Designation: E3205 – 20

Standard Test Method for Small Punch Testing of Metallic Materials[1]

This standard is issued under the fixed designation E3205; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers procedures for conducting the small punch deformation test for metallic materials. The results can be used to derive estimates of yield and tensile strength up to 450 °C, and estimates of the ductile-to-brittle transition temperature from the results of small punch bulge tests in the temperature range from -193 °C to 350 °C for iron based materials or 0.4 T_m for other metallic materials, where T_m is their melting temperature in K.

1.2 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.4 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E8/E8M Test Methods for Tension Testing of Metallic Materials

E21 Test Methods for Elevated Temperature Tension Tests of Metallic Materials

E74 Practices for Calibration and Verification for Force-Measuring Instruments

E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods

E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

E220 Test Method for Calibration of Thermocouples By Comparison Techniques

3. Terminology

3.1 *Definitions:*

3.1.1 *force, F [F], n*—force applied to the test specimen by the punch.

3.1.1.1 *Discussion*—This includes the weights of the equipment acting on the punch.

3.1.2 *force-punch displacement (F-v) curve, n*—relationship between force and punch displacement, which is continuously recorded during the small punch (SP) bulge test.

3.1.3 *force-specimen deflection (F-u) curve, n*—relationship between force and deflection, which is continuously recorded during the SP bulge test.

3.1.4 *punch displacement, v [L], n*—displacement of the center of the top of the punch in contact with the specimen.

3.1.4.1 *Discussion*—Determination of the punch displacement from the measurement of machine crosshead displacement requires correcting for machine compliance.

3.1.4.2 *Discussion*—In this test method, specimen deflection, *u*, is used as the reference displacement signal. However, if specimen deflection is unavailable or not measured, punch displacement, *v*, may be used instead.

3.1.5 *small punch (SP) bulge test, n*—mechanical test consisting of loading a small disk-shaped specimen clamped between two dies by means of a hemispherical-shaped punch, deforming it to failure, and analyzing the resulting *F-u* curve.

3.1.6 *specimen deflection, u [L], n*—displacement of a point at the center of the specimen opposite to the punch during the small punch (SP) bulge test.

4. Significance and Use

4.1 The safety margins provided in the design for a component or structure can be reduced throughout its service life by aging. Aging is the process by which the physical and mechanical characteristics of component or structure materials change with time or use; this process may proceed by a single aging mechanism or a combination of several aging mechanisms.

[1] This test method is under the jurisdiction of ASTM Committee E10 on Nuclear Technology and Applications and is the direct responsibility of Subcommittee E10.02 on Behavior and Use of Nuclear Structural Materials.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

4.2 The term "safety margin" is used in a broad sense, meaning the safety state (that is, integrity and functional capability) of components in excess of their normal operational requirements (**1**).[3]

4.3 The determination of mechanical properties such as yield strength, tensile strength, and ductile-to-brittle transition temperature of structural components is, hence, desirable for optimization of operating procedures and inspection intervals, as well as repair strategies and residual lifetime assessment. Current standardized mechanical tests require relatively large volumes of test material that cannot be extracted from in-service equipment without post-sampling removal repair (**2**).

4.4 The need to obtain estimates of the mechanical properties of components without post-sampling removal repair has led to the development of small punch (SP) test techniques based on penetration/bulge tests of miniaturized test specimens (often disk-shaped, or square) (**3**, **4**, **5**). It can be considered as a quasi-nondestructive technique because of the very limited amount of material to be sampled. It is an efficient and cost-effective technique and has the potential to provide estimates of the material properties of the specific component, identifying the present state of damage and focusing on the most critical (most stressed, most damaged) locations in the component. Examples of empirical correlations that have been established between small punch test results and mechanical properties for specific classes of materials are provided in Appendix X1.

4.5 This test method can be also used for identifying the most suitable materials with respect to their resistance against operational damage, like neutron irradiation, thermal aging etc., as well as for optimization of their chemical composition, thermal heat treatment, etc. This test method is beneficial in the study of the effect of radiation damage when test specimen dimensions are limited by small irradiation volume or high activity.

4.6 Due to the small sample size, this test method also allows estimating mechanical properties of non-uniform materials such as welds (**6**). Examples of weld techniques that produce narrow geometric gradients include electron beam or laser beam welds, and metal coatings (**7**, **8**). This test technique provides a more direct means of estimating material properties than indirect methods based on laboratory simulations of the localized regions or analytical predictions based on generalized methods.

5. Apparatus

5.1 *Test Rig:*

5.1.1 In Fig. 1, a cross-sectional view of the specimen holder with a hemispherical tipped punch and a test specimen is illustrated schematically. The receiving die bore diameter shall be d_2 = 4.00 mm ± 0.01 mm and the punch tip radius shall be r =1.25 mm ± 0.01 mm. The corner radius of the receiving die (Fig. 1) shall be R = 0.20 mm ± 0.05 mm. Roughness of the die bore and punch tip radius shall not be greater than Ra = 2 µm.

5.1.2 The test rig shall have a hemispherical tipped punch or ball capable of forcing the central portion of the specimen through the hole in the receiving die until the end of the test occurs. The hemispherical portion of the punch or the whole ball volume shall be hard enough not to be plastically deformed during the test (55 HRC is sufficient for testing most steels).

5.1.3 The clamping surfaces of the specimen holder in contact with the test specimen shall be plane and parallel to each other within ± 0.5°. Both surfaces shall be clean, free from oxide buildup, corrosion and dirt, and sufficiently rigid not to be deformed during the test (hardness of 55 HRC or higher) with roughness not greater than Ra = 0.8 µm. The clamping torque shall be between 5 N m and 15 N m and shall be recorded. The recommended torque value is 10 N m.

5.1.4 The surface finish of the punch and die in contact with the specimen shall not exceed 0.004 mm based on maximum peak-to-peak distance.

5.2 *Loading System*—A screw-driven or servo-hydraulic testing machine is generally used for SP tests. It shall be equipped with a fixture for holding and loading the test specimen, a load cell, and a measuring system for specimen deflection or punch displacement, or both. The percent error for the force measurement system within the capacity of the load cell shall not exceed ±1 % of the actual measured force, in accordance with Practices E74. The loading system should be calibrated for accuracy using a proving ring or similar certified device and the results shall be recorded at least once a year.

5.3 *Punch Displacement, v, or Specimen Deflection, u, Measurement System*—Any method of measuring specimen deflection or punch displacement may be used. The displacement indicator shall monitor specimen deflection with an accuracy of at least ±1 % of the original specimen thickness, h_0.

NOTE 1—It may be convenient to measure the deflection by monitoring the displacement of a measuring rod as indicated in Fig. 1.

5.4 *Heating or Cooling System*—Testing temperature significantly affects the nature of the F-u curve. For this reason, temperature shall be maintained constant within ±3 °C throughout the test. Any method of cooling or heating may be used. The method of temperature measurement shall be sufficiently sensitive and reliable to ensure that the temperature of the test specimen is within the limits specified below. A temperature measuring system shall include thermometers, usually thermocouples, appropriately located to determine that the full test section remains within the temperature limits prescribed for the test. The thermocouples shall be of a type and composition suitable for the test temperature regime selected for the test and calibrated in accordance with Test Method E220. The temperature of the test specimen shall be maintained within ±3 °C of the designated test temperature throughout the test in accordance with Test Methods E8/E8M and Test Methods E21.

5.5 *Test Environment*—Usually the SP test is performed in air. For studies in which the effect of the environment is of specific interest, other environments may be used, but this shall be clearly stated in the test report.

[3] The boldface numbers in parentheses refer to the list of references at the end of this standard.

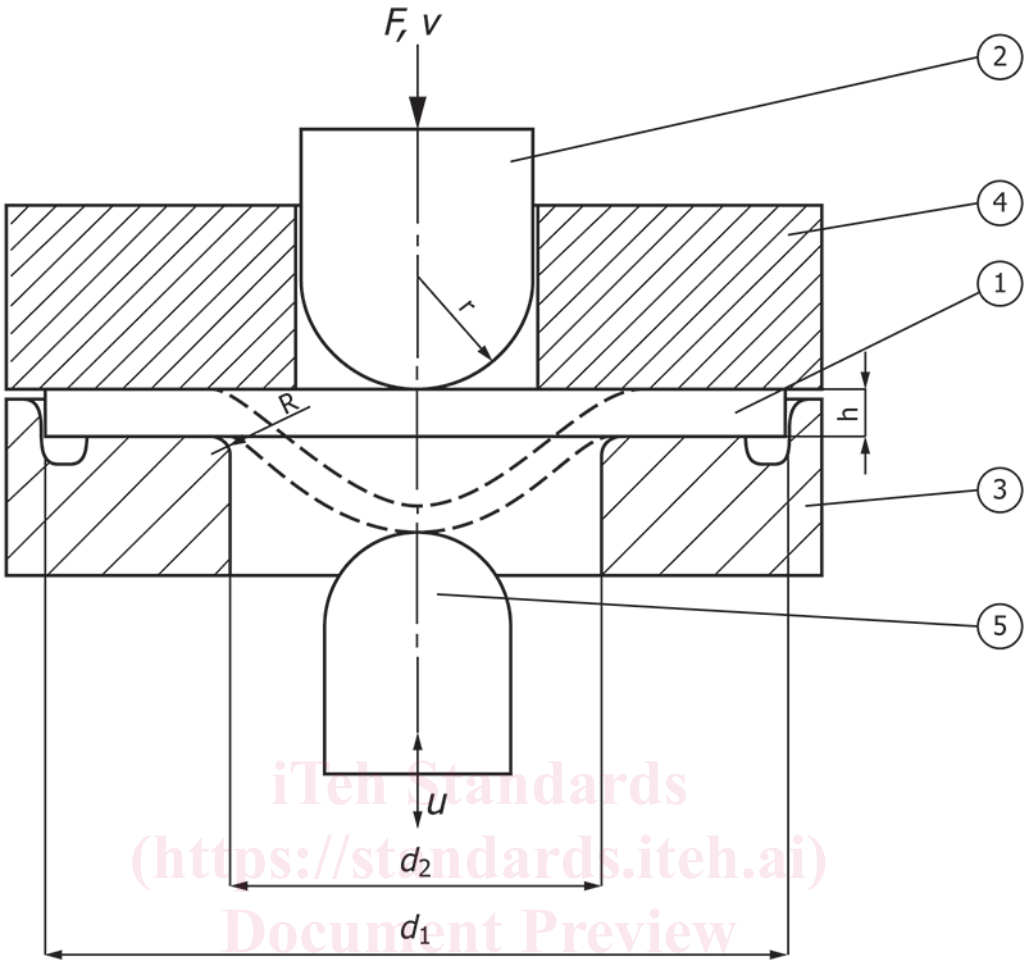


FIG. 1 Cross-Sectional Scheme of the Test Rig (1– Test Specimen, 2– Punch, 3– Receiving Die, 4– Clamping Die, and 5– Deflection Measurement Rod) (9)

5.6 *Additional Measurements*—Other test parameters may be monitored, such as crack initiation, by continuous or discontinuous methods. These additional measurements shall not affect the results of the SP test.

5.7 *Calibration Frequency*—Calibration shall be as frequent as necessary to ensure that errors do not exceed the permissible variations listed in this test method. The maximum interval between calibrations of the testing machine shall be one year. Instruments in either continuous or nearly continuous use shall be calibrated at least once a month; those used only occasionally shall be calibrated before each use.

6. Test Specimens

6.1 The test specimen shall be obtained from test material removed from or to be used in engineering components before or during operation. To minimize work hardening on the surface of the specimen, the disk shall be machined to a thickness of approximately $1.2 \cdot h_0$ and then ground on abrasive paper with a recommended abrasive grit size designation P320 followed by fine grinding (P1200) to the final thickness with an accuracy of $\pm 1\ \% \cdot h_0$. Surface roughness *Ra* shall be better than 0.25 µm.

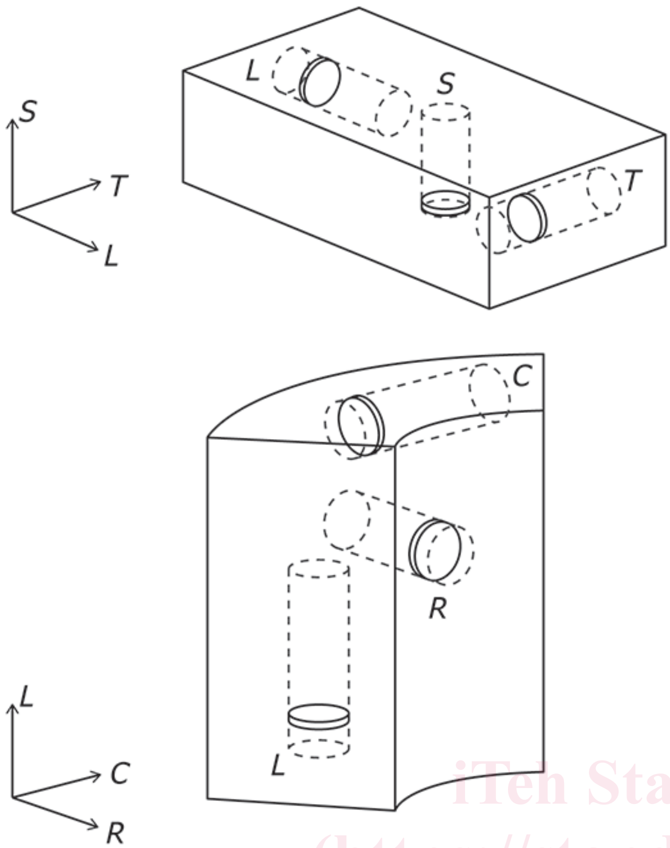
6.2 Disk-shaped test specimens with diameter $d_1 = 8$ mm ± 0.01 mm and original thickness $h_0 = 0.5$ mm ± 0.005 mm shall be used. The thickness of the specimen shall be measured at four positions around the perimeter at 90° intervals from each other and in the middle. The diameter shall be measured in two positions at 90° from each other.

6.3 Specimen orientation shall be as defined in Fig. 2.

7. Procedure

7.1 Insert the test specimen centrally below the punch. Clamp the specimen rigidly between receiving die and clamping die. Position the deflection measurement system under the center of the specimen. When testing at different temperatures or in other environments, close the chamber system and set the required conditions.

7.2 *Test Speed*—The test speed shall ensure that the stress and strain rates are within the bounds given in Test Methods E8/E8M or Test Methods E21. Stress and strain rate are not constant during the SP test even for a constant punch displacement rate. For the recommended specimen geometry, the following formula provides a good estimation of the maximum



where:

L = longitudinal direction (that is, rolling direction),
T = transverse direction,
S = short transverse direction,
C = circumferential direction, and
R = radial direction.

FIG. 2 Orientation of SP Specimens

punch strain rate $\dot{\varepsilon}_{SP}^{max}$ in s^{-1} as a function of punch velocity *dv/ds* in $m.s^{-1}$:

$$\dot{\varepsilon}_{SP}^{max} \approx 1000\, m^{-1} \cdot \frac{dv}{ds} \tag{1}$$

The displacement rate of the punch (punch velocity) shall be in the range between 0.2 mm/min and 2 mm/min (the most commonly used value is 0.5 mm/min).

7.3 *Test Record*—Accurate records shall be kept of *F-u* and temperature for the whole test duration. In addition, a record shall be kept of all adjustments made to control or alter the test conditions and of any events that lead to test interruptions.

7.3.1 *End of the Test*—Loading of the test sample should be terminated when a 20 % force drop from maximum force F_m occurs.

8. Post-Test Analyses

8.1 The objective of the test is to produce a *F-u* record, containing information about the elastic-plastic deformation and strength properties of the material. The following characteristic parameters from a *F-u* curve are used for the estimation of strength and fracture characteristics (see Fig. 3):

8.1.1 F_e *[N]*—force characterizing the transition from linearity to the stage associated with the spread of the yield zone through the specimen thickness (plastic bending stage).

8.1.2 F_m *[N]*—maximum force recorded during the SP test.

8.1.3 u_m *[mm]*—specimen deflection corresponding to the maximum force F_m.

8.1.4 u_f *[mm]*—specimen deflection corresponding to a 20 % force drop with respect to F_m, i.e., $F_f = 0.8\ F_m$.

8.1.5 E_{SP} *[J]*—SP fracture energy calculated under the area under the *F-u* curve up to u_f.

8.1.6 E_m *[J]*—SP total energy (elastic + plastic) calculated under the area under the *F-u* curve up to u_m.

8.1.7 E_{PL} *[J]*—SP plastic energy calculated from the area under the *F-u* curve up to u_m.

8.2 *Determination of the Elastic-Plastic Transition Force,* F_e—The elastic-plastic transition force, F_e, can be correlated with the yield strength obtained from tensile tests and is, therefore, of specific interest. The following procedure describes how to obtain F_e (Fig. 4) from the *F-u* curve.

8.2.1 A bilinear function *f(u)* from the origin through the points A and B is defined as:

$$f(u) = \begin{cases} \dfrac{f_A}{u_A} u & \text{for} \quad 0 \le u \le u_A \\ \dfrac{f_B - f_A}{u_B - u_A}(u - u_A) + f_A & \text{for} \quad u_A \le u \le u_B \end{cases} \tag{2}$$

8.2.2 Minimizing the error:

$$err = \int_0^{u_B} [F(u) - f(u)]^2 du \tag{3}$$

by varying f_A, u_A, and f_B leads to final values for the variables, and therefore to a best fit of the function *f(u)* to the measured *F-u* curve.

8.2.3 The yield displacement is $u_e = u_A$, while the force F_e shall be obtained from the experimental *F-u* curve as $F_e = F(u_A)$.

8.2.4 The only free parameter in this optimization is the value of u_B. It is recommended to choose $u_B = h_0$.

8.3 *Determination of the SP Fracture Energy,* E_{SP}*:*

8.3.1 The SP fracture energy, E_{SP}, is defined as the area under the *F-u* curve up to u_f:

$$E_{SP} = \int_0^{u_f} F(u)\,du \tag{4}$$

8.3.2 When SP tests are carried out at low temperatures, sudden force drops are occasionally recorded on the *F-u* record (**4**). By observing the sample surface during the test using a camera, it has been shown that the occurrence of the first force drop is due to the initiation of the first circular crack. In this case, the fracture energy shall be calculated as the area under the *F-u* record up to the first crack initiation, instead of up to a 20 % force drop (**10**).

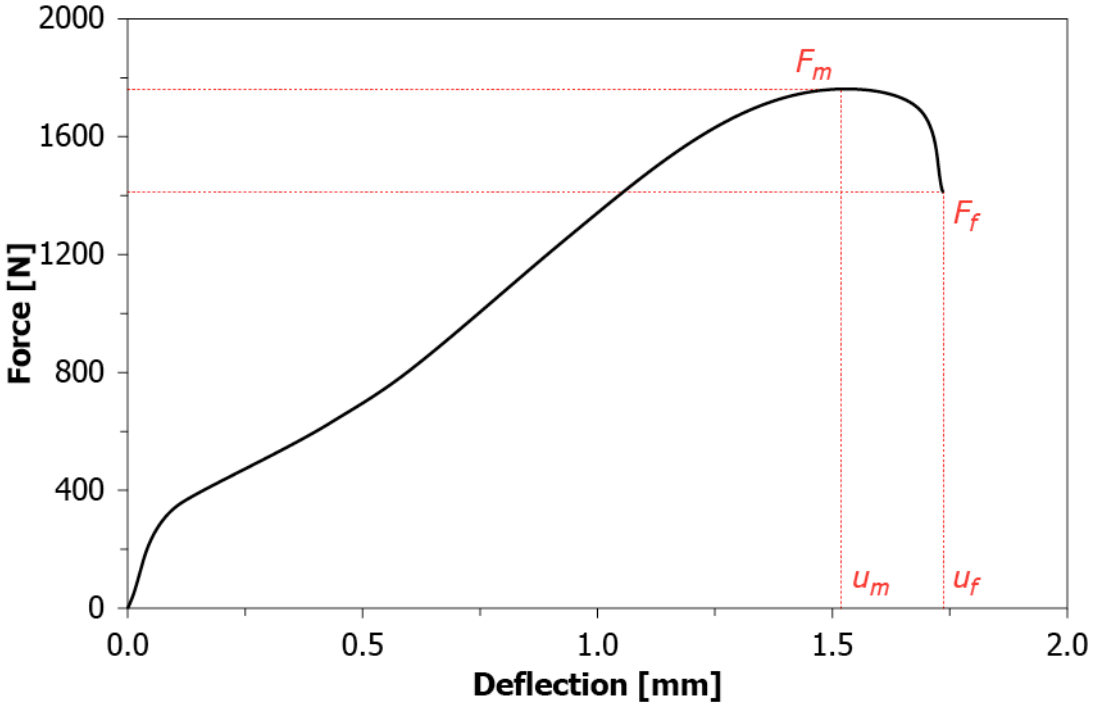


FIG. 3 Force-Specimen Deflection Curve Recorded during a SP Test of a Ductile Material

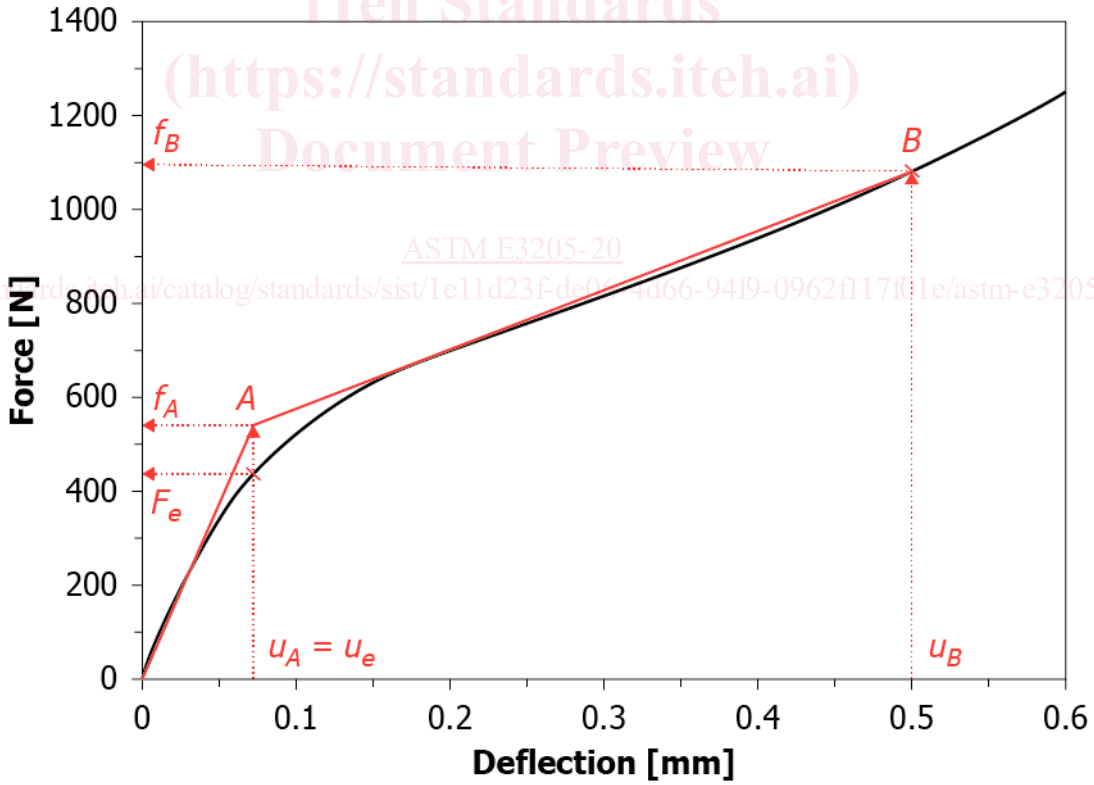


FIG. 4 Experimental Force versus Specimen Deflection Curve, *F(u)*, and Least Square Fit, *f(u)*

8.4 *Determination of the SP Energy E_m:*

8.4.1 The SP total energy E_m, is defined as the area under the *F-u* curve up to u_m:

$$E_m = \int_0^{u_m} F(u)du \quad (5)$$

8.5 *Energy Calculation in case of Pop-ins:*

8.5.1 In case of brittle materials, the *F-u* record can exhibit discontinuous force drops (pop-ins) caused by crack initiation followed by crack arrest (**11**). In this case, the procedure for energy calculation shall be modified as follows (Fig. 5):

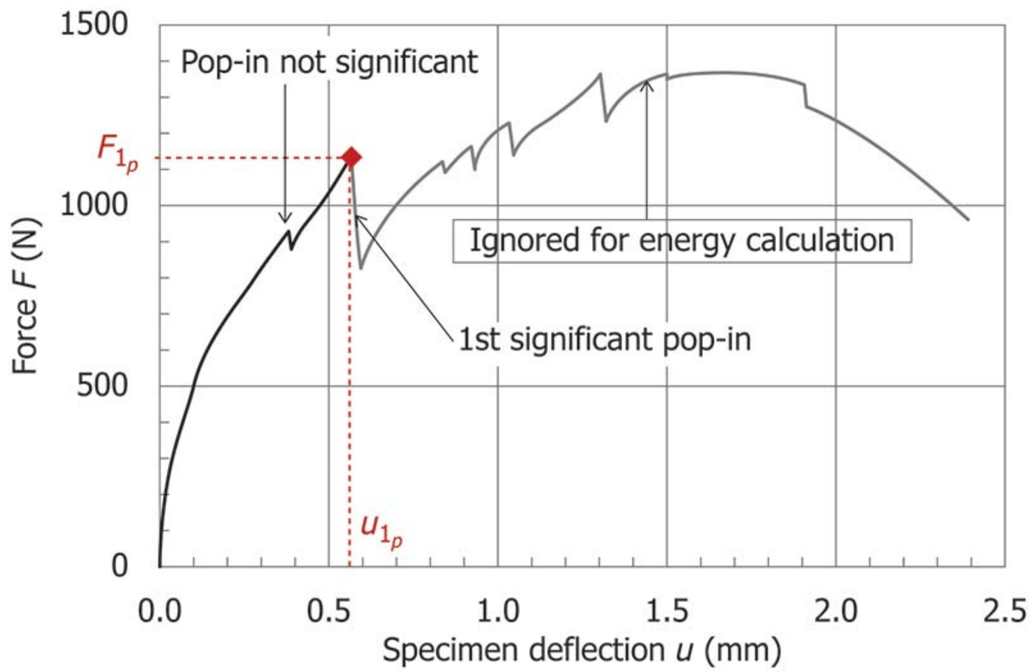


FIG. 5 Force-deflection Curve for a 13Cr-ODS-steel, Showing Not Significant and Significant Pop-ins

8.5.1.1 In Eq 6, replace u_m with u_{1p}. u_{1p} is the value of specimen deflection corresponding to the first significant force drop.

8.5.1.2 A pop-in shall be considered significant if force drops by at least 10 % of F_m.

8.6 *Determination of the SP Plastic Energy E_{PL}:*

8.6.1 The SP plastic energy, E_{PL}, is defined as the plastic area under the *F-u* curve up to u_m:

$$E_{PL} = E_m - 0.5\frac{F_m^2 \cdot u_A}{f_A} \quad (6)$$

8.7 *Determination of the Effective Fracture Strain, ε_f:*

8.7.1 The effective fracture strain, ε_f, is defined as:

$$\varepsilon_f = \ln\left(\frac{h_0}{h_f}\right) \quad (7)$$

where:

h_f = final thickness adjacent to the area of failure.

8.7.2 In order to measure h_f, the specimen should be sectioned through the location of fracture after the test (Fig. 6). Use of other methods for measurement of h_f (for example, tomography or scanning electron microscopy), shall be reported.

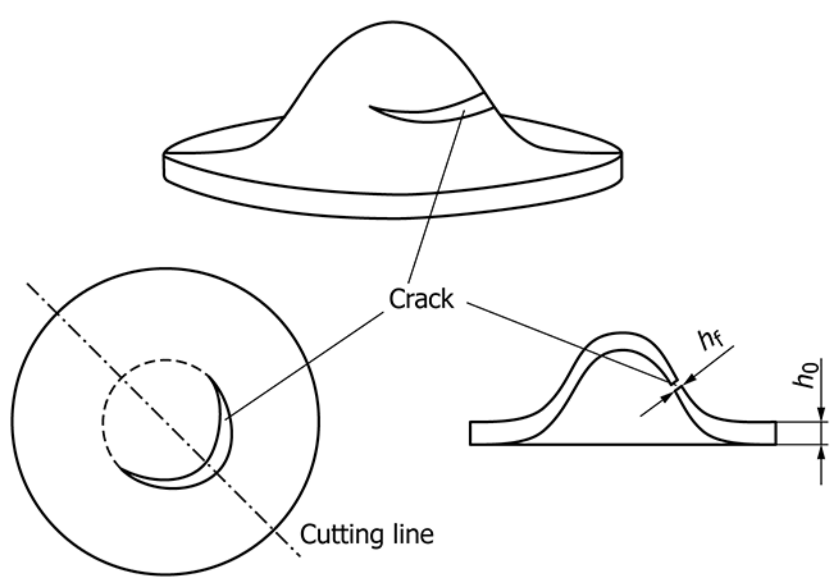


FIG. 6 Schematic Drawing of a Cracked SP Specimen, Indicating Where to Cut the Specimen, and Cross-Sectional View of the Cracked SP Specimen, Indicating Where to Measure h_0 and h_f (9)

9. Report

9.1 The test report shall include the following information:

9.1.1 Material specification, location of specimens in the component/product, and specimen orientation.

9.1.2 Specimen identification, including manufacturing procedures and finishing, and initial dimensions (h_0 and d_1).

9.1.3 Test conditions including test temperature, loading rate ($\dot{\varepsilon}_{SP}^{max}$), and test environment.

9.1.4 Description of testing equipment, including methods for controlling test conditions.

9.1.5 Type of displacement measured (specimen deflection, u, or punch displacement, v, or both).

9.1.6 Test results, including: *(1)* F-u or F-v curve, *(2)* SP test parameters (F_e, F_m, u_m or v_m, u_f or v_f, E_{SP}, E_m, E_{PL}, ε_f), *(3)* final measured dimensions (h_f and d_f), and *(4)* position of failure.

9.1.7 Fracture mode.

9.1.8 Any deviations from test conditions or recommended procedures, such as unscheduled interruptions or excursions in temperature or force.

9.2 *Additional Information*—Although not mandatory, the following information should be reported whenever possible:

9.2.1 Additional specimen information, including chemical composition, metallurgical characteristics of material, and service history.

9.2.2 Results of any post-test examination, including failure analysis.

9.2.3 Use of test results in further analyses, for example, comparison with other data, incorporation in residual life assessment methods, etc.

10. Precision and Bias

10.1 *Precision*—The precision of this test method is based on an Interlaboratory Study, ILS 1408, of WK 61832 (continuation of WK 47431) Test Method for Small Punch Test Method for Metallic Materials, conducted in 2017. Twelve laboratories tested seven different materials each. Every test result represents an individual determination. Each laboratory reported at least five replicate test results for the analyses. Practice E691 was followed for the design and analysis of the data; the details are given in ASTM Research Report No. RR:E10-1001[4].

10.1.1 Repeatability and reproducibility limits are listed in Tables 1-7. The above terms are used as specified in Practice E177.

10.1.2 The precision statement was determined through statistical examination of 3240 test results from 463 specimens tested by twelve laboratories on seven materials. The materials were the following:

Material 1a: Cr-Ni-Mo pressurized water reactor pressure vessel steel (ASTM A533B)

Material 1b: Cr-Ni-Mo pressurized water reactor pressure vessel steel (ASTM A533B)

Material 2: Cr-Mo-V pressure vessel steel (15CrMoVA)

Material 3: 18Cr-10Ni austenitic stainless steel (AISI 316 type)

Material 4: C-Mn pressure vessel steel (22 K, ASTM A 212 B type)

Material 5: 11Cr-20Ni high-alloyed ferritic stainless steel for reactor internals (10Cr11Ni20TR type)

Material 6: 10Cr-1Mo turbine steel (T-91 type)

10.2 *Bias*—The procedure in this test method for measuring small punch bulge properties has no bias because these properties can only be defined in terms of this test method.

11. Keywords

11.1 crosshead speed; deflection; displacement; ductile-to-brittle transition temperature; extensometer; failure; force; fracture; fracture energy; punch; strain; stress; ultimate tensile strength; yield stress

[4] Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR:E10-1001. Contact ASTM Customer Service at service@astm.org.

TABLE 1 F_m Results from ILS 1408[4]

Material	Average[A] N	Repeatability Standard Deviation, s_r N	Reproducibility Standard Deviation, s_R N	Repeatability Limit, r N	Reproducibility Limit, R N
1a	1751.96	34.44	115.58	96.45	323.63
1b	1747.70	29.17	124.04	81.67	347.30
2	2147.13	106.28	217.33	297.60	600.15
3	2163.91	52.12	224.66	145.66	629.05
4	1500.72	30.56	151.69	85.56	424.43
5	2567.46	50.16	248.80	140.36	696.64
6	2056.52	79.68	126.24	223.09	353.46

[A] Average of the laboratories calculated averages.