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REACTOR STRUCTURAL MATERIALS: REACTOR PRESSURE VESSEL STEELS

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Background

Safe operation of nuclear power plants relies primarily on the integrity of the reactor pressure vessel. Neutron exposure induces temperature dependent embrittlement of the vessel and alters the mechanical properties of the vessel materials. It is, therefore, of prime importance to monitor the material degradation by surveillance programs. On the other hand, integrity analysis is based on regulatory concepts that were mostly established on an empirical basis. During the last decade, a major milestone was reached by acknowledging the possibility to measure fracture toughness with small specimens and by the use of the master curve approach to account for specimen size effects. Reconstitution technology is used to remanufacture specimens from archive and surveillance specimens in order to directly measure fracture toughness of the material.

In 1999, the convention Electrabel-SCK•CEN was renewed for 4 years. The EN45001 accreditation for the treatment and analysis of Nuclear Power Plant (NPP) surveillance capsules and for the use of the reconstitution technique was confirmed for 1999 and 2000.

Objectives

In support of Reactor Pressure Vessel (RPV) integrity assessment the general objectives are

- To complete the fracture toughness data bank of various reactor pressure vessel steels by using precracked Charpy specimens that were tested statically as well as dynamically;
- To implement the enhanced surveillance approach in a user friendly software;
- To improve the existing reconstitution technology by reducing the input energy (short cycle welding) and modifying the stud geometry;

To investigate the use of sub size specimens (3x4x27 mm-PCCv and Ø4x27 mm-CRB) for fracture toughness testing.

In 1999, the fracture toughness databank was enlarged and emphasis was put on examining RPV steels with particular behaviour. One of the major corner stones of the Enhanced Surveillance Strategy is the use of reconstitution technology to manufacture Charpy specimens for the determination of static, as well as, dynamic initiation fracture toughness in the transition range. The Charpy geometry is also used for measuring the crack resistance behaviour of RPV steels at upper shelf temperatures (up to 300 °C).

Fracture Toughness Characterisation using small size samples (PCCv)

A reactor pressure vessel steel (20MnMoNi55), characterised with various types of cleavage initiators in the ductile-to-brittle transition regime by GKSS, has been studied both experimentally and analytically. Fracture toughness tests on precracked Charpy specimens have been performed in the transition region, and the applicability of the Master Curve analysis has been verified using:

- the conventional Master Curve methodology;
- the Generalised Maximum Likelihood (GML) method;
- the Monte Carlo method.

Based on the investigations performed, it was found that the Master Curve methodology is fully applicable to the 20MnMoNi55 steel, even in the presence of different cleavage triggering mechanisms.

Toughness tests on Pre-Cracked Charpy-v (PCCv) and 0.5T-CT specimens have been performed on an RPV low upper shelf A533B steel. The aim was to assess whether PCCv specimens yield significantly unconservative results with respect to 0.5T-CT samples of this material: the results, which have been analysed taking also into account the uncertainty of the measured parameters, show that the non-conservatism of PCCv samples is consistent although the deviation remains within the statistical uncertainties. This difference, which in terms of reference temperature amounts to 10 to 15 °C, is in line with the technical literature on the subject.

Reconstitution technology

Reconstitution technology is being successfully used at SCK•CEN for a decade. However, improvement of this technology becomes necessary to reduce the machining time, radioactive material transport between hot cells (In view of the use of the new machining equipment in BR2 hot cells, the radioactive material transportation will be optimised), waste and costs. The temperature control inside the insert material has also received more attention. Three main aspects were investigated in 1999:

- short cycle welding: This procedure allows a significant reduction of the temperature in the insert material without altering the overall resistance of the welds. Preliminary tests gave satisfactory results.

- dual reconstitution: The equipment was modified to allow welding of both studs before any machining is done. It is found that the temperature distribution remains unaffected by this procedure with a good quality of the welds.
- optimisation of the stud configuration: In order to minimise the machining time and the waste production, the use of a squared cross section 11x11 mm² stud is investigated. Preliminary tests gave satisfactory results. The temperature will be affected by the use of short cycle welding.

The combination of the three modifications, namely dual reconstitution with square studs with short cycle welding is the ultimate goal.

Miniaturisation

The reliability of fracture toughness measurements in the ductile-to-brittle transition region using two types of miniature specimens, the sub-size precracked Charpy specimen (dimensions 3x4x27 mm) and the miniaturised Cracked Round Bar (dimensions Ø4x27 mm) has been assessed. Comparison with reference data obtained on larger and conventional-type specimens was performed for two reactor pressure vessel steels. The data have been found to be in good agreement (Figure 1), but for miniature specimens the loss of constraint considerations can force to test at very low temperatures, approaching lower shelf conditions. The situation is, however, more favourable for the mini Cracked Round Bar, for which an analytical loss of constraint correction is readily available.

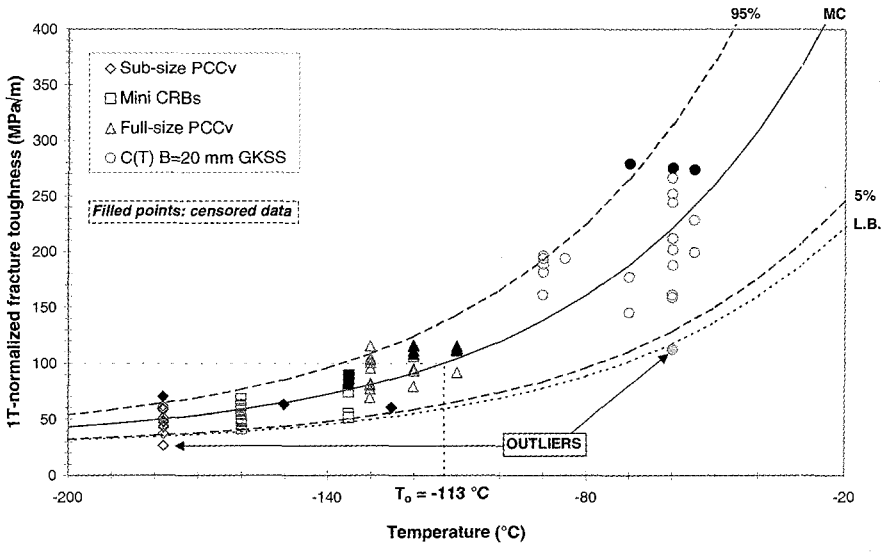
A simple tool for selecting the optimal test temperature has been proposed and has been checked against experimental results.

Qualification of forces measured with an instrumented striker

Forces measured during instrumented impact tests are used for different purposes, including the assessment of irradiation effects using the "Enhanced Surveillance Approach". Thus, confidence in the calibration procedure to convert tup strain-gage output into force applied on the test specimen must be verified. In order to establish the best way to proceed, the following three different strategies have been compared and assessed:

- static calibration on a flat surface;
- static calibration on a "grooved" support;
- dynamic force calibration (based on the equivalence of the energy values given by the pendulum encoder and calculated from the test record).

The assessment was based on the comparison between maximum forces obtained in quasi-static and dynamic (impact) tests, using an Aluminum alloy that is quasi strain-rate insensitive. The results obtained show that the dynamic force calibration is the most reliable way to evaluate forces during an instrumented impact test.



Comparison between miniature and standard size samples for the 20MnMoNi55 steel.

Dynamic tensile testing

The reliability of a novel technique for dynamic tensile testing, by means of a gripping device used in conjunction with an instrumented pendulum, has been assessed using three different materials (two steels and an Aluminum alloy). For each material, the strain rate dependence of the tensile properties had been previously assessed by means of conventional tensile tests performed with various crosshead displacement rates or using data available from international Round-Robin activities.

The results have shown that the innovative technique is very sensitive to the influence of friction and extraneous bending components, as well as heavily depending on the quality of the instrumented striker calibration. On the other hand, it has been demonstrated that strain rates equivalent to those of conventional Charpy tests can be easily achieved using a servohydraulic machine, without having to resort to the use of this pendulum adapter.

Crack Resistance (J-Da) Measurement using Precracked Charpy Specimens

The objective of this work is to assess the use of small specimens to determine the initiation toughness and the crack resistance behaviour of reactor pressure vessel steels. The multiple specimen test technique (MST) and the single specimen test technique using the unloading compliance technique (UCT) are compared. The JRQ IAEA monitor RPV steel was selected for this investigation at upper shelf temperature (200 °C). The one-inch compact tension (CT) geometry is selected because of its validity according to prevailing standards (ASTM E1737). Precracked Charpy V-notch (PCCv) specimens were tested using the unloading compliance test technique. Some of the specimens were tested without unloading to be used for a multiple specimen analysis. The results show an overall good agreement between the different sizes and the two techniques. However, the MST exhibits less scatter in comparison to the UCT.

3D Finite Element Modelling of Precracked Charpy for Loss of Constraint Analysis

Fracture toughness testing in the transition regime was recently standardised by American Society for Testing and Materials (ASTM E1921-97). This standard proposes a normalised way to analyse test results of standard specimens and to determine a single parameter for ferritic steels in the transition range, the reference temperature T_0.

Nevertheless, published literature shows that the PCCv specimen, analysed using ASTM 1921-97, generally shows a 10 °C lower reference temperature than standard specimens. According to the inherent scatter in the transition regime, this difference is small but systematic. The reasons of this 10°C difference can be:

- a non adequate formulation to derive the fracture toughness from the load displacement record;
- a different level of constraint in single edge notch bend SE(B) and C(T) geometry's;
- a different level of constraint due to side grooving;
- a different level of constraint due to the width-to-thickness ratio (W/B) which is equal to 1 for PCCv and 2 for Compact Tension (CT);
- an inadequate size limit defined to avoid loss of constraint (M=30 according to E1921-97);
- a lower reference temperature for lower test temperature, as PCCv specimens are generally tested at lower temperatures than large specimens to increase-number of valid data.

The formulation and constraint issues can be addressed through 3-dimension finite element calculations of a fracture toughness test in the transition region.

In a first step, an adequate mesh, boundary conditions and finite element modelling of a PCCv were selected and evaluated. After this preliminary study, the results of the PCCv calculations will be used to analyse:

- the relation between the load point displacement and the crack mouth opening displacement;
- the h-factor formulation;
- the size effect;
- the loss of constraint and the possible corrections;
- the effect of side grooving.

Microstructure Research: Internal Friction

Internal friction research was carried out within the frame of a Ph.D. project, which has been brought to conclusion. Its main findings are the following:

- the interstitial content of a C-Mn pressure vessel steel can be determined and the effect of irradiation and/or ageing investigated;

- a wide range of dislocation-and/or-defect type mechanisms has been proposed to explain the observations after cyclic deformation; the effect of irradiation, thermal ageing and post-irradiation annealing is to influence the dislocation mobility and/or dislocation segment length;
- an important quantity, the yield stress of the material, can be determined on the basis of amplitude-dependent (non-linear) internal friction. The results are in excellent agreement with measurements of the yield stress from static tensile tests and with a model of the yield stress taking into account short- and long-range dislocation defect interactions including those proposed to explain the results after cyclic deformation.

In summary, the research has shown the microstructural internal friction technique to be a non-destructive brother to tensile testing in the realm of phenomena of yielding. The technique is furthermore highly sensitive to dislocation-and/or-defect interactions and has the potential of both qualifying and quantifying the processes involved thereby contributing greatly to damage modelling.

Radiation Effects on RPV steels irradiated in Chivas

This work was performed to support the understanding and modelling of damage mechanisms induced by irradiation. The Chivas irradiation programs in the BR2 reactor created the opportunity to irradiate a large number of reactor pressure vessel steels under well-controlled conditions. Among them were the BR3 vessel plate and the Yankee Rowe coarse grain surrogate materials, YA1 and YA9. Two specially dedicated irradiations were carried out: Chivas-2 and Chivas-3. The irradiation temperature is 260°C -the operation temperature of BR3 and Yankee Rowe reactors- while the fast neutron fluence is about 4.4 10^{19} and 8.8 10^{19} n/cm^2 for Chivas-2 and Chivas-3, respectively. Our data were compared to those of the Yankee Atomic Electric Company (YAEC) test programs on YA1 and YA9 steels. The main results can be summarised as:

- The recovery of the BR3 vessel after wet-annealing at 343°C/1 week was found to be inefficient;
- The Ni-content does not seem to have the effect attributed to this element according to regulatory evaluation;
- The Chivas results on coarse grain YA1 and YA9 surrogate material are in line with those of YAEC results.

BAS – SCK•CEN Agreement

The co-operation agreement between SCK•CEN and the Bulgarian Academy of Science (BAS), sponsored by the Belgian Office for Scientific, Technical and Cultural Affairs (OSTC) was extended by financially supporting a Bulgarian visiting scientist, through OSTC, working in the field of laser reconstitution technology. Part of the work on reconstitution was performed within this framework. Together with IMS (the Bulgarian Institute for Material Science) on irradiation of a mock-up surveillance capsule in Koslodui 6 is in preparation. The aim is to look at the temperature and fluence distribution at the surveillance position.

EU R&D Programs: TACIS

The development of advanced methods for the evaluation of irradiation embrittlement of WWER 1000/320 type (a consortium gathering Belgatom, EdF, Rossendorf and Siemens KWU). The role of SCK•CEN is concentrated on fracture toughness testing evaluation, dosimetry and temperature monitoring.

EU R&D Programs: REFEREE

The degradation of reactor pressure vessel steels is indicated by material hardening (increase of the yield stress) and an increase of the ductile-to-brittle transition temperature (DBTT). The change of DBTT is usually monitored by Charpy impact testing. It is assumed that the shift of the Charpy impact transition curve is equal to the shift of fracture toughness. However, this is not always the case. To address this issue, this project aims to obtain an in-depth comparison of dynamic Charpy-V shifts, dynamic fracture toughness shifts and quasi-static fracture toughness shifts. Moreover, the basic understanding of the relation between the different measures of DBTT and in particular the materials-specific differences was investigated. The SCK•CEN part of the program was finalised and submitted to the co-ordinator.

EU R&D Programs: RESQUE

The EC international Reconstitution Techniques Qualification and Evaluation to study Ageing Phenomena of Nuclear Pressure Vessel (RESQUE) project aims at optimising and normalising reconstitution techniques and was in its final phase. In 1999, all work packages were finalised and a presentation

was given to the FISA '99 symposium. The overall information is being recapitulated in a "Proposal for Code of Practice for Reconstitution of Irradiated Charpy-type Specimens", to be issued early 2000.

EU R&D Programs: PLAN

The activity within PLAN (Plant Life Assessment Network) has continued in 1999 with two meetings, held respectively in Leeds (April) and Lisbon (September). Within the Cluster Task 1 (Innovative Test Techniques), a draft version of the Compendium of Innovative Test Techniques has been produced and circulated, including reviews for the different groups. SCK•CEN provided the review for the group of techniques related to the Measurement of Mechanical Properties.

IAEA – VVER-440

The "Round Robin Exercise on WWER 440 RPV Weld Material Irradiation, Annealing and Re-embrittlement", was almost finalised. The objective of SCK•CEN to contribute to this round robin on WWER-440 weld material is twofold:

- to gain experience in the field of WWER-440 steels;
- to analyse the Round Robin data according to the models used and developed at SCK•CEN in order to check their validity and applicability.

The VVER-440 weld was successfully irradiated (I), irradiated-annealed (IA) and irradiated-annealed-reirradiated (IAR) in the BR2 reactor under well-controlled conditions (CHIVAS-7 and 8).

The embrittlement of this material is assessed through different mechanical tests: the Charpy and mini Charpy V-notch impact tests, tensile tests and fracture toughness tests using precracked Charpy specimens. The weld is characterised in four conditions: un-irradiated, irradiated (I), irradiated and annealed (IA) and irradiated annealed and re-irradiated (IAR).

The testing program, which contains about 240 specimens, was completed at 90% in 1999. A complete recovery of the transition temperature shift and an over-recovery of the upper shelf are observed. The re-irradiation embrittlement kinetics is very similar to the first irradiation behaviour. Therefore, a simple lateral shift model describes accurately this material. The test results are being reported and will be presented in 2000.

IAEA CRP-IV

Within the IAEA CRP-IV programme on "Assuring Structural Integrity of Reactor Pressure Vessels", the test results were compared to the CRP-III data. This comparison clearly shows that while the material strengthening as measured by the tensile properties are similar, the Charpy impact data are more degraded in the Doel-IV capsule than in Material Test Reactor (MTR) capsule (Chivas-6). By contrast, the fracture toughness in the Chivas-6 irradiation is significantly larger than in the Doel-IV capsule. These data support the idea that irradiation damage is very much dependent on the irradiation conditions and that strengthening-embrittlement relationship is not a one-to-one correlation.

Partners

Electrabel

Electric Power Research Institute (EPRI)

Oak Ridge National Laboratory (ORNL)

Tractebel Energy Engineering (TEE)

United States Nuclear Regulatory Commission (USNRC)

Rijksuniversitair Centrum Antwerpen (RUCA)

Vrije Universiteit Brussel (VUB)

Customers

Electrabel

Tractebel Energy Engineering (TEE)

Centro Technológico da Marinha em São Paulo (CTMSP)

European Commission (EU)

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