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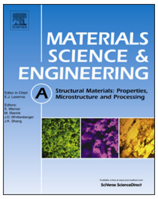

# Quantification of brittle-ductile failure behavior of ferritic reactor pressure vessel steels using the Small-Punch-Test and micromechanical damage models

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ABSTRACT

Two German ferritic pressure vessel steels are examined in the brittle to ductile transition regime as a function of temperature and irradiation. The experiments are done by a miniaturized Small-Punch-Test in hot cells within the temperature range of $-185\,^{\circ}$C up to $70\,^{\circ}$C. From the load–displacement curve of the SPT, the yield curves and parameters of both a non-local Gurson-Tvergaard-Needleman ductile damage model and a modified Beremin model are identified. The influence of temperature and irradiation on the model parameters is analyzed. All parameters are verified by comparison with results from standard test methods. The parameters, identified from SPT, are used to simulate the failure behavior in standard fracture mechanics specimens. In the upper shelf, the non-local GTN-model is applied to simulate crack resistance curves, from where the fracture toughness data could be successfully predicted. In the lower shelf, the Weibull-stress of the specimens was computed to find out the statistics of fracture toughness values. Finally, the modified Beremin model and the non-local ductile damage model were combined to evaluate the failure of fracture specimens in the brittle-ductile transition region. This way, an acceptable agreement with Master-curve data for non-irradiated steels could be achieved in the whole temperature range.

## 1. Introduction

To ensure the safety of light water reactors, both exact calculation of the mechanical stresses and realistic modeling of the deformation and failure behavior of the used ferritic steels are required. Due to micro-defects and inhomogeneities in the microstructure of ferritic steels, deformations can cause the formation of microcracks [1], for example by breaking of carbide particles [2]. In the brittle and brittle-ductile transition region trans- or intergranular cleavage fracture initiates at these microcracks, leading to macroscopic brittle failure at sufficiently high stress levels. In the upper shelf microvoids nucleate as a result of plastic deformation. Further loading leads to the growth and coalescence of voids. The associated irreversible changes in the microstructure are referred to as ductile damage.

Damage mechanics can be used to assess the integrity of a mechanical structure with micro-defects by evaluating local criteria only. The concept of Local Approach [3] is, in contrast to the methods of fracture mechanics, applicable to any structure. However, the application of Local Approach for the determination of fracture characteristics requires precise knowledge of the materials hardening and softening behavior. Because of the neutron irradiation embrittlement [4] during the operation of nuclear power plants and the associated scatter of fracture properties, statistical methods must be used for the characterization of material properties. This requires a large number of experiments. Therefore, testing of miniaturized specimens is predestinated for determining the current state of the material.

The Small-Punch-Test (SPT) is one of the most important miniaturized test procedures used in the reactor safety research. It has been developed to monitor the shift of the brittle-ductile transition temperature due to neutron irradiation during the operation of nuclear power plants [5–9]. The SPT offers excellent possibilities for monitoring safety-related components in power plants, since the small specimens can easily be sampled. The Small-Punch-Testing derive is simply installed in standard testing machines. To adjust a desired temperature requires heating or loading of a minimal volume only. The load–displacement curve (LDC) measured in the SPT can be divided into distinctive parts as depicted in Fig. 3, which depend on the elastic, plastic and damage

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mechanical properties of the material [10–13]. Therefore it contains all information for the identification of these material properties. However, as with all miniaturized test methods, the determination of transferable material properties from experimental results is a challenging task.

In this paper, two ferritic reactor pressure vessel (RPV) steels are examined in the entire toughness region, covering brittle, brittle-ductile and ductile region. The parameters of mechanical models describing the hardening and softening behavior of the materials are identified from the SPT with the help of Neural Networks and parallel optimization algorithms. Fracture mechanical parameters are calculated following the concept of Local Approach.

## 2. Experimental data

This section provides a brief overview over the experimental data that provides the basis for the parameter identification method presented in this paper, the experimental results have partly been published in [12,13].

The experiments were carried out at the Forschungszentrum Dresden-Rossendorf (FZD). Remnants of Charpy specimens of two reactor vessel steels, A533B Cl.1 (IAEA JRQ) and A508 Cl.3 (IAEA JFL), were used for manufacturing and preparing Small Punch Test (SPT, see sketch in Fig. 3) specimens. Both non-irradiated and irradiated (irradiation levels see Table 1) specimens of the steels were tested extensively using the SPT to investigate the influence of temperature and irradiation on the material properties. The complete test program is shown in Table 2.

Two major influences were observed from the measured load–displacement curves: First, for both irradiated and non-irradiated materials higher forces are measured as the test temperature is decreased, while the observed displacements at failure diminish. Second, irradiation leads to embrittlement of the material, reflected by the expected shift of the measured curves. In [12,13] the type of failure was determined visually from remains of the tested specimen and with the help of SEM fractography of the fracture surface. It was shown that the test program covered the complete range of brittle, ductile and brittle-ductile transition region. Furthermore, shape and size of the fracture surface of tested SPT specimens depends on the failure mode: there is one single crack with a circular shape in the ductile region while there are several straight cracks in the brittle region.

The *specific* fracture energy, i.e. the work done up to specimens failure related to the size of the resulting fracture surfaces, is shown in Fig. 1. A clear shift of the ductile-brittle transition temperature $T_0^{\mathrm{SPT}}$ is observed for the material JRQ, while the specific fracture energy of the material JFL is less sensitive to neutron irradiation. Here the temperature at which the specific fracture energy reaches a mean value between the ductile and brittle region is understood as ductile-brittle transition temperature $T_0^{\mathrm{SPT}}$. In the non-irradiated state both materials JFL and JRQ show little differences regarding the observed failure mechanism.

**Table 1**
Irradiation levels of the tested RPV steels ($F_{\mathrm{ne}}$ in $10^{18}$ neutrons/cm$^2$ ($E > 1$ MeV)).

| RPV steel | Irradiation level | Neutron fluence $F_{\mathrm{ne}}$ | Designation |
|---|---|---|---|
| JRQ | Low | 7.28 | RH6 |
| | Medium | 54.85 | RH7 far (cf) |
| | High | 98.18 | RH7 close (cn) |
| JFL | Low | 6.52 | RH6 |
| | Medium | 51.21 | RH7 far (cf) |
| | High | 86.69 | RH7 close (cn) |

**Table 2**
SPT test program for the RPV steels JFL and JRQ (numbers of tests; (b)-brittle, (t)-transition, (d)-ductile).

| JFL | Test temperature $T$ | −185 °C | −175 °C | −150 °C | −135 °C | −125 °C | −105 °C | −80 °C | 22 °C |
|---|---|---|---|---|---|---|---|---|---|
| Non-irradiated | | 6 (b) | 13 (b) | 11 (b) | 4 (t) | 8 (t) | 14 (t) | 10 (d) | 4 (d) |
| RH6 | | | | | 20 (b) | | | 20 (t) | 5 (d) |
| RH7 far | | | | | 20 (b) | | | 19 (t) | 5 (d) |
| RH7 close | | | | | 19 (b) | | | 5 (t) | 5 (d) |

| JRQ | Test temperature $T$ | −150 °C | −140 °C | −120 °C | −100 °C | −70 °C | −50 °C | −30 °C | 22 °C | 70 °C |
|---|---|---|---|---|---|---|---|---|---|---|
| Non-irradiated | | 2 (b) | 2 (b) | 2 (t) | 3 (t) | 5 (d) | 5 (d) | 5 (d) | 5 (d) | |
| RH6 | | | | 21 (b) | | 19 (t) | | 20 (d) | | |
| RH7 far | | | | | | 19 (b) | | 20 (t) | 9 (d) | |
| RH7 close | | | | | | | | 19 (b) | 17 (t) | 12 (d) |