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A novel fracture toughness testing method for irradiated tubing - Experimental results and 3D numerical evaluation

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ABSTRACT: A new loading mode and test method for evaluation of fracture toughness of thin-walled tubing have been analysed. Several parameters are estimated: a) pre-cracking; b) load-displacement value when the crack propagation is initiated; c) initial gap and bending moment at the notch tip; d) friction between the specimen and holder. Fatigue pre-cracking and potential-drop measurements have been used in the research.. The results obtained for different Zircaloy cladding show very promising capacities of the Pin-Loading tensile test technique.

INTRODUCTION

First experimental data on fracture toughness of ZIRCALOY cladding have been recently obtained by means of a new technique called the Pin-Loading (PL) tension test [1, 2]. Further development of the technique included: 1) numerical modelling by means of 3D elastoplastic finite element method; 2) sharpening of the notch by fatigue pre-cracking; 3) Direct Current Potential Drop (DCPD) measurements of the crack propagation. Both fatigue pre-cracking and DCPD measurements were adapted for testing of irradiated fuel cladding.

The numerical modelling and further development of the testing technique were aimed at evaluating of the following factors: a) pre-cracking; b) load-displacement value when the crack propagation is initiated; c) initial gap and bending moment at the notch tip; d) friction between the specimen and holder.

EXPERIMENTAL PROCEDURE

The procedure of the PL-testing has been described in details elsewhere [1, 2]. The J-integral values were calculated on the basis of the load-displacement curves recorded during testing and specimen's uncracked ligament area before testing (Fig. 1a, b). Cold-worked (CW) Zircaloy-2 cladding in as-received condition and after gaseous hydriding (~500 wtppm) havebeen used for fatigue pre-cracking and PL-testing. The pre-cracking of the specimens was performed at room temperature under constant-amplitude fatigue (~1 Hz) with a maximum initial load of 300-800 N. The crack propagation in the specimen was marked due to changing the fatigue amplitude. The reversing DCPD system has been used for crack growth rate monitoring. Three different positioning of the DCPD probes on the specimens were used. The DCPD signal from the specimen was recorded during both fatigue pre-cracking and PL-testing. To characterise the crack propagation the ratio V/V_0 was used, where V and V_0 are the actual and the initial values of the DCPD signal, respectively. The load-displacement curves from PL-testing were synchronised with the DCPD measurements and collected into a computer file.

NUMERICAL MODELLING

ABAQUS STANDARD 5.4 Finite Element Code was used for the numerical calculations [3, 4]. The material behaviour used in the modelling was considered as Elastoplastic with Linear Isotropic Hardening for the specimen (Zircaloy cladding) and as Elastic Linear behaviour for holders. Three-dimensional second order isoparametric finite elements (20 and 27 nodes) to generate the specimen mesh and second order reduced integration shell elements (9 nodes) for the holder (Fig. 1c) have been used. The initial diametric gap between specimen and holder was considered in the range of 0.04-0.1 mm. Two cases with different friction coefficients f at the contact surface were considered. The value f=0.1 was related to a practical case with good lubrication and compared with the case without friction (f=0). The J-integral values for annealed and cold-worked Zircaloy cladding were computed by performing the Virtual Crack Extension Technique available on the finite element code.

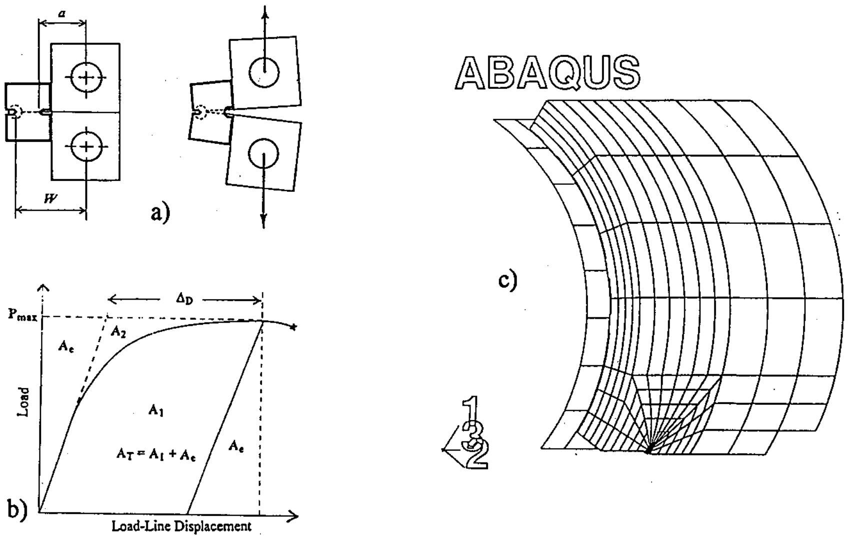

Fig. 1. a) The specimen-fixture assembly before and during PL testing, b) load-displacement curve schematically illustrating the areas used for experimental evaluation of the J-integral, and c) finite element mesh used for specimen and holder in numerical modelling of the PL test technique.

EXPERIMENTAL AND NUMERICAL RESULTS

The fracture surfaces of two specimens, cold-worked (CW) and another one hydrided up to about 500 wtppm (H500), are shown in Fig. 2 after fatigue pre-cracking followed by PL-testing at room temperature. The following surface areas can be distinguished in the CW-specimen (from the left to the right): 1) notch, 2) fatigue crack, 3) area of crack propagation during PL testing, and 4) area of final fracture of the specimen. Before the specimen was broken in two pieces during final fracture, the fracture surface was tinted by means of oxidisation. The surface of the H500-specimen contains the following areas: 1) notch; 2) fatigue pre-cracking (two areas corresponding to the different parameters used during the fatigue can be distinguished); 3) PL-testing at room temperature (fractured circumferential hydrides can be seen on the fracture surface); 4) repeated fatigue cracking (narrow light area showing the position of the crack-tip after previous PL-testing); and 5) repeated PL-testing at room temperature up to complete failure of the specimen.

Effect of fatigue pre-cracking

Experimental results have shown, that: *i*) pre-cracking of the notched specimen decreases the *J*-values, and *ii*) the effect of pre-cracking depends on the cladding ductility. Data obtained from the PL testing of the notched and pre-cracked specimens of the same materials are presented in Fig. 3. Previously obtained data for the specimens pre-cracked by means of interrupted PL testing at 300°C are combined with the data for specimens pre-cracked by means of fatigue. Thus, the lower the ductility (or fracture toughness) of the cladding the less influence of the notch sharpening. This trend has also been predicted from the numerical modelling.

DCPD measurements

The DCPD values, recorded versus the time duration of the PL testing, have no abrupt transition which could be related to the moment of crack initiation. A more or less obvious increase of the DCPD signal (V/V_o) usually follows the beginning of plastic flow at the notch or crack tip (t_{pl} is marked in Fig. 4a). The DCPD signal increases gradually, as a rule without any specific points in the curve up to the end of testing or to specimen failure (Fig. 4b). It has been concluded, that the DCPD measurements in the thin-walled specimens are very much affected by specimen thinning due to the plastic deformation which occurs at the notch or crack tip. For the same crack length, the V/V_o values for the PL crack are always higher compared to the fatigue crack (Fig. 5).This is also the effect of the specimen wall thinning due to plastic deformation at the crack tip during PL testing. Such plastic deformation does not occur at the fatigue crack tip, thus providing less changes of the non-cracked ligament area in the specimen.

Initial gap and bending moment

The existence of a bending moment across the wall of the specimen seems to be the most probable explanation for the advanced crack propagation close to the inner specimen surface.

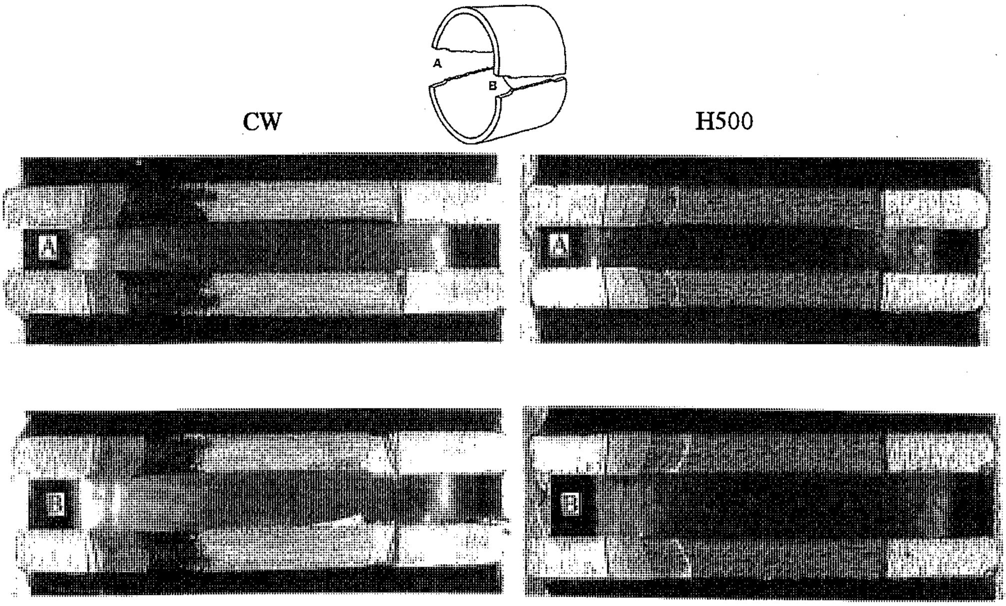

Fig. 2. Examples of the fracture surfaces of the specimens after testing: CW specimen (after fatigue pre-cracking, PL-testing, and oxidising) and hydrided specimen, H500 (after fatigue pre-cracking with two different regimes, PL-testing, and short term fatigue).

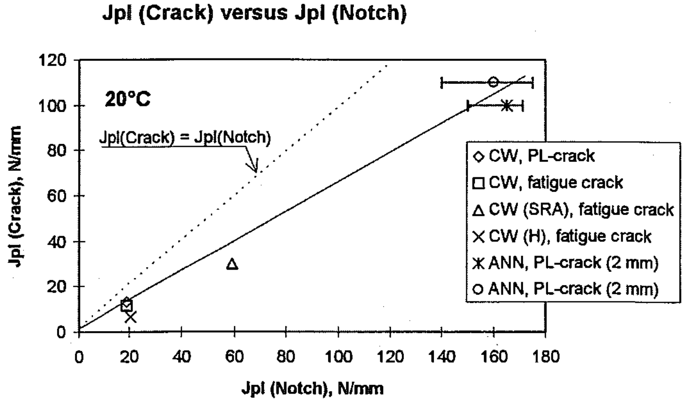

Fig. 3. Effect of pre-cracking on the J_{pl}-values for cladding with different ductility.

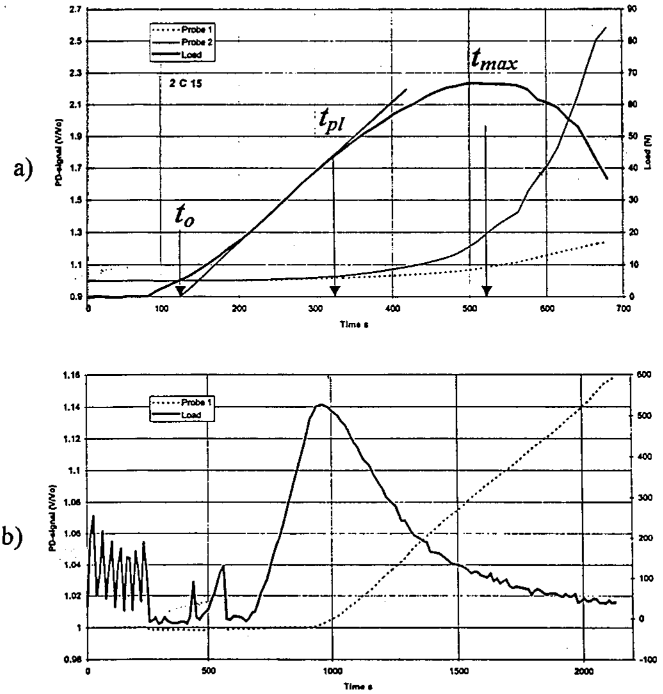

Fig. 4. The load-displacement curves with simultaneous DCPD measurements for ductile (a) and low ductile cladding (b): t_o-beginning of loading, t_{pl}-beginning of plastic deformation, t_{max}-the moment of maximal load; Probes 1, 2 - different positions of DCPD active probes.

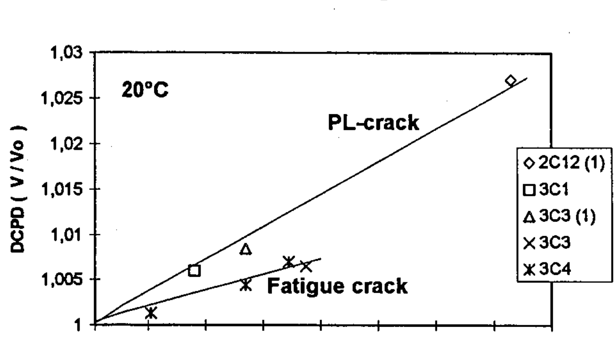

Fig. 5. The DCPD values (V/V_o) versus crack propagation in Zircaloy-2 cladding.

Nevertheless, we cannot rule out the influence of other probable factors such as a through wall gradient of material properties, or appearance of the slant fracture, which is typical for thin-walled materials. The *J* values, obtained from numerical modelling, were the same for both internal and external faces of the specimen for an initial radial gap of 0.035 mm. Experimentally obtained J_{pl} and J_{max} values for annealed (ANN) and cold-worked (CW) specimens tested with initial radial gaps in the interval of 0.02 to 0.07 mm did not reveal any significant changes either (Fig. 6). In practice, the values of initial radial gap are in the interval of 0.01-0.04 mm, as it was, for example, for irradiated specimens [2]. Also, for common dimensions of the cladding the decrease of initial radial gap due to different thermal expansion of Zircaloy cladding and holder is about 0.015 mm at test temperature 300°C.

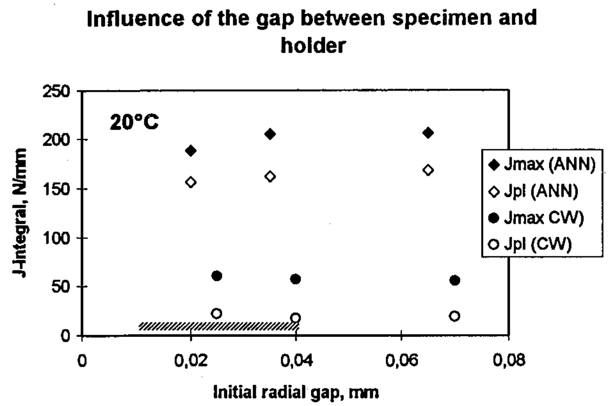

Fig. 6. Experimental values of J_{pl} and J_{max} obtained from PL testing with different initial gaps. The area of the gap values, typical for the testing of irradiated cladding, is shadowed.

Friction between specimen and holder

Qualitatively, one should take care of minimisation of the test to test friction variation by means of common procedures. Quantitatively, a good reproducibility of the test results, including those for irradiated cladding, confirms the conclusion from the numerical modelling, showing the effect of the friction variation of about few percents of the *J*-integral value.

Finally, Fig. 7 illustrates the main trends for the fracture toughness (J_{pl}) of different Zircaloy-2 cladding (annealed, cold-worked, stress-relieved, hydrided, and irradiated), tested at room temperature and at 300°C without and with pre-cracking (notch, crack). A longer notch or crack gives lower J_{pl} -values for ductile cladding (ANN, CW/300°C), however, does not change the J_{pl} -values for low-ductile cladding (CW/RT, Irradiated). Different types of crack (either after fatigue or after interrupted PL testing at 300°C) show the same level of fracture toughness at room temperature. The notched hydrided specimens (CW(H)/Notch) show similar J_{pl}-values as material without hydriding (CW/Notch), as a result of two opposite effects: 1) decreasing of the fracture toughness due to hydriding, and 2) increasing of J_{pl} due to annealing during hydriding (compared with data for CW/SRA specimens).

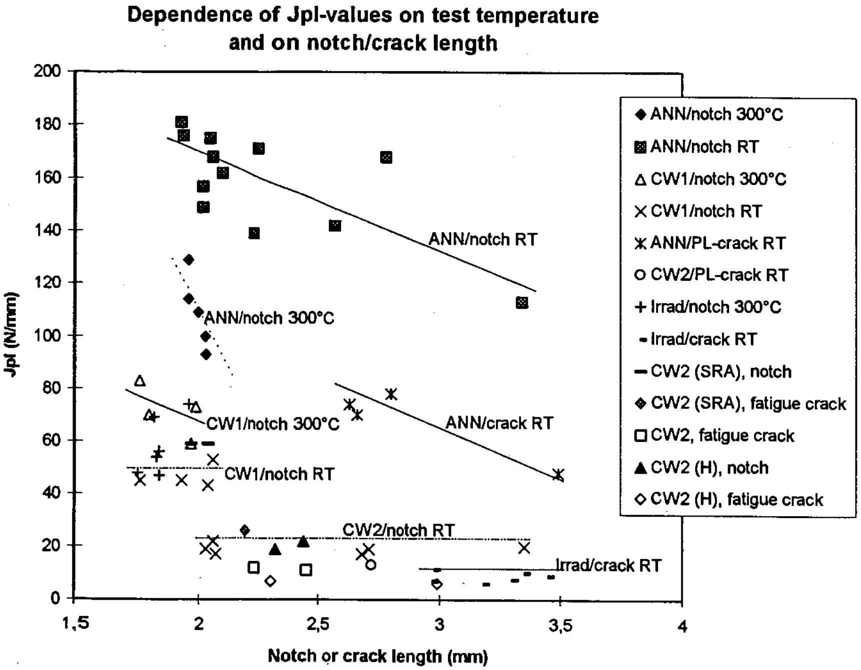

Fig. 7. Experimental J_{pl}-values for annealed (ANN), cold-worked (CW), stress-relieved (SRA), hydrided (H), and irradiated cladding tested at room temperature (RT) and at 300°C without (Notch) and with pre-cracking (Crack).

CONCLUSIONS

Both experimental data and numerical modelling lead to the conclusion that the Pin-Loading (PL) tension test is an actually very promising testing method to provide quantitative evaluation of Zircaloy cladding fracture toughness. The test to test variation of the friction between specimen and holder can provide for practically important case the changes of the *J*-integral value of about few percents. No significant effect of initial radial gap of 0.02-0.07 mm has been revealed experimentally. The sharpening of the notch tip by means of fatigue pre-cracking resulted in lower *J*-integral values for all tested materials. The effect depends on the ductility of the material and is more pronounced in ductile materials. Fatigue pre-cracking is included into procedure for irradiated cladding. Detection of crack initiation in the specimen by means of Direct Current Potential Drop measurements during PL testing is complicated due to wall thinning of the specimen by plastic deformation at the notch or crack tip. Thus, it is reasonable to evaluate the *J*-integral value for thin-walled cladding at the point of the maximum load at the load-displacement curve.

ACKNOWLEDGEMENT

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