Journal of Nuclear Materials 509 (2018) 620–630

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

# Determining the ultimate tensile strength of fuel cladding tubes by small punch testing

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## HIGHLIGHTS

- Small punch test applied to nuclear fuel cladding type specimens.
- Correlation equations applied to curved small punch specimens.
- Correlation coefficients for curved small punch specimens developed.
- Mapping of Fm and vm values from the flat to the curved small punch specimens.

## ARTICLE INFO

*Article history:*
Received 30 January 2018
Received in revised form
16 July 2018
Accepted 19 July 2018
Available online 20 July 2018

*Keywords:*
Small punch
Miniature testing
Claddings
FE simulation
Ultimate tensile strength

## ABSTRACT

The Small Punch (SP) test with constant deflection rate is a miniature technique that can provide estimates on the material tensile properties. Linear correlations are usually used for relating the maximum force and displacement at maximum force, recorded during the SP test, to the ultimate tensile strength. Fitting coefficients used in the correlations are calibrated on data from flat SP specimens. SP test requires only a small amount of testing material which represents a clear benefit when irradiated samples have to be tested. Therefore, there is a considerable interest in using SP for testing fuel cladding material properties. In this study we show that the same correlation equations, albeit with adjusted fitting coefficients, can be used to estimate the ultimate tensile strength from tube SP specimens made out of P91 ferritic/martensitic and 15-15Ti austenitic stainless steel. The calculated fitting coefficients lead to reasonable estimates of the ultimate tensile strength at temperatures of up to 650 °C although the coefficients themselves have been computed at room temperature. The coefficients are more suited for assessing ductile materials as the models used for computing the coefficients do not take into account damage (degradation of the material stiffness) or crack initiation and propagation, observed during the SP tests of brittle material. Finally, using the calculated ratios of maximum forces and displacements at maximum forces, one can map the two values of a given curved SP test to the equivalent flat SP values.

## 1. Introduction

The small punch (SP) test is a simple and quick engineering miniature testing technique [1,2] using disc shaped specimens (diameter $D_S = 8$ or 3 mm and thickness $h_0 = 0.5$ or 0.25 mm). It can be used for providing approximate data of the properties with as small amounts of material as possible. In a SP test, a punch with a hemispherical tip is pushed at constant velocity (typically 0.3–0.5 mm/min) through the specimen, see Fig. 1. The force, F, needed to keep the punch moving at constant velocity is recorded as a function of the displacement, v, of the punch tip. As the punch moves, the directions perpendicular to the force axis are tested simultaneously. The SP test induces a complex stress-strain state in the specimen that depends on the location and varies during the test. Nevertheless the ultimate tensile strength, $R_m$, is often estimated by means of simple linear correlations from the maximum

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https://doi.org/10.1016/j.jnucmat.2018.07.041

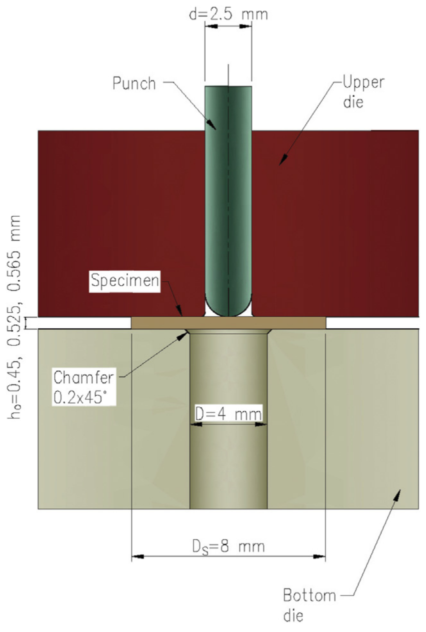

**Fig. 1.** Scheme of a SP test setup with a flat SP specimen. "d" punch diameter, "D" receiving hole diameter, "$D_s$" flat sample diameter, "$h_0$" specimen thickness.

force, $F_m$, and displacement at maximum force, $v_m$, in SP tests [3–7]. These correlations depend on geometry of the test rig i.e. the specimen thickness, punch diameter or the receiving hole diameter.

The SP test is currently being standardized. There is a work-item ASTM WK61832 to develop a new SP test method for metallic materials. Furthermore, there is a pre-normative document, CEN Workshop agreement, the CWA 15672 [1]. An EN standard is currently under development under the auspices of the European Committee for Iron and Steel Standardization (ECISS), Technical Committee 101 (TC101), working group 1 (WG1) [2]. The standardization efforts are currently geared towards the flat SP specimens. However, due to the small amount of testing material required, there is a considerable interest in using SP for testing fuel cladding material properties. The intention of this work is to study the applicability of the correlation equations used for the flat SP specimens to the curved/tube specimens.

In a previous study we have presented a finite element model that allows one to calculate the force-displacement curve for curved SP specimens cut from nuclear fuel cladding tubes [8]. In the current work, we determine the correlation coefficient $\beta_1$ for the tube specimen, allowing one to compute the ultimate tensile strength from a SP test of a tube specimen. Furthermore, we introduce factors that allow one to transfer the maximum force and displacement at maximum force of a tube specimen into equivalent flat specimen values. To that end finite element calculations for varying tube diameters and wall thicknesses are compared for P91 and two batches of 15–15Ti material with different degrees of cold work with the experimental data and the correlation coefficients at room temperature are calculated.

## 2. Methods

In small punch (SP) tests of flat specimens correlations are used for estimating the ultimate tensile strength. The correlations relate the maximum force and displacement at maximum force, recorded during the SP test, to the ultimate tensile strength. The correlations are described in the "Results" section. The correlations have so far been only applied to the flat specimens. To check the applicability of the correlations to the cladding tubes, cladding tube designs from SCK•CEN, the European FP7 MATISSE project and CEA are used. The SCK•CEN design is intended for the Multi-purpose hYbrid Research Reactor for High-teach Applications (MYRHHA) [9]. The cladding tube design used in the MATISSE [10] project is the one used in the current PWR designs. The CEA cladding tube design is the one that was offered to the European Commission, Joint Research Centre, by the CEA so that they could compare the SP results with their own test program.

The SCK•CEN cladding tube is the thinnest ($h_0 = 0.45$ mm) and has the smallest inner diameter ($D_{in} = 5.65$ mm), the one from the MATISSE project has middle thickness ($h_0 = 0.525$ mm) and the largest inner diameter ($D_{in} = 9.7$ mm) while the CEA cladding tube is the thickest ($h_0 = 0.565$ mm) and has middle inner diameter ($D_{in} = 7.37$ mm), see Table 1. Finite element (FE) models of tube SP specimens are then created to cover the whole matrix of all the thicknesses and inner diameters for each of the three different materials used, see section "Materials". Corresponding flat SP FE models are also created. FE models are validated against the available experimental SP results. Estimated ultimate tensile strengths from the simulated SP tests are then compared to the experimental data to test the applicability of the correlations to the cladding tubes.

### 2.1. FE models

3D FE simulations using ABAQUS were performed for all the tube cases with different thicknesses and inner diameters and for the flat specimen cases as a reference, see Table 1. In the case of flat SP specimens, the specimen diameter, $D_S$, is 8 mm while the receiving hole of diameter D = 4 mm has a 0.2 mmx45° chamfer to avoid shearing of the specimen at the edges. In the case of tube specimens, manufacturing of a constant thickness chamfer with a simple drilling tool is not possible. Therefore, the lower dies of curved specimen have no chamfer. Geometrical symmetry is exploited to model only ¼ of the geometry, consisting of the top die (red), specimen (brown), bottom die (grey) and the spherical punch (green), as given in Fig. 2.

### 2.1.1. Materials

The type of materials used here are the ones used for SCK•CEN cladding tube design for MYRHHA research reactor. Grade 91 ferritic/martensitic steel is to be used. However, since this material still needs to be qualified, 15-15Ti austenitic stainless steel is to be used for the initial core loadings [9]. 15-15Ti is also the primary choice for cladding tubes of a number of GEN IV [11] and fast spectrum research reactors.

Grade 91 Ferritic/Martensitic steel from the European FP7 MATTER project [12] is used and labelled here as P91. Heat treatment consists of austenizing for 4 h at 1060 °C, followed by tempering for 3.3 h at 760 °C [13]. The 15-15Ti tube claddings were produced by Sandvik, Sweden, for the Belgian Nuclear Research Centre (SCK•CEN) [11]. Heat treatment consists of short annealing (few minutes) at 1100 °C after each of four cold-drawing passes [11]. The cold work is defined as the reduction in tubular cross-section during the last cold-drawing step. Two cold worked (CW) states of 15-15Ti steel from the EERA JPNM pilot project TASTE [14,15] are used, i.e. 24% CW and 46% CW. The 24% CW falls within the cold work level bounds (20–25%), providing optimal resistance to irradiation swelling and thermal creep while providing excellent mechanical strength [11]. The 46% CW deformation level is used to mimic irradiation damaged material in the sense of work-hardening saturation demonstrated by the small difference between the proof stress and the ultimate tensile strength. Chemical compositions are given in Table 2.