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Small punch tensile testing of curved specimens: Finite element analysis and experiment

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ABSTRACT

The Small Punch (SP) technique is a miniature test used for characterizing irradiated materials or when a testing material is available only in small quantities. In this work Finite Element (FE) models are developed to support the parametric analysis of SP fuel cladding tube specimens in comparison to standard flat ones. FE analysis shows that there are practically no differences between circular and rectangular flat specimens. The tube specimen results in only slightly higher maximal force (F_m). However, F_m is attained at significantly lower displacements. This is attributed to the curvature of the specimen. The friction linearly increases the F_m and to a lesser extent the displacement at F_m. FE analysis also shows that the yield stress and different hardening, while keeping ultimate tensile strength constant, practically do not affect the F_m. Significant specimen deformation can be expected at already small (0.1 mm) puncher deflection, which could limit the applicability of the small punch test to ductile materials. Varying degree of clamping in the experimental procedure can cause large scatter in the yield stress estimates. In all cases good agreement between the simulation and experimental results was obtained, best with a friction coefficient of 0.2.

1. Introduction

The Small punch (SP) technique is a miniature test developed in Japan and the US in the 1980s [1–5]. SP test can be performed for determining both tensile and creep properties [6]. It is especially suited for: (1) testing materials available only in small quantities, such as novel materials produced in laboratory quantities [7,8], (2) testing specimens from irradiated components [2,4,5], (3) testing of material with local inhomogeneities such as heat affected zones in weldments [9] and (4) estimation of neutron embrittlement [10]. In this work only tensile SP is used.

In the SP tests a small spherical tip or ball ("punch") indents a thin disc type specimen, Fig. 1. The tensile SP tests are performed at a constant displacement rate and the force is measured either as function of displacement of the puncher tip or as a function of specimen deflection i.e. the deflection of the specimen measured on the opposite side of the puncher. In the former case the displacements need to be corrected for the compliance. The latter configuration is recommended by the current European Code of Practice (CoP) [6]. The specimen deflection is measured by a ceramic rod which can also include a thermocouple for controlling the specimen temperature.

A typical force-deflection curve of a tensile SP test is characterized by several zones, e.g. [11], roughly distinguished by different deformation modes of the specimen, Fig. 2. Zone I corresponds to indenting of the specimen surface by the puncher tip and elastic bending of the specimen. In zone II plastic bending spreads through the entire sample. In zone III the specimen behaviour is dominated by membrane stretching while in zone IV necking and cracking occur, decreasing the force and, finally, resulting in a failure.

Due to the changing and non-homogeneous deformation state in the SP specimen, the extraction of the tensile material properties from the force-deflection curve is not a straightforward task and it is still a topic of research [13–16]. Finite Element Analysis (FEA) often needs to be used to better understand the experiments and supplement them. FEA has therefore been used from the beginning for analysing SP tests [1] and is now widely used to gain detailed insight into the SP tests [13,15], including evaluation of applicable theoretical equations [17], crack propagation [18], creep [19] and the significance of specimen displacement definition [20].

Traditionally SP tests are performed on flat specimens. In this work the current FEA support for the SP tests is extended to the curved specimens extracted from a sectioned fuel cladding tube. These tube specimens can be used as a "component test" of nuclear fuel claddings by applying the SP test. To our knowledge FEA assessment of SP test tube specimens has not yet been reported in the literature. Systematic FEA analysis is done to assess the impact of friction, uniaxial tensile

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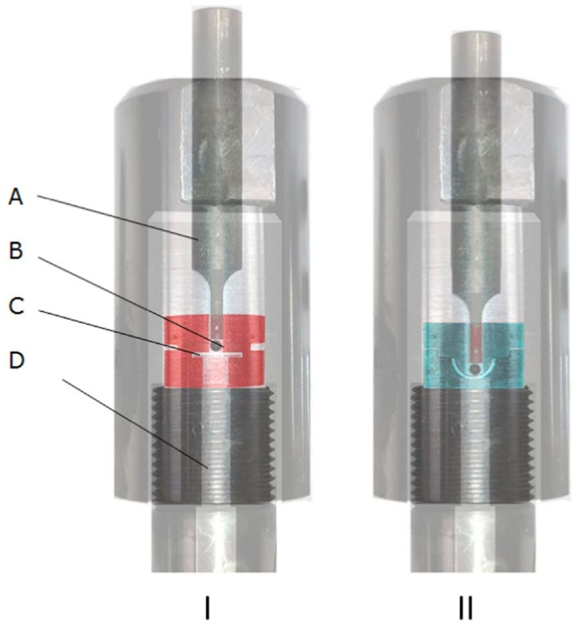

Fig. 1. Typical SP test setup: I. Modified SP test setup for tube specimen: II. A) puncher, B) puncher ball, C) specimen, D) clamping thread.

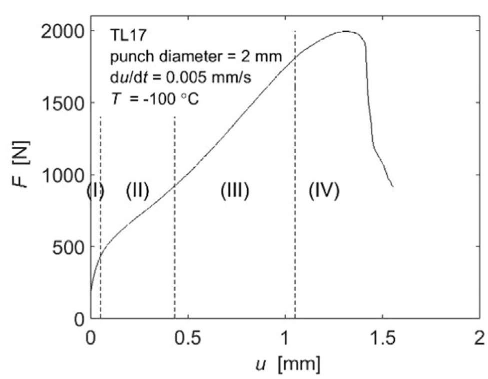

Fig. 2. Force-deflection curve for a tensile SP test of a Grade 91 stainless steel at −100 °C [12].

properties (true stress-strain curves), clamping, specimen type (tube and flat) and dimensions, including different material thicknesses (0.5 and 0.45 mm). FEA simulations are compared with experimental results.

2. Methods

2.1. Material

The material used is a Grade 91 Ferritic/Martensitic steel from the European FP7 MATTER Project. Standard uniaxial tensile test and SP specimens were extracted from a 60 mm thick plate (heat 20057) acquired from ArcelorMittal and produced in full accordance with RCC-MRx nuclear requirements (STR RM 2432) [21]. Grade 91 has been chosen because the literature contains a significant amount of published results on flat specimens and it is easier to manufacture cladding tube specimens from Grade 91 than manufacturing flat specimens from the cladding tubes.

The required minimum yield stress and range of ultimate tensile strength are $R_{p0.2} \geq 445$ MPa and $R_m = 580–760$ MPa, correspondingly. The tensile uniaxial test, conducted at room temperature (RT) with "as received" material state, measured $R_{p0.2} = 510$ MPa and $R_m = 680$ MPa with a fracture strain of $\varepsilon_f = 38.7\%$ [22]. For the FEA simulations, the

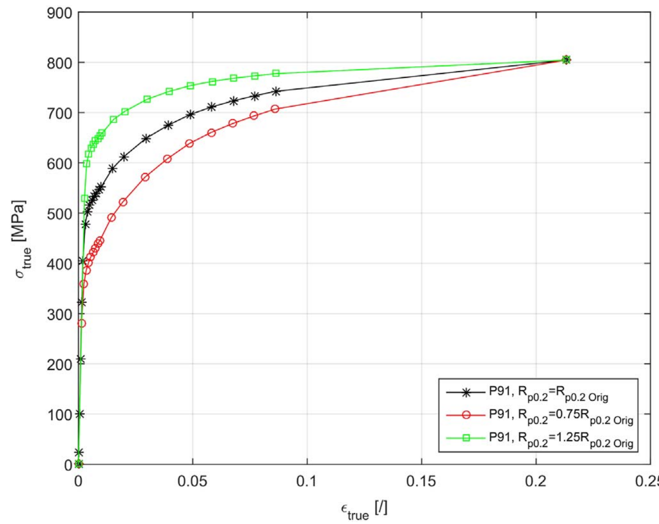

Fig. 3. P91 true stress-strain curves.

true stress-strain curve from the uniaxial test was simplified (point reduction) and labelled as $R_{p0.2\ Orig}$, Fig. 3. Two additional tensile curves were created from the original curve by decreasing/increasing the yield strength by 25%. All three stress-strain curves reach the same ultimate tensile strength strain at the same strain. Ultimate tensile strength was kept constant to decrease the number of independent variables. The modified tensile curves are used for yield strength sensitivity analysis. Beyond 0.2 of strain ideal plastic response is used. The Young's modulus and Poisson ratio of 200000 MPa and 0.3 are used, respectively.

2.2. Experimental method

The SP tensile tests were conducted on an Instron hydraulic testing machine (D-11797) with a 20 kN load-cell. The test set-up allows for high temperature SP testing up to 800 °C. The load cell was calibrated to the load range 0–5 kN to suit the needs of the test type. The tests were performed at room temperature. The puncher was pressed into the specimen at a constant displacement rate of 0.3 mm/min. Force and displacements were recorded. The puncher displacement was obtained from the cross-head displacement by correcting for the temperature dependent compliance by a procedure similar to the one described in [20].

The classical methodology for determining the yield stress $R_{p0.2}$ and ultimate tensile strength R_m from SP test results is to correlate them with "yield" force F_e and the maximum force F_m, Fig. 4. F_m is the maximum force reached during the tests and F_e can for instance be obtained by the "two-secant" method, i.e. finding the intersection of two linear least squares fits for the force-displacement data in the deflection

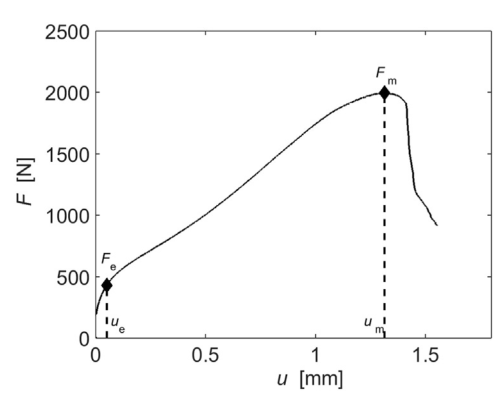

Fig. 4. Locations of the parameters F_m, u_m, F_e and u_e from the force-displacement curve.