Evaluation of Dynamic Fracture Toughness on Reactor Pressure Vessel Materials

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ABSTRACT

A new test method suitable for the dynamic fracture toughness evaluation with a small single specimen has been developed. The method is based on the application of the new pendulum type impact tester equipped with a self-adjusting infra-red(IR)-laser extensometer and fully computerized data acquisition and processing. The testing system contains several unique features, which make the impact testing more appropriate from the fracture mechanics point of view, enabling the determination of the energy-based fracture toughness parameters.

The method has been extensively verified by comparing it to the other methods normally based on the use of the multi-specimen technique. The feasibility study of the testing procedure was performed on different materials.

In this paper some results of the test method verification are shown and the method application on the characterization of the unirradiated and irradiated IAEA phase III correlation monitor materials (A533B Cl.1.) for surveillance programmes are presented.

1 INTRODUCTION

The Charpy impact test provides a convenient means of assessing dynamic material characteristics for quality control and structural safety. It is easy and fast and specimens are inexpensive to produce. Due to space limitations in surveillance capsules, it is also the generally used method for evaluating the effects of radiation embrittlement on reactor pressure vessel materials. However, the application of the conventional impact tester for characterization of dynamic fracture behaviour of materials suffers many drawbacks and limitations. To avoid the drawbacks of normal designs and to make the impact testing more reliable and appropriate from a fracture mechanics point of view, a new pendulum type testing apparatus with advanced instrumentation has been developed and constructed. In this paper the testing procedure is described and the application on the fracture toughness determination of reactor pressure vessel steels is presented.

2 DESCRIPTION OF THE TESTING PROCEDURE

2.1 VTT impact hammer equipped with COD detector

The new pendulum type impact tester makes use of an inverted test geometry. This means that the specimen rests against the instrumented tup and the ends of the specimen are exposed to the impact (Fig. 1). The purpose of the geometry inversion is to reduce the inertial and specimen oscillation effects in the recorded load data (Rintamaa et al., 1984). Further, the new tester contains several novel features which make the impact testing more suitable for determining fracture mechanics parameters. These features include, e.g., choice of two specimen sizes - normal Charpy-size (10x10x55 mm) and larger 3PB (10x20x100 mm) specimens - and an optical COD detector mounted relatively close to the specimen (this is possible because of the stationary instrumented tup, nearly stationary rotation axis of the specimen, and the double pendulum (Fig.1). A more detailed description of the new instru-

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mented impact tester has been presented by Rintamaa et al. (1984).

The measurement of crack opening displacement (COD), understood as a distance between the notch flanks of a standard Charpy V-notch specimen, is performed by the optical COD measuring device installed to the new impact tester (Fig.1). The device consists of two units: an infra-red laser, whose beam is directed to the notch and surrounding area of the specimen front surface, and a stray-light detector, which is focused on the light scattered back from the specimen. This reflected light is used for accurate COD detection. The device has been constructed so that the voltage signal from the stray-light detector is linearly dependent on COD up to the value of 1.4 mm.

2.2 Determination of dynamic fracture toughness parameter

The method generally used for the evaluation of dynamic fracture toughness values is based on the measurement of the stored energy up to the crack initiation. The main problem with this method is to detect the moment of true ductile crack initiation, without extensive specimen instrumentation. In cleavage initiated fracture, the fracture toughness up to some specific limit can be derived fairly reliably using the energy at the cleavage load drop point. Ductile crack growth, however, starts prior to the limit load without showing a load drop. Consequently, the fracture toughness based on the energy up to cleavage fracture initiation can be unconservative.

In the new tester, crack initiation is detected by means of the COD detector. At the beginning of the loading COD signal is a linear function of time but at a certain stage deviation from the linearity occurs as can be seen in Fig. 2. This sudden change in the slope corresponds to the onset of macroscopic ductile crack initiation. The various phases in the test record can be considered by a double displacement ratio (DDR) which is the ratio of plastic crack opening displacement change ($dCOD_p$) and plastic specimen deflection change (dD_p) (Rintamaa et al. 1989).

After determining the crack initiation point on the load-time/load-deflection curve, the stored energy needed for fracture initiation can be derived. This is the area below the load deflection curve from the start of test to the onset of crack propagation (cleavage or ductile). The fracture initiation toughness value can be calculated using the stored energy value (E_{id}) in the Rice's equation as shown in Fig. 2. The graphs in the figure is a typical example of the final test plots.

3. EXPERIMENTAL PROCEDURE

3.1 Validation of the double displacement ratio (DDR) method

Experimental validation of the double displacement ratio (DDR) method was performed by applying the multispecimen technique. The stop block technique was used for the materials with fully plastic fracture behaviour. Different materials were used. One of the materials was a reactor pressure vessel steel (A533B Cl.1 steel plate with the code designation JRQ) from the IAEA coordinated Research Programme on "Optimizing of Reactor Pressure Vessel Surveillance Programmes and Their Analyses" (Wallin et al, 1989).

The evaluation of the fracture resistance curve by the multispecimen technique was also based on the tests in the transition region, where cleavage fracture is preceded by ductile tearing. Some specimens made of the IAEA monitoring material were tested in this way. In these tests the J-integral was calculated by the stored energy at the cleavage fracture initiation. The crack growth was measured from SEM-photos taken from the fracture surfaces. The stretch zone width (SZW) and the stable crack growth (Δa_s) was separately measured.

Besides the verification of the DDR method, the effect of the side-grooves on the dynamic fracture toughness was studied.

3.2 Testing of reactor pressure vessel steels

The materials currently used for the application of the DDR method are ASTM A533B Cl.1 steels from the ongoing IAEA Research Programme. In this study two different steels with the code designations JRQ and JFL were selected. Precracked Charpy V (PCVN) specimens were not side-grooved except some JRQ plate samples with 20%. Specimens were tested with a VTT instrumented impact hammer. The impact velocities were 1.9, 2.8 and 3.6 m/s. For each test the load, energy and COD were plotted as a function of specimen deflection.

For studying the radiation embrittlement, samples (precracked Charpy V specimens) from the JRQ and JFL steel plate were irradiated in the Loviisa nuclear power plant.

4. RESULTS AND DISCUSSION

4.1 Validation of the douple displacement ratio (DDR) method

In the verification work of the new dynamic fracture toughness test method the J_{id}-values are compared to the critical values of the fracture resistance curves obtained by multi-specimen test technique. The results for the IAEA JRQ plate are given in Figs. 3. The left side in the figures represents the ductile fracture initiation toughness (J_{id}) obtained with the new DDR method, and the right side the J-R curve obtained by either the stop block or the test specimen data where some amount of stable crack growth had occured before cleavage fracture. The ductile fracture initiation values determined via the multispecimen method seems to agree very well with the average J_{id} -value of each material.

4.2 Application of the DDR method on reactor pressure vessel materials

4.2.1 The effect of side-grooves on the dynamic fracture toughness

Dynamic fracture toughness values of the PCVN specimens without and with 20 % side-grooves are presented in Fig 4. The results indicate that the side-grooves have almost no effect on the ductile fracture initation toughness. In some specimens with 20% side-grooves, the J_{id} -values in the upper self region were somewhat higher than the values with the non-side-grooved specimen. The J-value at the maximum load was remarkably lowered by the side-grooves. In all tests performed with the side-grooved specimen, the side-grooves shifted the maximum load to the smaller deflection values which decreased the stored energy from the start of test to the load maximum.

4.2.2 The effect of neutron irradiation on the dynamic fracture toughness

Precracked Charpy specimens made of A533B Cl.1 type steels (codes JRQ and JFL) were irradiated in the Loviisa nuclear power plant to average fluences of 1.5 and 1.9 x 10^{19} 1/cm^2 (E > 1 MeV), respectively. The fluence rate was approximately 1.6 x 10^{11} 1/cm^{2}s.

The preliminary fracture toughness results (J_{id}, J_{Fmaxd}) for JRQ and JFL materials are given in Figs 5 and 6. The figures show that the transition temperature shift of the JRQ material is much higher than that of the JFL material as expected also on the basis of the intrinsic impurity contents of the materials.

The figure 4 shows that the upper shelf ductile fracture initiation toughness J_{id} is increased but the value J_{Fmaxd} is reduced by the irradiation. The increase of the J_{id} value is apparently due to the enhanced yield strength of the irradiated material.

5. SUMMARY AND CONCLUSIONS

A new single specimen test method for evaluating dynamic fracture toughness parameters has been developed. The double displacement ratio (DDR) method is based on the measurement of the stored energy up to the crack initiation and on the calculation of the corresponding energy-based J-value. The DDR method was validated by methods based on the multispecimen technique. In addition, the method has been applied to the fracture toughness evaluation of the reactor pressure vessel steels. In this context, the effect of specimen side-grooves, specimen size and neutron irradiation on the fracture toughness have been studied. The investigations are continuing. For the time being, the following conclusions can be drawn:

- The new DDR method gives the same values for the ductile fracture initiation toughness as the multispecimen technique. The good agreement is observed for the application of different materials.
- The effect of side-grooves (20%) on the ductile fracture initiation is nearly negligible. However, the side-grooves lower remarkably the J value at the load maximum, particularly in the upper shelf region.

- The transition temperature shift of the fracture initiation toughness J_{id} caused by the irradiation is clearly different in JRQ and JFL materials. The J_{id} transition temperatures of the reference and irradiated materials are nearly the same as the Charpy-V transition temperatures.
- Irradiation increases the ductile fracture initiation toughness in the upper shelf region but decreases the J_{Fmax} -values calculated from the energy at the load maximum point.

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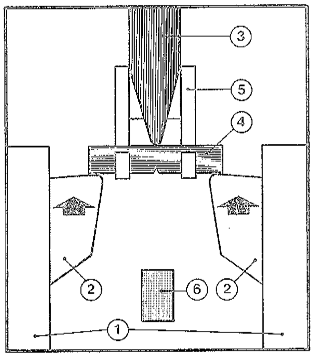

Fig. 1. Principle of the inverted impact testing geometry applied in the new testing facility.
1 = Moving hammer
2 = Anvil (span width 40 or 80 mm)
3 = Instrumented tup
4 = Specimen
5 = Mechanical specimen lifting device
6 = Optical COD measuring device

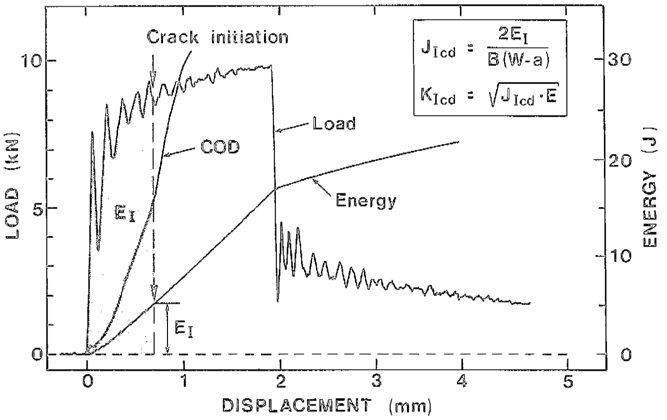

Fig. 2. Typical final test results and method to determine the dynamic fracture toughness based on the determination of crack initiation energy by the optical COD device.

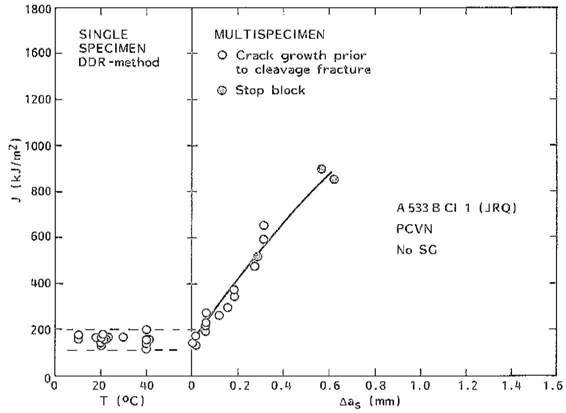

Fig. 3. Comparison of the ductile fracture initiation toughness obtained by the single specimen DDR method and the multispecimen method. Precracked Charpy V (PCVN) specimens with side-grooves a) and without side-grooves b) were made of the A533B Cl.1 steel (JRQ).

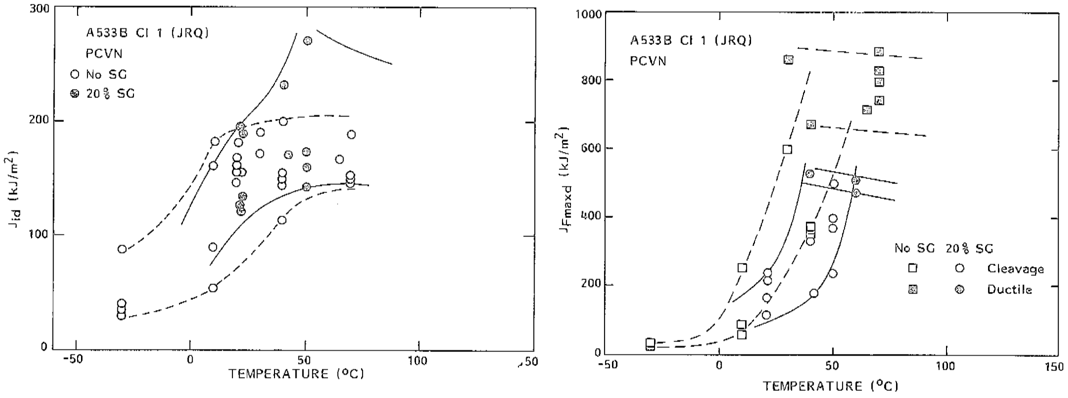

Fig. 4. The effect of the side-grooves (20%) on the dynamic ductile crack initiation toughness (J_{id}) a) and J-values corresponding to the maximum of the load deflection curve (J_{Fmax}) b). Precracked Charpy (PCVN) specimens were taken from the centre part of the JRQ-plate made of a A533B Cl.1 steel.

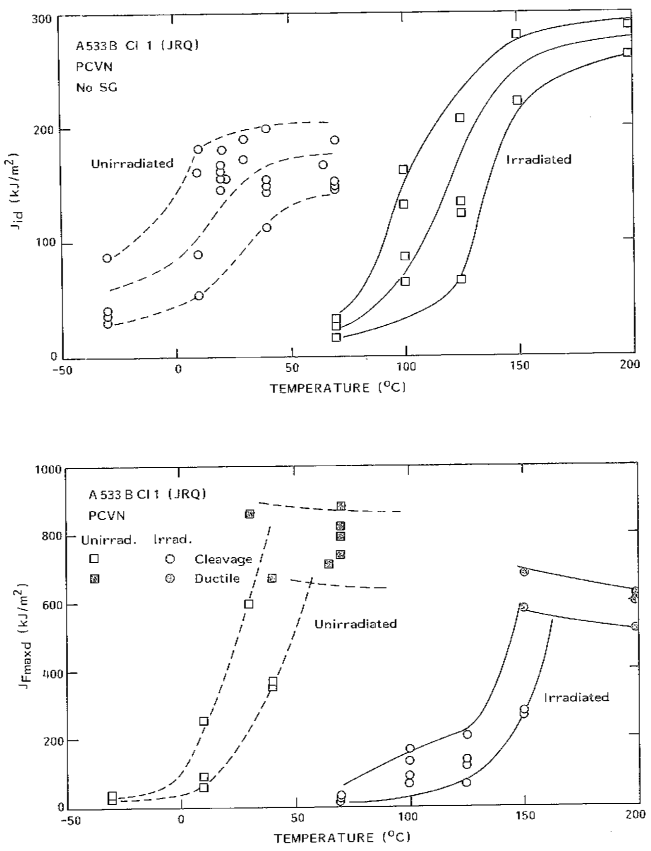

Fig. 5. The effect of the neutron irradiation on the fracture toughness parameters (J_{id} and J_{Fmax}). Precracked Charpy (PCVN) specimens were taken from the JRQ-plate of a A533B Cl.1 steel.

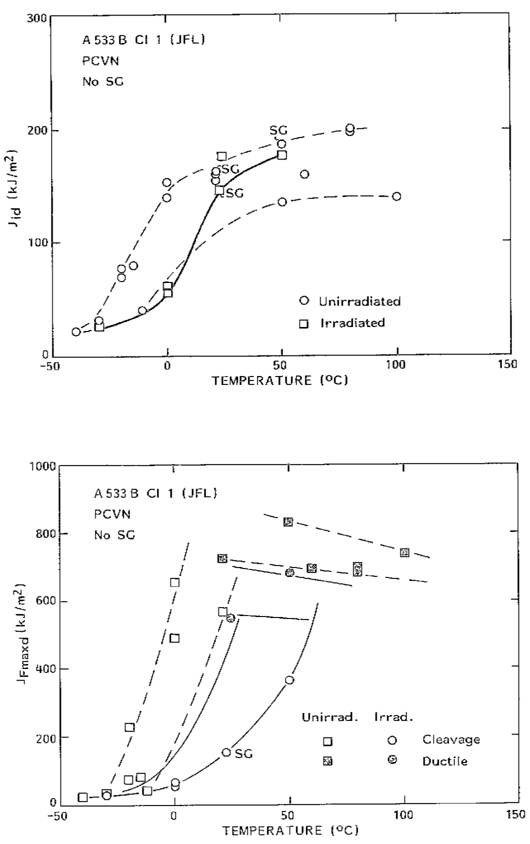

Fig. 6. The effect of the neutron irradiation on the fracture toughness parameters (J_{id} and J_{Fmax}). Precracked Charpy (PCVN) specimens were taken from the JFL plate of a A533B Cl.1 steel.