Theoretical and Applied Fracture Mechanics 86 (2016) 2–10

Contents lists available at ScienceDirect

Theoretical and Applied Fracture Mechanics

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

Recent developments in small punch testing: Tensile properties and DBTT

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ARTICLE INFO

Article history:
Received 29 June 2016
Revised 15 September 2016
Accepted 26 September 2016
Available online 28 September 2016

Keywords:
Small punch testing
Yield stress
Ultimate tensile strength
Ductile to Brittle Transition Temperature (DBTT)
Miniature testing techniques

ABSTRACT

Neutron irradiation and temper embrittlement in nuclear power plants (NPPs) lead to microstructural changes in structural materials which induce a shift of the ductile to brittle transition temperature (DBTT) towards higher temperatures. Monitoring of the DBTT in NPP components receives therefore considerable attention — in particular in the context of long term operation. In that context small specimen testing techniques are developed for characterizing structural materials with a limited amount of material.

One of the most used of these miniature testing techniques is the small punch (SP) test which is based on disc shaped specimens. Although SP testing has been used for more than 30 years, there is still no commonly agreed procedure for deriving basic material properties from SP test data. We describe the current status of the SP test with regard to data evaluation procedures for obtaining yield stress, ultimate tensile strength and DBTT from SP tensile/fracture data. The methods for deriving the quantities characterizing the SP force-deflection curve and their use for determining basic mechanical properties are discussed.

Possible reasons for the difference between the DBTT determined from Charpy and SP tests are presented. Data from the present study as well as from the literature suggest that neither notch nor strain rate effects can explain the observed discrepancies.

Based on data from ongoing research projects the importance of Finite Element Analysis (FEA) for studying SP tests is presented for the example of tube specimens derived from fuel claddings.

Finally an overview over the currently available standards and standardization developments is given.

1. Introduction

During the investigation of irradiated materials from fission and fusion programs limiting the exposure of the experimentalists to irradiation is a high priority. Consequently the use of miniature specimens receives significant attention in the nuclear community. The high cost of irradiation experiments is a further incentive for using small specimen testing techniques. The Small Punch (SP) test initially developed in the U.S. and Japan in the 1980s is one of these miniature testing techniques.

In an SP test a small hemispherical tip or a ball ("punch") is pushed through a disc-shaped specimen along its axis of symmetry. SP tests can either be carried out as creep tests, where a constant force is applied and displacement is measured as a function of time, or as tensile/fracture tests, where a constant displacement rate is applied to the punch and the force is measured as function of time [1].

At the beginning of the development two specimen thicknesses of 0.25 mm (derived from TEM specimens) [2–4] and 0.5 mm [5–7] have been used. Although both geometries are still in use today [8], the 0.5 mm thickness specimens are more common.

The triaxial, time dependent stress state in the specimen and the sensitivity of the test geometry make determining even basic mechanical properties from SP testing a challenge. Although significant effort has already been put into deriving mechanical properties from SP data, the evaluation of SP tests is still a topic of research [8–13].

The current paper describes recent developments related to SP testing with a focus on the determination of tensile material properties and the ductile to brittle transition temperature (DBTT). The current situation with regard to international standards is also reviewed.

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http://dx.doi.org/10.1016/j.tafmec.2016.09.012
0167-8442/

2. Small punch tensile tests

2.1. Set-up

A typical scheme of an SP test setup is shown in Fig. 1. The disc shaped specimen (in red[1]) is clamped between two dies. In an SP tensile test, the punch is pushed with a constant displacement rate through the specimen. Fig. 1 shows a solid punch in a single piece as recommended in the current CEN Workshop Agreement (CWA) [1] and used by many authors [10,12,14,15]. An alternative, frequently used configuration is based on a punch with a flat or concave tip pushing a ball through the specimen [7,13,16]. The latter configuration has the advantage that the tip (i.e. the ball) can be replaced after every test. Changing the ball after each test avoids potential problems caused by wear of the punch which might lead to less reproducible results.

The force needed to push the punch through the specimen is recorded and plotted as a function of either the displacement of the punch tip/ball or — as shown in Fig. 1 and recommended in the CWA [1] — as a function of the specimen deflection measured on the specimen surface opposite to the point of contact between the punch and the specimen. The displacement cannot be measured directly at the tip of the punch but has to be inferred either directly from the cross-head displacement or from a clip gage or a similar device attached to the push rod or the punch. In both cases the displacement signal has to be corrected for force line compliance.

This problem does not occur when the specimen deflection is used instead of the displacement of the punch. In such a case a rod is touching the specimen from below. The rod simply transfers the deflection of the specimen to an LVDT or a similar device. Since the force applied on the rod is very small, no compliance correction is necessary for the rod. There might be a small compliance from the entire setup though. A hollow ceramic rod can be used which can contain a thermocouple in direct contact with the specimen surface allowing determination of the test temperature.

Ideally, the compliance corrected displacement and the deflection only differ because of the specimen thinning. A detailed discussion of the implications of the different approaches has recently been published [13].

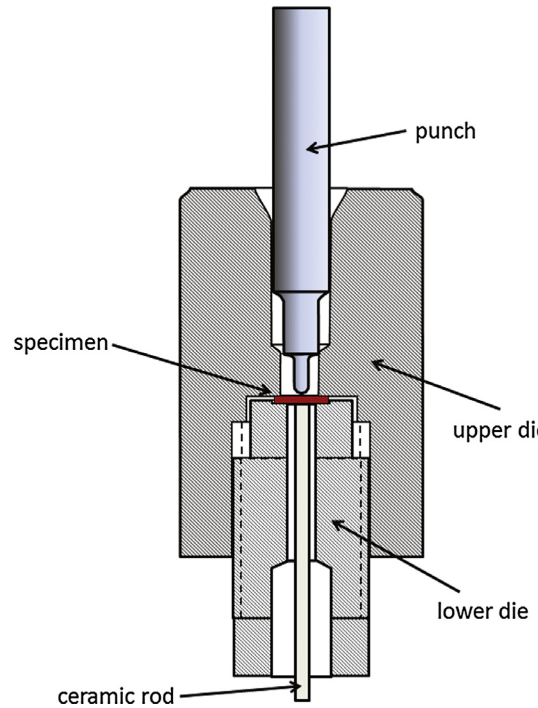

Fig. 1. A typical SP test setup. The basic dimensions are listed in Table 1.

2.2. Characteristics of the force-deflection curve

A typical force-deflection curve for a ductile material is shown in Fig. 2. The force-deflection curve is generally divided in different stages [18–21]: zone I corresponds to the indenting of the specimen surface and elastic bending. During zone II plastic bending spreads through the specimen. In zone III the specimen behaviour is dominated by membrane stretching and in zone IV by necking and crack initiation. In zone V fracture softening occurs and final fracture occurs in zone VI.

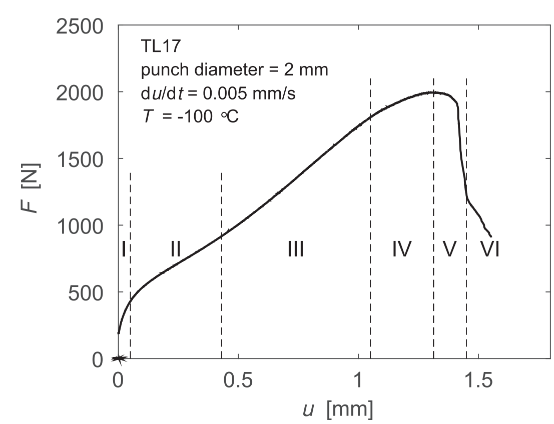

Fig. 2. Typical SP force-deflection curve for a ductile material [17]. The roman numbers indicate the different zones of the curve.

For the evaluation of an SP tensile test data a number of characteristic values determined from the force-deflection $F(u)$ curve are used [1,22] (Fig. 3):

- F_m, the maximum force,
- u_m, the deflection at maximum force,
- F_e, the elastic-plastic transition force,
- E_{frac}, the fracture energie $E_{frac} = \int_0^{u_{frac}} F(u)\,du$.

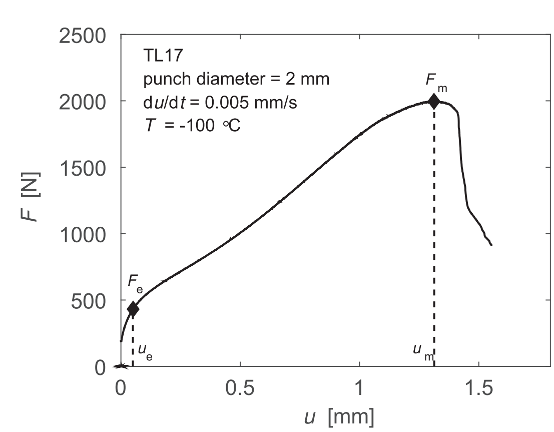

Fig. 3. Characteristic points in the force-deflection curve [17].

For the determination of E_{frac} the force F is integrated over the deflection u up to the point u_{frac} where fracture occurs. Different

[1] For interpretation of colour in Fig. 1, the reader is referred to the web version of this article.