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EUROPEAN STANDARD ON SMALL PUNCH TESTING OF METALLIC MATERIALS

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ABSTRACT

Life extension of aging nuclear power plant components requires knowledge of the properties of the service-exposed materials. For instance, in long term service the tensile and creep properties might decline and the ductile-to-brittle transition temperature (DBTT) might shift towards higher temperatures. Monitoring of structural components in nuclear power plants receives much attention – in particular in the context of lifetime extension of current plants, where the amount of material available for destructive testing is limited.

Much effort has therefore been invested in the development of miniature testing techniques that allow characterizing structural materials with small amounts of material. The small punch (SP) test is one of the most widely used of these techniques. It has been developed for nuclear applications but its use is spreading to other industries.

Although the SP technique has been used for more than 30 years, there is currently no standard covering its most widely used applications. Within the auspices of ECISS TC 101 "Test methods for steel (other than chemical analysis)" WG 1 is currently developing an EN standard on the "Small Punch Test Method for Metallic Materials". The standard will address small punch testing for the determination of tensile/fracture properties as well as small punch creep testing.

This paper gives an overview of the state-of-the art of the SP tests and describes the scope of the standard under development.

NOMENCLATURE

Acronyms

CEN European Committee for Standardization
CWA CEN Workshop Agreement
ECISS European Committee for Iron and Steel Standardization

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FP7 7th EU Framework Programme for Research and Technological Development
EN European Standard
ODS Oxide Dispersion Strengthened
SP Small Punch
SPC Small Punch Creep
TC Technical Committee
TEM Transmission Electron Microscope
WG Working Group

Physical quantities

α Correlation factor for T_{SP}
α_i Correlation factors for $R_{\mathrm{p0.2}}$
β_i, β_i' Fitting factors for R_{m}
d Punch diameter
D Diameter of receiving hole
D_{S} Specimen diameter
$DBTT_{\mathrm{Charpy}}$ Ductile to Brittle Transition Temperature from Charpy testing
ε_{f} Fracture strain
E_{m} Energy to maximum force obtained by integrating $F(u)$ from the start of the test to u_{m}
F Force applied to the specimen
F_{e} Elastic-plastic transition force in a small punch test
F_{m} Maximum force in a small punch test
h Specimen thickness
h_0 Initial specimen thickness
h_{f} Specimen thickness at fracture
J_{Ic} Elastic-plastic fracture toughness
K_{Ic} Plain strain fracture toughness
k_{SP} Correlation factor in SPC testing
L Chamfer length
ω Chamfer angle
r Punch radius
$R_{\mathrm{p0.2}}$ Yield strength
R_{m} Ultimate tensile strength
σ Stress
T_{SP} Transition temperature as determined by SP testing
u Deflection
u_{m} Deflection at F_{m}

INTRODUCTION

The need for characterizing the mechanical properties of structural materials when only small amounts of material are available has led to the development of small-specimen test techniques. The small punch test is one of these techniques that uses disc shaped specimens. It was developed in the 1980s to characterize structural materials in the fission and fusion programmes in the U.S. and Japan [1–6] and is currently used for monitoring the aging of the components of nuclear power plants in some countries [7].

From its initial development for the characterization of structural materials in the nuclear energy sector, the SP technique is spreading to other sectors like the aeronautics [8] and offshore [9] industries or completely different classes of materials like polymers [10–12].

Figure 1 shows the number of documents listed in the scopus database in the subject areas "engineering", "materials science" and "energy" in which the expression "small punch" is included in the title, the abstract or the key words. Although not all these documents relate to small punch testing in the sense in which it is used here and other documents are likely missing because the authors used terms like "bulge test", it is clear that the interest in small punch testing has strongly increased in the last few decades.

Nevertheless, there is currently no standard available covering the most relevant applications of small punch testing to metallic materials. In the US, ASTM standards have been published for small punch testing of polymers [14, 15]. However, these standards are limited to ensuring the repeatability of the tests at room temperature and do not address the determination of material properties like yield or ultimate tensile strength. A small punch test standard for metallic materials is currently under development under the auspices of ASTM as work item WK47431 [16].

In China, standards exist for the assessment of metallic materials in in-service pressure equipments. They address the de-

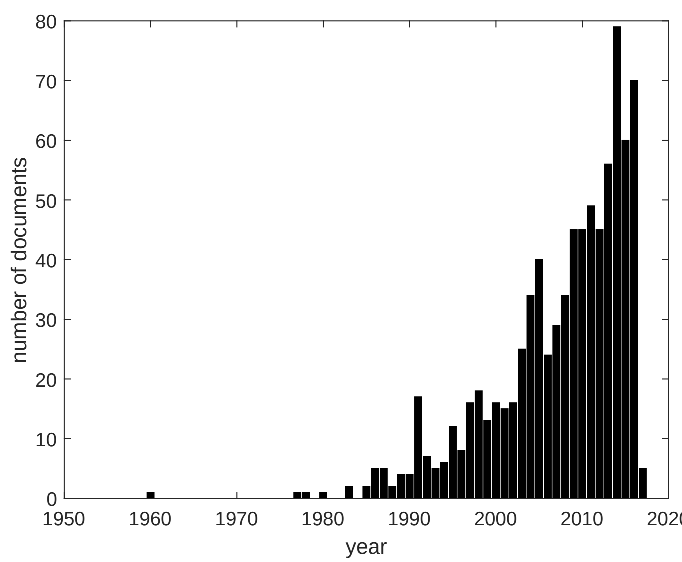

FIGURE 1. NUMBER OF DOCUMENTS IN SCOPUS RELATING TO "SMALL PUNCH" [13]. FOR DETAILS ABOUT THE QUERY SEE TEXT.

TABLE 1. LIST OF ORGANIZATIONS TAKING PART IN DRAFTING THE STANDARD (STATUS: JAN. 2017)

Organization	Country
Academy of Sciences	Czech Republic
Bay Zoltán Nonprofit Ltd.	Hungary
CIEMAT	Spain
European Commission - JRC	The Netherlands
Helmholtz-Zentrum Dresden-Rossendorf	Germany
Inesco Ingenieros	Spain
Material & Metallurgical Research, Ltd.	Czech Republic
UJV	Czech Republic
UKAEA	United Kingdom
University of Cantabria	Spain
Swansea University	United Kingdom
VUJE	Slovak Republic

termination of tensile properties at room temperature [17, 18].

The Japanese Society of Materials Science (JSMS) [19] has published a document which addresses SP creep testing. However, from the three parts of the document ("text", "description" and "appendix") only the first section seems to be available in English.

The most recent European document is CWA 15627 in its revised version from 2007 [20]. A CWA is a pre-normative document that is not confirmed by balloting of the national CEN members; it is designed to be a document for the preparation of a standard. To fill this existing gap, the European Committee for Iron and Steel Standardization (ECISS) has formed a new working group (WG 1) within the Technical Committee (TC) 101 "Test methods for steel (other than chemical analysis)" for establishing an EN standard for small punch testing of metallic materials. The standard will cover small punch (SP) testing, as well as small punch creep (SPC) testing. The organizations currently taking part in drafting the standard are listed in Table 1.

An extensive round-robin test campaign has been launched to support the standardization work with data. The test programme includes SP testing on two different batches of the ferritic/martensitic steel P92, one batch of the austenitic steel 316L and one batch of MA956, a ferritic 20Cr ODS steel. SPC tests are only planned for the P92 and 316L steels. In addition to these data obtained specially for the standard, previous existing data are also available e.g. from an interlaboratory comparison carried out within the Euratom FP7-Project MATTER [21].

This paper presents the current status of the development of a European standard on small punch testing of metallic materials, which is expected to become available in 2019. Note, however, that this is ongoing work and the final standard may differ from what is presented here.

PRINCIPLE OF SMALL PUNCH TESTING

The principle of a SP test is shown in Fig. 2: the specimen, a small circular disc with diameter D_S and initial thickness h_0, is clamped between two dies. A ball or hemispherical tip with a radius r is pushed with a constant displacement rate through the specimen along its axis of symmetry. During a small punch test, the force F needed to push the punch with constant displacement rate is recorded together with deflection u, the distance by which the centre of the specimen surface opposite to the point of contact between the punch and the specimen has moved during the test. In a configuration such as the one depicted in Fig. 2, the deflection can be measured by an LVDT contacting the specimen from below.

The result of an SP test is a force-deflection curve, an example of which is shown in Fig. 3 [23, 24]. The characteristic points on the curve are the maximum force F_m, the corresponding deflection u_m and energy $E_\mathrm{m} = \int_0^{u_\mathrm{m}} F\,\mathrm{d}u$, as well as the SP elastic-plastic transition force F_e and the related deflection u_e.

F_e is generally related to the transition from elastic to plastic bending [23, 25, 26]. Several approaches for determining F_e, based on bilinear fits of the force-displacement curve or offset methods similar to the practice in uniaxial tensile testing, have been discussed in the past and are considered for the new standard [23, 27, 28].

F_m and u_m are the most frequently used parameters for determining the ultimate tensile strength R_m (Eqs. 1 and 2), whereas F_e is used to infer yield strength $R_\mathrm{p0.2}$ (Eq. 3) [27, 28]:

$$R_\mathrm{m} = \beta_1 \frac{F_\mathrm{m}}{h_0 u_\mathrm{m}} + \beta_2 \tag{1}$$

$$R_\mathrm{m} = \beta_1' \frac{F_\mathrm{m}}{h_0^2} + \beta_2' \tag{2}$$

$$R_\mathrm{p0.2} = \alpha_1 \frac{F_\mathrm{e}}{h_0^2} + \alpha_2 \tag{3}$$

β_i, β_i', and α_i are fitting coefficients. An extensive study that applies Eqs. 1-3 on a variety of alloys can be found in [27].

Besides these most frequently used approaches based on F_m and F_e, other proposals, such as the rising point of inflection method (around $u = 0.5$ mm in Fig. 3), will be considered for the standard.

To determine the energy absorbed by the specimen before failure, one needs to integrate the force applied to the specimen

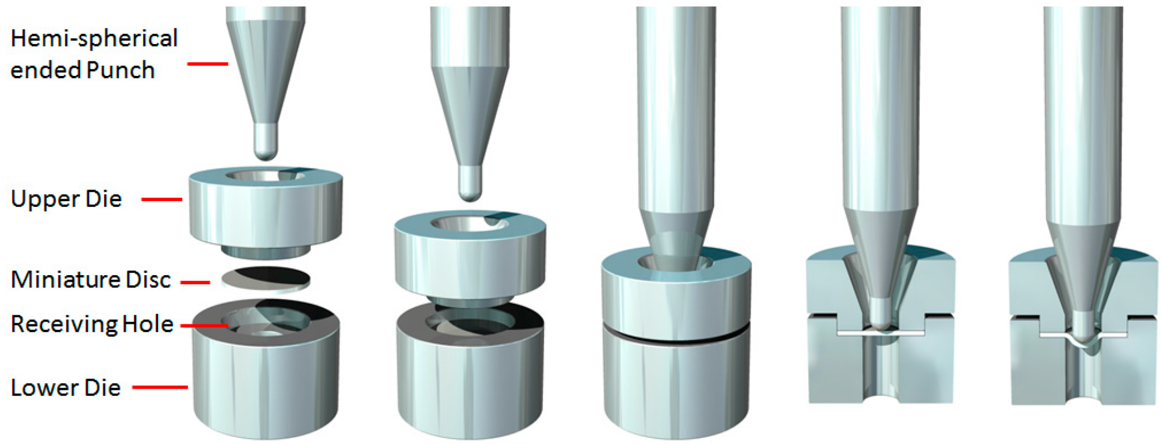

FIGURE 2. SCHEMATIC OF THE SMALL PUNCH TEST [22].

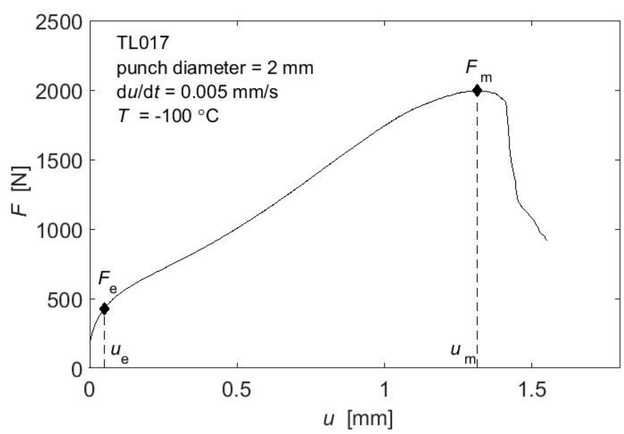

FIGURE 3. FORCE-DEFLECTION CURVE RESULTING FROM A SMALL PUNCH TEST [23, 24].

over the displacement of the punch tip up to the point of failure. Currently several approaches for defining the point of failure are under consideration (see below). For some materials (e.g. ferritic/martensitic steels), this energy drops significantly below a certain transition temperature T_{SP} – similar to what is observed in Charpy impact testing. Characterizing the shift of the transition temperature through neutron embrittlement or other aging mechanisms was one of the drivers for developing the SP technique. It turned out, however, that the SP transition temperature T_{SP} is significantly lower than the $DBTT_{Charpy}$ determined by Charpy testing. The relationship between these two transition temperatures, expressed as absolute temperatures (i.e. in K), is often characterized by a factor α [20], where:

$$T_{SP} = \alpha \cdot DBTT_{Charpy} \tag{4}$$

Values of α depend on the geometry of the test rig, the fitting procedure and, to some extent, also on the material. Reported values of α typically lie around 0.4 [5, 29].

From a physical point of view, it is correct to perform the integration over the displacement of the punch tip where the force is applied to the specimen, rather than over specimen deflection, which is measured on the opposite side of the specimen. Since the specimen is thinning during the test, using deflection systematically underestimates the energy.

However, the displacement of the punch tip cannot be measured directly but has to be inferred from the displacement measured at the crosshead or at another location along the load line. When determining the punch tip displacement, the measurement has to be corrected for the temperature-dependent compliance of the test equipment. In contrast, the forces below the specimen are much lower, so no compliance correction is needed when measuring specimen deflection, making this approach much simpler.

When determining the transition temperature T_{SP}, the energy is only required to determine the point where the transition from brittle to ductile behaviour occurs; the energy values themselves are normally not used. The difference between using displacement or deflection in calculating the energy for determining T_{SP} is limited. From a practical point of view, it might therefore be more advantageous using deflection rather than displacement, although the latter would be physically correct. The issue is currently under discussion within the WG.

CWA 15627 [20] recommends integrating up to a point where the force has dropped to 80% of its maximum value but integration up to the maximum force is also frequently used [23]. This latter approach has the advantage of being more appropriate in the case of brittle failure accompanied by a quasi-instantaneous drop of the force instead of a continuous decrease as in the case of ductile failure, as shown in Fig. 3.

Another possibility for determining T_{SP} is by means of the fracture strain ε_f:

$$\varepsilon_f = \ln\left(\frac{h_0}{h_f}\right) \tag{5}$$

where h_f is the specimen thickness after failure adjacent to the area of failure and h_0 is the initial specimen thickness. The transition from ductile to brittle failure is also visible from the change in ε_f. The transition temperature determined from ε_f is quite similar to that calculated from the energies [30, 31].

The fracture strain ε_f can also be used for estimating the fracture toughness of the material in terms of J_{Ic}, by means of Eq. 6, where k and J are fitting parameters [32].

$$J_{Ic} = k\varepsilon_f - J \tag{6}$$

Other possibilities for the estimation of fracture properties use empirical correlations between T_{SP} and $DBTT_{Charpy}$ in combination with approaches reported in the literature for correlating $DBTT_{Charpy}$ and K_{Ic} to obtain a relation between T_{SP} and K_{Ic} [33]. Recent proposals for estimating fracture properties rely on notched SP specimens, which allow the application of fracture mechanics concepts to SP testing. Further, the introduction of a notch breaks the SP specimen symmetry, so that one test characterizes a single material orientation [34].

A different application is the small punch creep (SPC) test. The basic setup for the test is the same as for the SP test (Fig. 2), but instead of a constant displacement rate a constant force F is applied to the punch and the specimen deflection u is measured as a function of time. The immediate result of such a SPC test is a creep deflection curve $u(t)$, as shown in Fig. 4. In order to compare the results of a SPC test to those of a standard uniaxial creep test, the force F applied to the SP specimen has to be converted to the (engineering) stress applied to a uniaxial creep specimen. According to CWA 15627 [20], this conversion can be achieved using the semi-empirical equation:

$$\frac{F}{\sigma} = 3.33 k_{SP} \frac{r^{1.2} h_0}{(0.5D)^{0.2}} \tag{7}$$

where k_{SP} is a material-dependent correlation factor introduced to take varying creep ductilities into account. The problem with Eq. 7 is that k_{SP} is not only material-dependent but also varies with stress and temperature [20,35]. Therefore, other approaches (e.g. [35]) for relating SPC to uniaxial creep rupture times will be explored.

SPECIFICATION OF THE TEST EQUIPMENT

The main components of the test rig, as shown in Fig. 2, are the punch with a hemispherical tip (or a combination of flat punch and ball) and the upper and lower dies between which the specimen is clamped, both of which have central holes. The upper die's main function is ensuring the clamping of the specimen and – depending on the details of the configuration – to centre the punch on the specimen. The clamping force has previously been found to have negligible impact on either SP or SPC [37,38]. The dimension of the hole in the upper die can therefore be adapted to the geometry of the punch, but is not critical as long as clamping of the specimen is ensured.

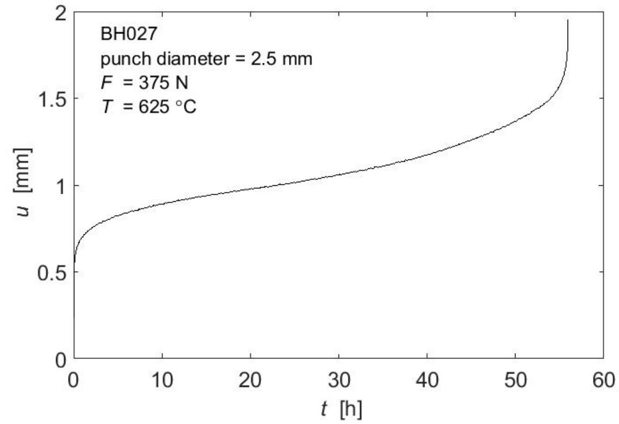

FIGURE 4. CREEP DEFLECTION CURVE RESULTING FROM A SMALL PUNCH CREEP TEST [36].

TABLE 2. DIMENSIONS OF SMALL PUNCH TEST PIECES

parameter	symbol	value	
diameter	D_S	8 mm	3 mm
thickness	h_0	0.5 mm	0.25 mm

Conversely, the diameter of the lower die has a direct impact on the characteristics of the force-displacement curve $F(u)$ and therefore needs to be well defined [20]. To avoid shearing of the specimen at the edge of the hole in the lower die, the lower die features a chamfer. The two variants shown in Fig. 5, i.e. curved chamfers (edges with a radius) and flat chamfers are commonly used [21]. The current CWA [20] recommends flat chamfers with $L = 0.2$ mm and $\omega = 45°$ (Fig. 5).

The most frequently used SP specimens have a diameter of 8 mm and a thickness of 0.5 mm. However, in some cases it is preferable to use smaller specimens with a diameter of 3 mm which is the typical size of a TEM sample holder. It is therefore expected that the standard will allow two specimen sizes (Table 2).

The dimensions of the different components, such as the

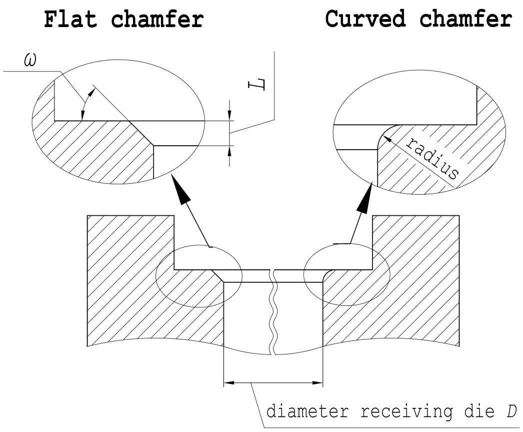

FIGURE 5. SCHEMATIC ILLUSTRATION OF THE CHAMFER IN THE LOWER DIE.

TABLE 3. DIMENSIONS OF A SMALL PUNCH TEST EQUIPMENT; THE DIAMETER OF THE PUNCH FOR THE 8 MM SPECIMEN IS STILL UNDER DISCUSSION

parameter	symbol	value	
		D_S= 8 mm	D_S=3 mm
punch diameter	d	1.5/2 mm	1 mm
receiving hole diameter	D	4 mm	1.75 mm
chamfer length	L	0.2 mm	0.2 mm
chamfer angle	ω	45°	45°

punch, need to be adjusted to the size of the test piece. The currently foreseen dimensions are listed in Table 3.

SCOPE AND STRUCTURE OF THE NEW STANDARD

The new standard will compile in its main text the information required to perform a SP test at various temperatures for the determination of tensile and fracture mechanics properties. It will also include a chapter detailing the specificities of SPC testing aiming at the determination of creep properties.

The current preliminary draft of the standard is structured in the following chapters:

1. Introduction
2. Scope
3. Normative references
4. Terms and definitions
5. Symbols and designations
6. Test piece
7. Apparatus
8. Small punch test
9. Small punch creep test.

Besides these recommendations for the main experimental aspects of the test, the document will include a number of informative annexes which address specific technical issues like compliance correction or temperature control. Other annexes will provide guidance for the use and evaluation of the obtained SP data. Further annexes will deal with the post-test examination of the test piece and the extraction of samples from structures or components.

With a view to enabling improved storage and transfer of small punch test data, a final annex will be dedicated to standardised data formats. As in the case of Appendix A.5 of the recently updated ISO 6892-1 ambient temperature tensile testing standard [39], such data formats are derived from documentary testing standards in accordance with a methodology developed in the scope of an ongoing series of CEN Workshops on formats for engineering materials data [40]. The full list of foreseen annexes is:

- A Procedure for determining compliance of a small punch test rig
- B Procedure for temperature control and measurement in small punch testing
- C Estimation of ultimate tensile strength R_m from small punch testing
- D Estimation of yield strength $R_{p0.2}$ from small punch testing
- E Determination of T_{SP}, the ductile-to-brittle transition temperature from small punch testing
- F Fracture toughness from small punch testing
- G Estimation of uniaxial creep stress from small punch creep testing
- H Evaluation of small punch creep tests
- I Post-test examination of test piece
- J Sampling from components
- K Data formats

SUMMARY

The development of an EN standard on small punch testing of metallic materials is currently in progress under the auspices of ECISS TC 101/WG 1. The standard will cover small punch testing for the determination of tensile and fracture properties, inlcuding test at elevated temperatures, as well as small punch creep testing. Currently 12 research organizations and companies from across Europe are taking part in the accompanying test programme and the preparation of the standard. The new standard is expected to be available in 2019.

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