quantify the crack-tip constraint [3, 4]. The *Q*-parameter, like the *T*-stress, is supposed to characterize the geometry dependent constraint. The physical interpretation of the *Q*-parameter is this: negative (positive) *Q* values mean that the hydrostatic stress ahead of the crack is reduced (increased) by $Q\sigma_0$ from the *J*-

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dominant stress state, or the standard small scale yielding (SSY) stress state. Here, σ_0 is the yield stress. Thus, the Q-parameter provides a framework for quantifying the determination of constraint as plastic flow progresses from small scale yielding to fully yielding conditions.

The objective of this study is to work out simple model and procedure to transfer the fracture toughness of standard fracture specimen, such as a compact tension (CT) specimen, to the fracture toughness of Zr-2.5Nb pressure tubes.

2. *J-Q* estimates for different specimen geometries of Zr-2.5Nb alloy

While Q provides an exact specification of the near crack tip fields, it must be obtained from a full field finite element analysis. The one-to-one relationship between T and Q under SSY conditions suggests the use of T as a constraint measuring parameter. Since T is an elastic quantity it can be determined much more easily than Q. A relationship between T and Q under contained yielding was obtained from a modified boundary layer analysis which leads to the following equations [5, 6]

$$
\begin{aligned}
Q &= \beta \frac{\sigma}{\sigma_0} & T/\sigma_0 &< 0 \\
Q &= 0.5\beta \frac{\sigma}{\sigma_0} & T/\sigma_0 &> 0
\end{aligned}
\tag{1}
$$

where σ is the applied stress (or load), β is the stress biaxiality ratio.

Different fracture mechanics specimen geometries including compact tension (CT) specimen, center-cracked tension (CCT) specimen and burst test specimen with an axial through-wall crack have been applied to investigate the constraint effect on the fracture toughness of Zr-2.5Nb alloy using the Q-parameter. In this case, the maximum values of the fracture toughness $J_{mp}(J_{ml})$ at corresponding maximum applied hoop stress σ_{mp} (load P_{ml}) reported by Davies et al. [7, 8] have been employed. Thickness of all specimens was equal to t=4.2 mm. Burst test were carried out using 2W=500 mm long sections of tube with diameter 103 mm and different total initial crack lengths (from 35 to 85 mm). The stress biaxiality ratio β depends on geometry and crack length a/W and has been tabulated for various geometries (e.g. [9]).

In Fig. 1 and 2 the comparison of values $J_{mp}(Q)$ and $J_{ml}(Q)$ is made for Zr-2.5Nb pressure tube material. The Q-parameter for the CT specimen (width W=17 mm) is close to zero (Fig. 1). Because of this the standard CT specimen $(a_0/W = 0.5 \ and \ W = 17mm)$ is referred to as high constraint geometry. The results revealed no significant evidence of a crack-tip constraint effect (initial crack size $2a_0 = 35$ to 85 mm and corresponding constraint parameter $Q = -0.05$ to -0.16) on the fracture toughness J_{mp} in burst test of irradiated material (Fig. 2) whereas there is the crack-tip constraint effect on the fracture toughness of different specimen configurations (Fig. 1).
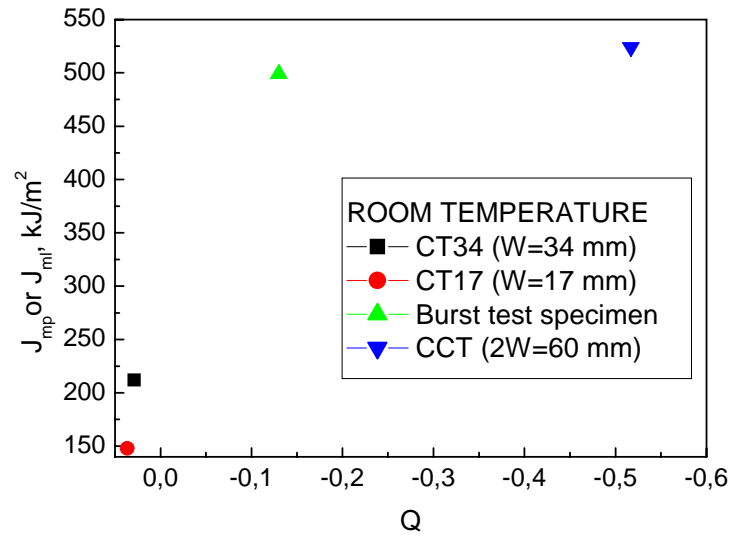
Figure 1. Dependence of the fracture toughness of unirradiated Zr-2.5 Nb pressure tube material at maximum hoop stress (load) on *Q* for four different specimen geometries.
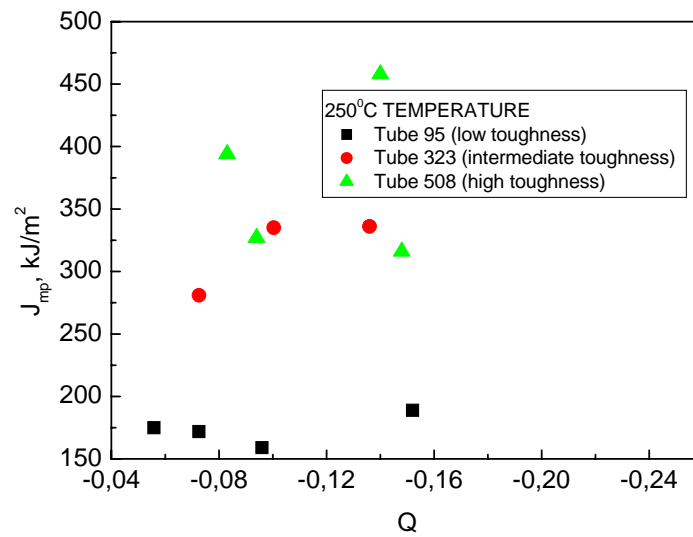

Figure 2. Dependence of the fracture toughness of irradiated Zr-2.5 Nb pressure tube material at maximum hoop stress on *Q* in burst test.

3. The fracture toughness scaling model

The toughness scaling methodology was successfully used to obtain a non-dimensional scaling function which correlates cleavage fracture toughness values in low-constraint (*T*<0)

configurations to high-constraint, reference (T=0) configuration [10]. This study employs an idea of the toughness scaling methodology to obtain a non-dimensional scaling parameter which correlates the fracture toughness J_{ml} in high-constraint (CT17 specimen) configuration as reference configuration to a low-constraint, burst test specimen (J_{mp}). Thus, the scaling parameter λ can be introduced as follows

$$\lambda = \frac{J_{mp}}{J_{ml,CT17}} \tag{2}$$

Clearly, that λ represents the single (non-dimensional) parameter, which characterizes the crack-tip constraint effect on fracture toughness values.

   Calculation of the toughness scaling parameter for Zr-2.5Nb pressure tube material at room temperature gives the following value of λ =3.37. As a first approximation, this value could be assumed to be a constant value for Zr-2.5Nb alloy independently on test temperature. Therefore, Eq. (2) enables construction of a toughness scaling model which relates J_{mp} and $J_{ml,CT17}$ values for two configurations, namely, burst test configuration and CT17 (W=17 mm) configuration at high temperature, i.e.

$$J_{mp} = 3.37 \times J_{ml,CT17}. \tag{3}$$

   The fracture toughness data $J_{ml,CT17}$ were measured using standard (17 mm – wide) curved CT specimens spark-machined directly from the tube sections after each burst test at high temperature [8]. Figure 3 shows toughness scaling model solutions for three different irradiated Zr-2.5Nb pressure tubes material representative of material of low, intermediate and high fracture toughness at 250^{0}C test temperature. It can be seen that the predicted results of J_{mp} (Eq. 3) are consistent with the burst test results for low and intermediate toughness materials and exhibit higher fracture toughness than expected from test results for high
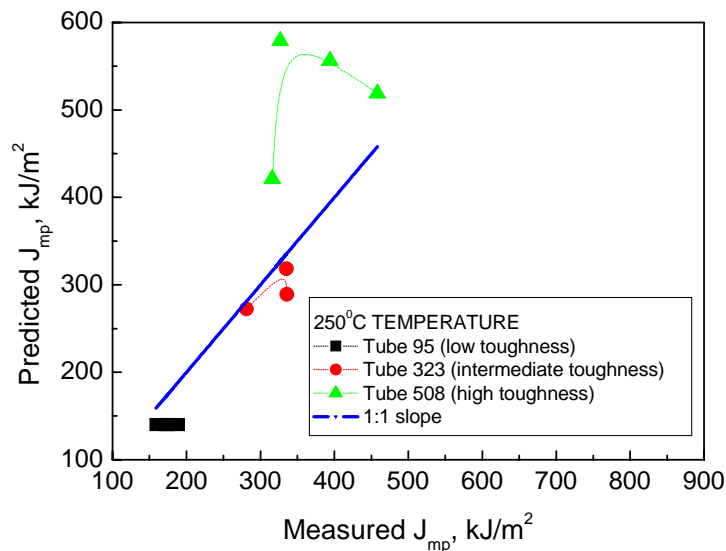

Figure 3. Comparison of fracture toughness predicted from curved CT17 of irradiated Zr-2.5Nb pressure tube material and Eq. (3) with measured fracture toughness from burst tests.

toughness material. The lower measured values of J_{mp} can be probably related to scattering and the increase in bulging (out-of-plane bending) observed by Davies et al. [8] for the burst test section from Tube 508 (high toughness).

The scaling parameter λ can be also directly calculated for each burst test and corresponding CT specimen as follows from Eq. (2). It can be seen that the lower scaling parameter is associated with tubes of higher toughness (Fig. 4). Therefore, further theoretical work is required to clarify the crack-tip constraint Q and material effects on the real scaling parameter of Zr-2.5Nb pressure tube material at high temperature.
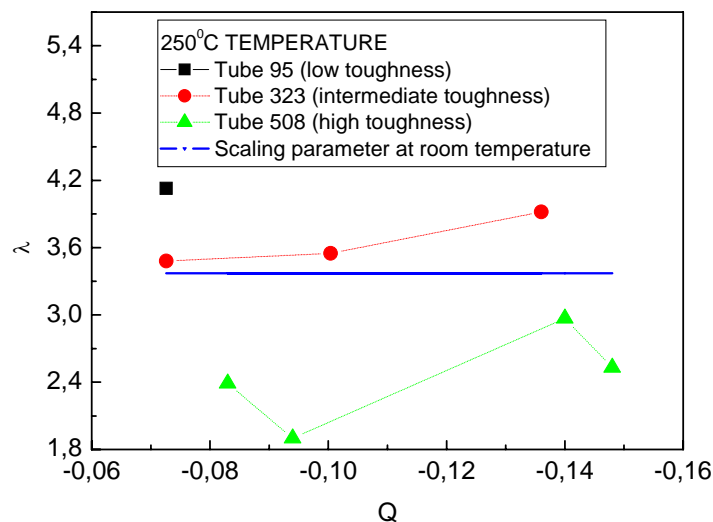

Figure 4. Dependence of the scaling fracture toughness parameter of irradiated Zr-2.5 Nb pressure tube material on Q in burst test at high temperature.

4. Conclusions

The effect of specimen configuration on the crack-tip constraint parameter Q and corresponding fracture toughness $J_{mp}(J_{ml})$ of unirradiated and irradiated Zr-2.5Nb pressure tube material at room and 250^0C test temperature has been analysed using material from tubes of low, intermediate and high toughness. The results revealed no significant evidence of a crack-tip constraint effect (initial crack size $2a_0 = 35$ to 85 mm and corresponding constraint $Q = -0.05$ to -0.16) on the fracture toughness J_{mp} in burst test of irradiated material whereas there is the crack-tip constraint effect on the fracture toughness of different specimen configurations.

The developed toughness scaling model simplifies the correction of measured high-constraint toughness values (CT17 specimens) to the fracture toughness of burst test specimens. Further theoretical work is required to clarify and quantify the crack-tip constraint Q and material effects on the real scaling parameter of Zr-2.5Nb pressure tube material at high temperature.

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