

ON THE USE OF NON-STANDARD SPECIMENS AND LOAD-SEPARATION TECHNIQUE TO EVALUATE FRACTURE RESISTANCE BEHAVIOR OF AXIALLY-CRACKED NUCLEAR REACTOR FUEL PINS

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ABSTRACT

In this work, axially-cracked specimens, directly machined from the reactor fuel pins, have been tested to obtain the fracture resistance behavior. A modified load-separation technique has been used to estimate the crack growth during loading. Subsequently, specimens with different initial crack lengths have been tested and their fracture resistance behaviors have been evaluated as a function of initial crack length to width ratio. A modified procedure for estimation of the material constant 'm' has been developed in this work so that data from multiple specimens can be used. It was observed that this modified method of load separation is a convenient and reliable technique for evaluation of fracture resistance behavior of non-standard specimens. Later on, specimens from two different types of Zirconium based alloys have been tested. It was observed that the re-crystallization annealed (RXA) Zircaloy-2 specimens have higher initiation fracture toughness as well as higher resistance to crack growth compared to the other type of specimens (i.e., SRA Zircaloy-4). The higher fracture resistance behavior of the RXA Zircaloy-2 specimens can be attributed to the presence of finer grain and sub-grain micro-structure, very low initial dislocation density and other defects in the material.

Key Words: Zircaloy fuel clad; Fracture resistance; J-R curve; Load-separation method; Pin-Loading-Tension setup

INTRODUCTION

Nuclear reactor fuel pins act as barriers to the release of radioactive fission products to the surrounding coolant. These tubes are of small thickness in order to have less resistance in the path of heat flow from the fuel to the coolant. Investigation of failure behavior of these fuel clad tubes is of utmost importance to the designers and plant operators in order to ensure the maximum residence time of the fuel bundles inside the reactor core as well as to ensure minimal activity during operation and refueling activities [1-4]. Various types of Zirconium based alloys are used to manufacture these pins. The focus is to obtain better strength, ductility, corrosion resistance, oxidation resistance and minimal creep including those due to irradiation-assisted damage and deformation processes [5]. Two such types of alloys, namely, re-crystallized annealed Zircaloy-2 and stress-relieved annealed Zircaloy-4, have been investigated in this work, for their fracture behavior.

One of the postulated design-basis accidents for the fuel clad tubes is the reactivity initiated accident (RIA). In such a situation, the control rod drops or ejects very rapidly from the reactor. This in turn deposits a large amount of energy in the fuel pellets and leads to adiabatic heating and large fission gas release in the fuel pins. The fuel pellets expand thermally and may cause fast straining of the surrounding Zircaloy clad tube through pellet-clad mechanical interaction [2-3]. The fast loading imposed by the mechanical expansion of fuel pellet may cause rapid propagation of pre-existing cracks. These pre-existing defects may have been initiated during the service life due to mechanical and chemical interaction of fuel pellets with the clad.

In order to conduct a fitness-for-purpose of service assessment of these fuel pins, information regarding crack resistance behavior is needed. However, it may not be possible to evaluate the fracture behavior of these thin-walled tubular components using standard ASTM test techniques [6], because of the stringent requirements of the ASTM test methods. A number of non-standard test techniques have been proposed in research literature for this purpose.

In this work, Pin-Loading-Tension (PLT) specimens [7-8] have been tested to obtain the fracture resistance behavior. A modified load-separation technique has been used to estimate the crack growth during the loading of these axially-cracked tubular specimens. Specimens with different initial crack lengths have been tested and their fracture resistance behaviors have been evaluated as a function of initial crack length to width ratio. A modified procedure for estimation of the material constant 'm' has been developed in this work so that data from multiple specimens can be used. This will lead to a more reliable estimation of crack growth during loading. The J-R curves, obtained using the current method, have also been compared with those obtained using load-normalization

technique. It was observed that this modified method of load separation is a convenient and reliable technique for evaluation of fracture resistance behavior of non-standard specimens (though these cannot be designated as material properties as validity requirements of ASTM test conditions are not met).

It was also observed that the re-crystallization annealed (RXA) Zircaloy-2 specimens have higher initiation fracture toughness as well as higher resistance to crack growth compared to the other type of specimens (i.e., SRA Zircaloy-4). In order to understand the micro-structural aspects of fracture resistance behavior of these materials, further investigation incorporating scanning electron and transmission electron microscopy have also been carried out. It was concluded that the higher fracture resistance behavior of the re-crystallization annealed Zircaloy-2 specimens can be attributed to the presence of finer grain and sub-grain micro-structure, very low dislocation density and other defects in the material.

ESTIMATION OF CRACK GROWTH THROUGH LOAD SEPARABILITY PARAMETER

According to the load separation theory [9-15], the load P at any instant of loading in a specimen, with crack length to width ratio a/W , can be expressed as the product of a geometry function $G(a/W)$ and a deformation function $H(V_p/W)$ in the following way.

$$P = G\left(\frac{a}{W}\right)H\left(\frac{V_{pl}}{W}\right) = WB\left(1 - \frac{a}{W}\right)^m H\left(\frac{V_p}{W}\right) \quad (1)$$

where B is the thickness of the specimen, V_p is the plastic part of displacement at load P and m is a material constant. Sharobeam and Landes [12] introduced a separable parameter S_{ij} , which is defined as the ratio of load of two blunt cracked specimens (with different crack lengths of a_i and a_j) at the same value of plastic displacement V_p , i.e.,

$$S_{ij} = \frac{P_i(a_i)}{P_i(a_j)} \Big|_{V_p} = \frac{G(a_i/W)H(V_p/W)}{G(a_j/W)H(V_p/W)} \Big|_{V_p} = \frac{G(a_i/W)}{G(a_j/W)} \quad (2)$$

The parameter S_{ij} is independent of the deformation function $H(V_p/W)$ and depends only on the geometry function $G(a/W)$. For a stationary crack, the geometry function remains constant and hence, the parameter S_{ij} remains constant over the whole domain of the plastic displacement. In order to study the load separation property for the specimens with crack growth during loading, the parameter was redefined in [13] as

$$S_{pb} = \frac{P_p(a_p)}{P_b(a_b)} \Big|_{V_p} = \frac{G(a_p/W)H(V_p/W)}{G(a_b/W)H(V_p/W)} \Big|_{V_p} = \left(\frac{a_p}{a_b}\right)^m \quad (3)$$

where the subscripts 'p' and 'b' represent the sharp cracked specimen and the blunt cracked specimen, respectively. The parameter S_{pb} remains constant while there is no crack growth in the sharp cracked specimen. With crack growth, the parameter S_{pb} changes according to Eq. (3). The material constant m need to be determined from testing of a set of specimens with and without crack growth during loading, obtaining a database for S_{pb} vs. r_{pb} (i.e., a_p/a_b) and evaluation of m from the best fit of Eq. (3) with experimental data points. Usually, the initial and final crack lengths are measured on the fracture surface of the broken cracked specimen. A third calibration point is initial point (i.e., $S_{pb} = 1$ when $r_{pb} = 1$). With these 3 points, a power law according to Eq. (3) is fitted.

MODIFICATION OF THE LOAD SEPARABILITY PARAMETER

In some situations, the three points (that are used in the method described in the previous section) may not be enough for a reliable estimation of the material constant 'm'. For this purpose, a modified procedure for estimation of the material constant m has been developed in this work so that data from many specimens can be used. This will lead to a more reliable estimation of crack growth during loading. The modified procedure is described here. Different fatigue pre-cracked specimens with known initial crack lengths are tested and their load-displacement curves are recorded. Let the data for these specimens with growing cracked is denoted by the subscript

‘g’. We need to find the load vs. displacement response of the specimens with same values of initial crack length, i.e., load-displacement response of the specimen with stationary crack during loading. Let the data for these specimens with stationary crack be denoted by subscript ‘s’. It may not be possible to obtain such a load vs. displacement data of a specimen (experimentally) with non-growing crack. Especially, obtaining a load point corresponding to the same value of plastic displacement V_p as recorded at the final load point of the specimen with propagating crack (the crack growth in the growing crack specimen at final point being equal to the final crack length as recorded in the specimen fracture surface). This is because the crack may not remain stationary even if we choose an initial highly blunted crack in such a test setup (i.e., the pin-loading tension test setup) due to the highly constrained nature of loading. Hence, we choose to perform a 3D elastic-plastic FE analysis in order to calculate the load vs. displacement response of the specimen with different initial crack lengths. The initial cracks remain stationary during loading due to elastic-plastic material constitutive equations which incorporates the phenomenon of plastic hardening (i.e., there is no material softening in the constitutive laws). However, there can be global geometric softening due to geometry nonlinearity in the analysis which is synonymous with plastic collapse and necking of the remaining ligament in the specimen.

The plastic part of displacement V_p is evaluated from the total displacement once the compliance of the specimen in the PLT setup (as a function of crack length to width ratio) is known. The compliance of the PLT setup for the specimen under consideration in this work has been estimated by both experiment and FE analysis in a previous work by the authors [16-17] and the same has been used here. For the specimen with stationary crack, the compliance is constant throughout the loading and hence, the computation of plastic displacement V_p is straight forward. Nevertheless, the calculation process of plastic displacement V_p for the specimen with growing crack needs an iterative procedure as the compliance of the system has to be updated at every load point with a new value of crack length to width ratio. The new load ratio S_{gs} is defined as the ratio of load for a growing crack to the load for a stationary crack with exactly same initial geometry and crack lengths at a particular value of plastic displacement. The crack length ratio r_{gs} is defined as the current crack length of the specimen with growing crack to the initial crack length of the specimen with the stationary crack (which is constant during loading). The current crack length a_g in the specimen with growing crack can be estimated from the following equation, i.e.,

$$a_g = a_s \left[(S_{gs})_{V_p} \right]^{\frac{1}{m}} \quad (4)$$

For a given plastic displacement V_p of the stationary cracked specimen, the load of the specimen with growing crack can be estimated with the known value of crack length (i.e., the initial crack length or crack length computed for a previous point with a lesser value of plastic displacement). However, this is a first estimation of the load P_g for a given value of V_p . Once S_{gs} is evaluated, the new crack length a_g can be computed.

The above procedure can be repeated till a converged value of crack length a_g is obtained. However, one must know the material constant ‘m’ in order to use Eq. (4) in estimation of crack growth in the PLT specimen. The evaluation procedure of the material constant ‘m’ from several specimen test data will be in the section of ‘Results and Discussion’.

RESULTS AND DISCUSSION

The axially-cracked specimens have been machined from the cladding tubes used both boiling water (BWR) and pressurized heavy water (PHWR) type of reactors. These tubes have inner diameter and wall thickness of 12.4 mm and 0.9 mm respectively for the BWR fuel pin, whereas these are 14.2 and 0.4 mm respectively for the PHWR fuel pin. The sketch of the tubular specimens with axial cracks is shown in Fig. 1(a) along with the loading device in Fig. 1(b). In order to determine the material constant ‘m’ for evaluation of crack growth using the load separability parameter S_{gs} , four tubular specimens (labeled as specimens 1 to 4) machined from the BWR fuel pins have been tested initially. The average initial crack lengths (i.e., average values of initial crack lengths on two diametrically opposite sides) after fatigue pre-cracking have been measured as 11.2, 11.3, 11.35 and 11.6 mm respectively for the specimens 1 to 4. The crack lengths on both sides were originally measured as (11.4, 11.0), (10.7, 11.9), (11.7, 11.0) and (12.1, 11.1) mm respectively for the specimens 1 to 4. Hence, the initial crack lengths of the four specimens are almost same except the specimen 4. These specimens were tested in the PLT setup and the load vs. load line displacement data obtained from the tests has been plotted in Fig. 2.

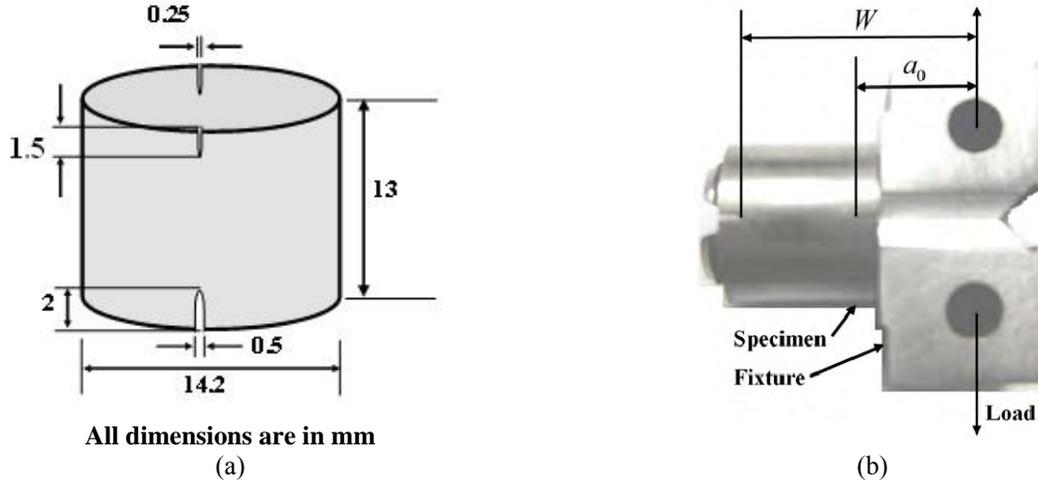


Fig. 1: (a) Geometric dimensions of the PLT specimen with longitudinal through-wall cracks; (b) Loading setup

The load-displacement data for specimen with stationary crack has been obtained through finite element (FE) analysis. The material stress-strain curve used for elastic-plastic FE analysis is shown in Fig. 3. The typical load-displacement data obtained from FE analysis is shown in Fig. 4. The data obtained from FE analysis is also plotted along with the experimental data (growing crack situation) in Fig. 4. Once the load-displacement results have been evaluated for the specimens with growing and stationary cracks with different initial crack length to width ratios, we need to evaluate the final crack lengths at the end point of the load displacement curves for each specimen. The final crack lengths have been measured on the fracture surface after heat-tinting operation in order to distinguish different regions of crack propagation.

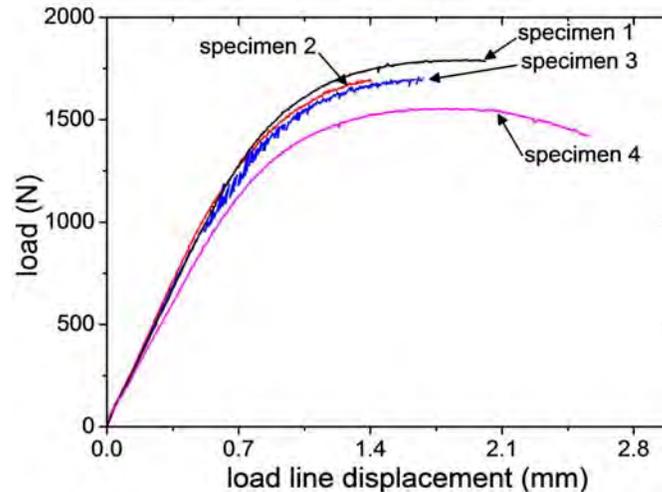


Fig. 2: Experimental load-load line displacement of four different specimens with different initial crack sizes

The crack length ratio r_{gs} for each specimen at the final loading point has been calculated as the ratio of final crack length of the specimen with growing crack (as obtained from the final fracture surface) to the initial crack length which is same as initial crack length of the stationary specimen. For calculation of the load ratio S_{gs} , the plastic displacement component V_p needs to be computed. As has been discussed earlier, this parameter can be computed from the displacement at the final point of load-displacement diagram once the compliance function for the PLT specimen with the initial a_0/W is known. In a previous work by the authors [16], the compliance functions for this particular BWR fuel pin have been evaluated using both analytical and numerical schemes. The details can be found in Ref. [16]. The compliance function $C(a/W)$ used in this work can be written as [in unit of mm/N]

$$C\left(\frac{a}{W}\right) = -0.01101 + 0.06113\left(\frac{a}{W}\right) - 0.11156\left(\frac{a}{W}\right)^2 + 0.0691\left(\frac{a}{W}\right)^3 \quad (5)$$

Using the above Eq. (5), the plastic displacement V_p for the specimen with stationary crack can be evaluated in a straight forward manner. For the specimen with growing crack, an iterative procedure is followed to evaluate the plastic displacement V_p as discussed earlier. For the same value of the plastic displacement V_p (at the final point of load-displacement data), the load ratio parameter S_{gs} is evaluated as the ratio of the load of the specimen with growing crack to the load of the specimen with stationary crack.

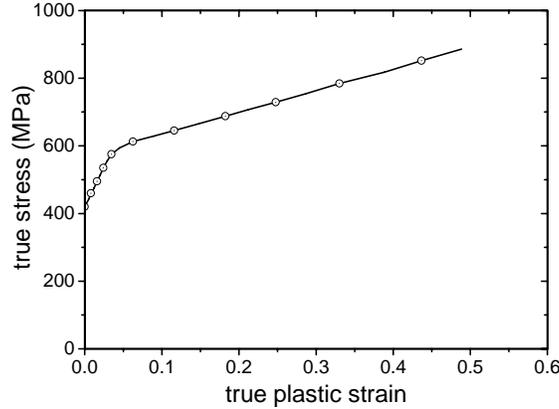


Fig. 3: Material stress-strain curve for the RXA Zircalloy-2 fuel pin specimen

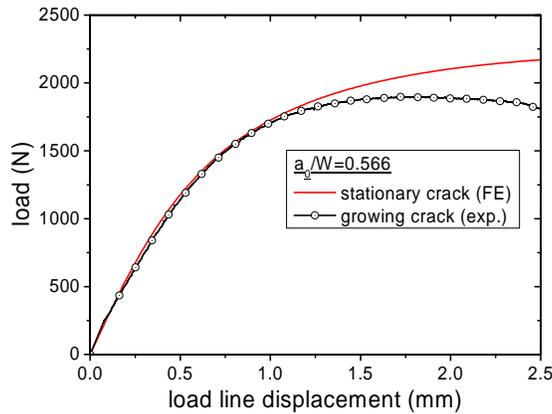


Fig. 4: Load vs. load line displacement for the PLT specimen (FE analysis vs. experiment)

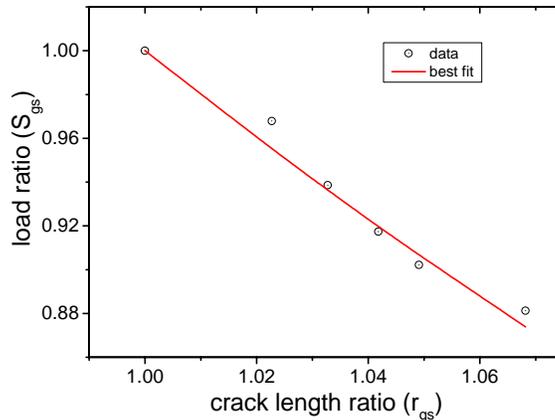


Fig. 5: Evaluation of parameter ‘m’ from experimental data of load and crack length ratios

Similar exercise were conducted for all the specimens and the data of S_{gs} is plotted as a function of r_{gs} in Fig. 5. Eq. (4) has been used to obtain a best fit to the experimental data points. The material constant parameter ‘m’ has thus been evaluated as -2.043. This material constant ‘m’ has later been used to evaluate crack growth in other PLT specimen with different initial crack lengths and loaded to different amount of displacements. Four such specimens have been machined from the same Zircaloy fuel pins of Indian BWR. The initial a_0/W of these specimens have been measured as 0.526, 0.578, 0.631 and 0.685 respectively.

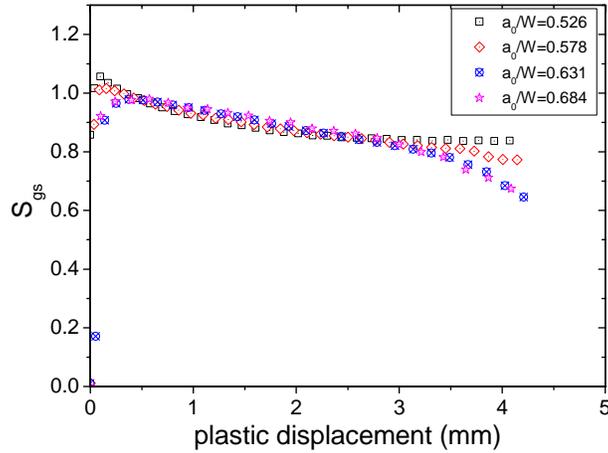


Fig. 6: Evolution of load separation parameter with plastic displacement for four PLT specimens with different initial crack lengths

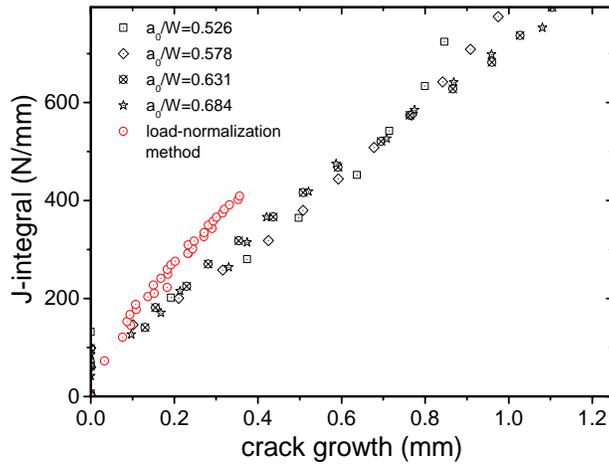


Fig. 7: Evaluation of J-R curve using modified load-separability method and its comparison with that obtained from load-normalization technique

The aim is to evaluate the fracture resistance (J-R) curves from the experimental load-displacement data. The necessary geometric functions, i.e., η and γ functions have been evaluated for these tubes as a function of a/W ratio in a previous work by the authors [17]. Elastic-plastic finite element analyses for these specimens have been carried out in order to evaluate the load-displacement response for the corresponding specimens with stationary cracks. The load ratio parameter S_{gs} has been evaluated as a function of plastic displacement for the four different specimens and is plotted in Fig. 6. The parameter S_{gs} decreases as the plastic displacement increases due to more and more crack growth due to increased loading. The behavior of the four specimens as regards to variation of the parameter S_{gs} as a function of plastic displacement V_p is nearly same except for the region beyond the plastic displacement of 3 mm approximately. In this region, the specimen with a higher value of a_0/W ratio exhibit a higher drop in the load ratio S_{gs} , which corresponds to the higher crack growth for this specimen.

The crack growth information Δa as a function of plastic displacement can be evaluated using an iterative procedure as discussed earlier along with the use of Eq. (4). This crack growth data is required along with the experimental load-displacement curve in order to evaluate the necessary fracture resistance (J-R) curve of these specimens which have different initial a_0/W ratio. For evaluation of the plastic part of the J-integral, the geometric functions, i.e., η and γ functions, are required to be evaluated as function of a/W ratio. These functions have been evaluated from the limit load expressions of these PLT specimens in Ref. [17]. The limit load values were previously evaluated from a detailed elastic-plastic FE analysis of this PLT setup. Fig. 7 shows the J-R curves of the four different PLT specimens with different values of initial a_0/W ratios. It can be observed that the fracture resistance behaviors of the four specimens are nearly similar as the initial a_0/W ratios are very close to each other. However, the J-R curves are slightly lower for specimens with higher values of a_0/W ratios beyond 0.8 mm of crack growth (Δa) approximately. The J-R curves obtained by this load separation technique have also been compared in the above figure with that obtained from the load normalization technique for a similar PLT specimen (made from same material and same fuel clad tube). The details of the load normalization technique as applied to a BWR fuel clad PLT specimen and the results of fracture resistance behavior has been discussed in Ref. [17].

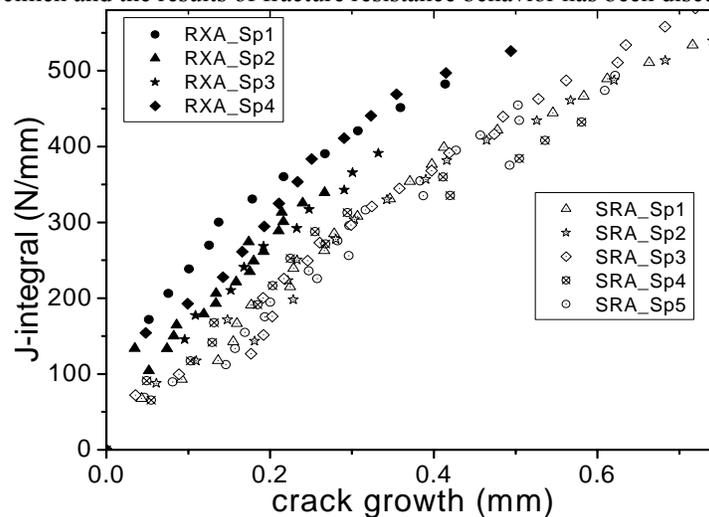


Fig. 8: Comparison of J-R curves of PLT specimens machined from RXA Zircaloy-2 and SRA Zircaloy-4 fuel pin specimens

It can be observed from Fig. 7 that the results obtained by both the techniques are very close to each other. Moreover, the new load separation method presented in this work can be used easily for other specimens with different initial crack length values as the material constant 'm' is same for all the values of a_0/W . Elastic-plastic FE analysis can replace the need for testing of specimen with stationary crack. Once the experimental data of the PLT specimen is obtained from the test, this can be directly used to evaluate the J-R curve without the need to measure the crack growth information by other conventional methods which may be cumbersome, inaccurate and time consuming. Hence, this method is very suitable for evaluation of fracture resistance behavior of thin-walled tubular specimens and can be extended to other loading environments such as high temperature, hydrogen and irradiations environments as encountered in nuclear fuel pin applications.

The same method has been applied to evaluate the fracture resistance behavior of PLT specimens machined from the PHWR fuel pins. The material is stress-relieved annealed Zircaloy-4. The chemical composition of the two materials as well as the manufacturing and heat treatment procedures for the two types of fuel pins are different. Fig. 8 shows the J-R curves of the PLT specimens for the two types of fuel pins with different a_0/W ratios. It can be observed that the re-crystallization annealed (RXA) Zircaloy-2 specimens have higher initiation fracture toughness as well as higher resistance to crack growth compared to the other type of specimens (i.e., SRA Zircaloy-4). In order to understand the micro-structural aspects of fracture resistance behavior of these materials, further investigation incorporating scanning electron and transmission electron microscopy have also been carried out. It was concluded that the higher fracture resistance behavior of the re-crystallization annealed Zircaloy-2 specimens can be attributed to the presence of finer grain and sub-grain micro-structure, very low initial dislocation density and other defects in the material.

CONCLUSIONS

Evaluation of crack growth during loading using conventional techniques can be cumbersome when using small specimens, dynamic loading conditions and harsh environment etc. Load-separability method provides a solution to this problem. A modified procedure as developed in this work can make use of the data from many specimens in order to reliably evaluate the material constant 'm' in the load-separability method. With combined FE analysis and experimental data, the J-R curves can be evaluated in a straight forward manner though an iterative procedure is needed for evaluation of the crack growth at different load steps. In this work, both load-normalization and load-separability techniques have been explored in order to evaluate the crack growth directly from the experimental load-displacement data of a PLT specimen. The load normalization technique requires parameters of the normalization functions to be fitted for each specimen, whereas the same parameter 'm' can be used here for each specimen with different a/W ratios in case of the load separability method.

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