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Small Punch Test Method for Metallic Materials

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Foreword

This CEN Workshop 21 on “Small Punch Test Method for Metallic Materials” has been established and a Business Plan approved by a Workshop of representatives of interested parties on 2004-09-24 [1], the constitution of which was supported by CEN following the public call for participation made on 2004-09-08.

Following a decision from the Workshop, it has been decided to re-publish CWA 15627:2006 in order to correct a typing error in a formula. This version corrects and supersedes the CWA published in December 2006.

The formal process followed by the Workshop in the development of the CEN Workshop Agreement has been endorsed by the National Members of CEN but neither the National Members of CEN nor the CEN Management Centre can be held accountable for the technical content of the CEN Workshop Agreement or possible conflict with standards or legislation. This CEN Workshop Agreement can in no way be held as being an official standard developed by CEN and its members. These organizations were drawn from a number of economic sectors including academia, accreditation authorities, aerospace, automotive, material producers, material testing laboratories, national standards institutions and power generation.

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The final review/endorsement round for this CWA was successfully closed on (2007-10-29).

This CWA has been developed with the aim of providing guidance in the selection of the experimental conditions in a special type of mechanical test, namely the Small Punch (SP) test, suitable to obtain robust, reproducible and accurate results. In addition to recommending in the main body of this document the experimental procedures (“code of practice”), in two separate annexes guidance is given in the interpretation of the SP test results (namely the question of the comparability with / derivation of fundamental material strength data, i.e. those from the standard tests), and guidance in the use of SP tests to address relevant technological issues (e.g. specimen sampling from components, characterization of heat affected zones in welds, SP test applicability for non isotropic materials ...).

Actually two main versions of this SP test were developed historically, covering the two distinct scopes of measuring mechanical properties of materials in the high temperature (time dependent, creep viscous) and low temperature (time independent) domains. Not only the experimental set up and test procedures have to be different in order to match the distinct aims and conditions of time-dependent and time-independent SP testing, but also the technological & market scenario (the demand of SP tests by industry) is often different too; consequently, depending on their business position and strategy, some labs had been developing (or newcomers may be willing to develop) the high temperature version, while others developed (or would like to develop) the low temperature version only.

Therefore, in view of the considerations above, the group of developers of this document felt convenient to provide a document made of two main and fully self-consistent parts, having the maximum flexibility of current use and of future development routes (modifications, standardizations):

Part A is for time dependent SP testing,

Part B is for time independent SP testing,

each part is equipped with its own Annexes, A1 and A2 for Part A and B1 and B2 for Part B,

it is noted only that A2 and B2 are identical.

This CEN Workshop Agreement is publicly available as a reference document from the National Members of CEN: AENOR, AFNOR, ASRO, BDS, BSI, CSNI, CYS, DIN, DS, ELOT, EVS, IBN, IPQ, IST, LVS, LST, MSA, MSZT, NEN, NSAI, ON, PKN, SEE, SIS, SIST, SFS, SN, SNV, SUTN and UNI

Comments or suggestions from the users of the CEN Workshop Agreement are welcome and should be addressed to the CEN Management Centre.

Part A: A Code of Practice for Small Punch Creep Testing

0. INTRODUCTION

The life assessment and potential for possible failure of in service components is a critical issue in the safety and reliability analysis of industrial plants. In the case of plant operating at elevated temperature for long times, any of several degradation processes may potentially impair the mechanical properties, in particular the creep resistance, of their structural components. For most of the plant operating currently, the design life at the time of construction was usually based on relatively simplistic codes endorsed by practical experience, and finally corrected by an appropriate safety factor. Indeed, in light of the major advances in metallurgical knowledge and currently available analytical methodologies, today it would be possible to reduce the safety factor and to thus extend design lives. In addition, the new policies for environmental protection and the safety regulations for industrial plants make it more practical and economically convenient to extend the lifetime of existing component beyond their original design life rather than to build new plants. However, major investment to modernise and make existing plants more efficient is only profitable if the plant under consideration has sufficient residual life. Hence, reducing the uncertainty in the estimation and monitoring of remaining life of plant components is of fundamental importance to industry.

The component integrity can be rarely evaluated with the traditional and well-standardised mechanical test techniques, such as the uniaxial creep test, because there is insufficient material to sample non-invasively from the component. Hence, the need for evaluating the residual mechanical properties of structural components by direct testing methods has led to innovative techniques based on miniaturised specimens. Among these, a technique called the Small Punch Creep (SPC) test has emerged as a promising candidate as it can be considered as effectively a non-destructive 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 enable measurement of the realistic material properties for the specific component, identifying the present state of damage and focusing on the more critical (more stressed, more damaged) locations in the component. Before the promise of the technique can be turned into reality, a standardized and acceptable test methodology must be made available which is the fundamental purpose of this Code of Practice.

This document guides the user through several steps necessary to carry out a SP Creep test. The available methods for analysing the test records and, when needed and feasible, to infer basic, fundamental material characteristics (i.e. test method independent, specimen size independent) are described in Annex A1. Moreover in the Annex A2 informative guidance is given on industrial and technological issue: e.g. sampling guidance such as for example from components, from coated elements in gas turbines, from weldments.

1. SCOPE

This Code of Practice gives guidance on the procedure to be followed when carrying out Small Punch Creep tests. The objectives of such tests are to evaluate the creep behaviour of materials exposed in operating plant components in order to provide data needed for plant life and integrity assessment. The Code of Practice primarily addresses metallic materials tested under creep loading but can also be used for other materials. Determination of tensile test data at elevated temperature can also be realised using the proposed methodology. But the methodology applied in Part B of this document should be applied.

The scope of the Code of Practice covers the following:

Test Piece

Test pieces are discs of specified dimensions procured from components or any other source. They may be homogeneous or contain manufacturing features such as for example joints, weldments, defects or coatings

Load

The load may be applied to the disc from a pneumatic, hydraulic or any other mechanical source. The Code of Practice particularly addresses the usual situation where the load is maintained constant throughout the test, but the general principles apply also to tests where the load is cycled, with dwell periods.

Temperature

The test temperature will usually be within the creep range for the materials under test. The Code of Practice specifically addresses the usual situation where the temperature is maintained constant throughout the test, but the general principles also apply to thermal cycling with or without dwell periods.

Environment

The test pieces will usually be tested in an inert gas environment. However, the general principles should also apply when other environments are used. Although special precautions will be necessary where hazardous or corrosive environments are used, these are not detailed in this document.

2. DEFINITIONS

For the purpose of this Code of Practice, the symbols and designations are as given in Table 1 and the following definitions apply.

2.1 Small Punch test

A mechanical test carried out on a small disc shaped test piece by means of the application of a mechanical load applied to one surface of the test piece by means of a shaped punch in order to investigate its response to the load.

2.1.1 Small Punch Bulge test

As 2.1 above, but under the condition that the perimeter of the disc is clamped and does not displace during the test.

2.1.2 Small Punch Drawing test

As 2.1 above but under the condition that the perimeter of the disc is not fully clamped and may displace during the test.

2.2 Small Punch Creep Test

Small Punch Test carried out under creep conditions

2.2.1 Test Piece

The disc under investigation, independent of its material of composition, its structure and its manufacturing route.

2.2.2 Test Piece Environment

The environment which is in contact with all surfaces of the test-piece.

2.3 Small Punch Creep Test Stress

The calculated stress induced in the test piece by the load, considered equivalent to the initial stress in a uniaxial test piece or component under creep conditions.

Table 1 - Symbols and Designations

Symbol	Unit	Designation
h_0	mm	SP disc initial thickness
r	mm	Radius of punch indenter
d	mm	Diameter of disc
D, R	mm	Diameter, radius of receiving aperture
L	mm	Length of receiving die edge chamfer
u_1, u_2	mm	Punch Displacement, Disc Deflection respectively
V	m/s	Punch velocity
F	N	Punch load
σ	Pa	SP disc initial stress (calculated)
k_{SP}	-	SP creep test correlation factor
t	s	Test time
T	K	Test Temperature

3. APPARATUS

The apparatus should comprise some or all of the following:

3.1 Test Rig

Fig. 1 illustrates schematically a cross-sectional view of the specimen holder with a spherical punch and the test specimen. It is recommended that, prior to the test, the holder is forced to clamp the specimen rigidly to limit specimen deformation in the region at the hole of the lower fixture. It is accepted that the test can be carried out without the disc being fully clamped but rather guided, known as clamp without load. For such a case this aspect must be recorded in the test report as this is known to influence the stress to which the disc is subjected. The receiving aperture of radius R is recommended to be 2mm with a 45° chamfer at $R + 0.2\text{mm}$. The materials of construction of the upper and lower die should be the same and of a similar coefficient of thermal expansion to the disc under test so as to minimise thermal stresses. The surface of the upper part of specimen holder in contact with the test specimen shall be plane and parallel to the surface of the lower part of specimen holder. Both surfaces shall be clean and free from oxide build-up, corrosion and dirt. The working surfaces of the upper and lower part of the specimen holder shall have a hardness of 55 HRC or higher. The test rig shall have a spherical (hemispherical)-ended punch capable of forcing the central portion of the test specimen through the aperture in the receiving die until the end point of the test occurs. Alternatively a spherical ball indenter may be used but is not recommended due to the difficulty to avoid ovality, the possibility of its' lateral displacement and the risk of it embedding within the disc at the end of the test. The hemispherical portion of the punch or alternatively the sphere shall have hardness not less than 55 HRC to be sufficiently rigid so as not to be deformed during the test. The punch radius r is recommended to be between 1.0 and 1.25mm.

3.2 Loading System

The method of application of the load shall be such that the load can be controlled to $\pm 1\%$ agreeing with the latest recommendations for creep testing provided by the European Creep Collaborative Committee (ECCC) and the draft EN/ISO standard for uniaxial creep testing of metallic materials. The loading system should be calibrated for accuracy using a proving ring or similar certified device and the results recorded at least once per annum.

3.3 Strain Measurement System

Extensometry, strain gauging or other methods of determining the deformation of the test-piece in a continuous fashion may be used providing that they are suitably calibrated and applied in accordance with good testing practice and the manufacturer's instructions. The accuracy and frequency of disc deflection measurements will be determined by the nature of the actual test being done. Alternatively, or additionally, the displacement of the punch should be continuously recorded. The difference between punch displacement and disc deflection represents eventual thinning of the disc and should be recorded if possible. Furthermore, a discontinuous method may be employed to take dimensional measurements. The technique is analogous to the taking of interrupted strain measurements during a uniaxial creep test and should conform to the appropriate standard. The method also permits the dimensions at a large number of locations within the disc to be monitored during the test but has serious drawbacks associated with re-insertion of the disc specimen after measurements.

3.4 Heating System

The heating system should provide a uniform temperature distribution throughout the test section of the disc. In the case of a clamped perimeter in the Small Punch Bulge test, the section beneath the clamp is not considered as part of the test section.

A temperature measuring system is to be supplied comprising thermometers, usually thermocouples, appropriately located to determine that the full test section remains within the temperature limits prescribed for the test. The thermocouples should be of a type and composition suitable for the test temperature regime selected for the test and calibrated in accordance with the appropriate ISO or EN standard.

The temperature control system should be capable of maintaining the temperature constant to within $\pm 0.25\%$ of the set temperature in degrees absolute, K, by automatic means throughout the test. See Table 2 for conversion to degrees C and comparison with the draft EN/ISO standard for uniaxial creep testing of metallic materials.

3.5 Test Environment

Due to the small dimensions of the Small Punch Creep test-pieces, it is recommended that the tests are carried out in an inert environment to prevent oxidation or corrosion of the exposed surfaces of the test-piece. For studies where the effect of the environment on creep behaviour is of specific interest, other environments may be employed but this purpose must be clearly stated in the test report and the publication of the test results. For all environments, including inert environments, the composition should be known and, if necessary, strictly controlled within specified limits.

3.6 Additional Measurements

Other test parameters may be monitored such as crack initiation or growth either by continuous (potential drop, acoustic emission) or by discontinuous methods. These additional measurements may not be allowed to affect the results of the Small Punch Creep test itself. Any additional measurement made should be reported with the test results.

3.7 Data recording

Equipment should be provided which will record the test parameters automatically with a resolution which matches that of the measuring instruments and should be accurate to within $\pm 1\%$ of full scale deflection at least and preferably within, $\pm 1\%$ of the measured signal, when all sources of error are taken into account.

4. TEST PIECES

4.1 Design

A single test piece design is recommended in this Code, which is a disc of diameter, d , 8mm and initial thickness, h_0 , 0.5mm. Exceptions to these dimensions can be accepted provided that they are fully reported with the test results as follows:

- i) a larger diameter is allowed for the case of a Small Punch Bulge Test where the disc is clamped with load around its periphery. The clamped area should be greater than one third of the total area.
- ii) a different disc thickness is allowed if there is a good justification made for micro-structural reasons such as grain size, coating thickness, inclusion of a weldment etc.

4.2 Manufacture and metrology

The test piece is to be procured from standard test material, e.g. bar or sheet or from engineering components prior to or during operation. Methods for extracting material from components are detailed in Annex A2. In order to minimise work hardening in the surface of the test piece, the disc should be machined to a thickness of approximately 0.55mm and then ground to at least 200 grit on both sides (one side for coated specimens) to achieve the final dimension of 0.5mm with a tolerance of no more than $\pm 0.5\%$. With the exception of the case mentioned in 4.1 i) above for a specimen clamped with load, the disc diameter should be $8\text{mm} \pm 1\%$. The thickness of the test piece should be measured at four positions around the perimeter at 90° intervals and at the central position. The diameter should be measured in two positions at 90° .

4.3 Identification and documentation

Test-pieces should be permanently marked on the curved edge with a unique identifier. The position of the identifier should also enable the position of the four thickness measurements to be traced.

A written record of each test piece should be kept, listing:

Identification
Material composition and cast
Material condition and original location
Test piece manufacturing route
Test piece original dimensions

This information should be transferred to the test documentation to form a complete test record.

5. TEST PROCEDURE

5.1 Test piece installation

- a) Insert the test piece and clamp it centrally into its position
- b) If preparing for an SP Drawing test, clamp the test-piece without load.
- c) Locate the extensometer against the test-piece at its centre opposite to the punch tip
- d) Close the system and evacuate and flush twice with high purity argon or other appropriate inert gas. In some cases an active gas may be used if required for the purpose of the test.

5.2 Determination of test load

The applied load in any test has to be determined from geometrical factors and material properties in order that creep failure in the Small Punch test will occur at the same time as that in a conventional uniaxial creep test at the same temperature. For the case where there is no prior information on expected behaviour, the ratio of SP test load (F) to the uniaxial creep stress (σ) should be given by:

$$F/\sigma = 3.33k_{\text{SP}} R^{-0.2} r^{1.2} h_0$$

where

r is the radius of the punch indenter,
 h_0 is the test-piece thickness,
 R is the radius of the receiving hole.

This equation is derived from stretching membrane theory (Annex A1) and applies for an unclamped test providing the disc deflection exceeds 0.8 mm. For the case of the disc clamped with load it is estimated that this ratio should be reduced by approximately 20%. The SP creep test correlation factor, k_{SP} , has first to be determined empirically for the particular material under test. Where k_{SP} is not known, the first tests should be set up assuming $k_{SP}=1$ and a series of a minimum of 5 tests at one particular temperature carried out in order to evaluate k_{SP} through comparison with the stress rupture behaviour defined from conventional uniaxial testing.

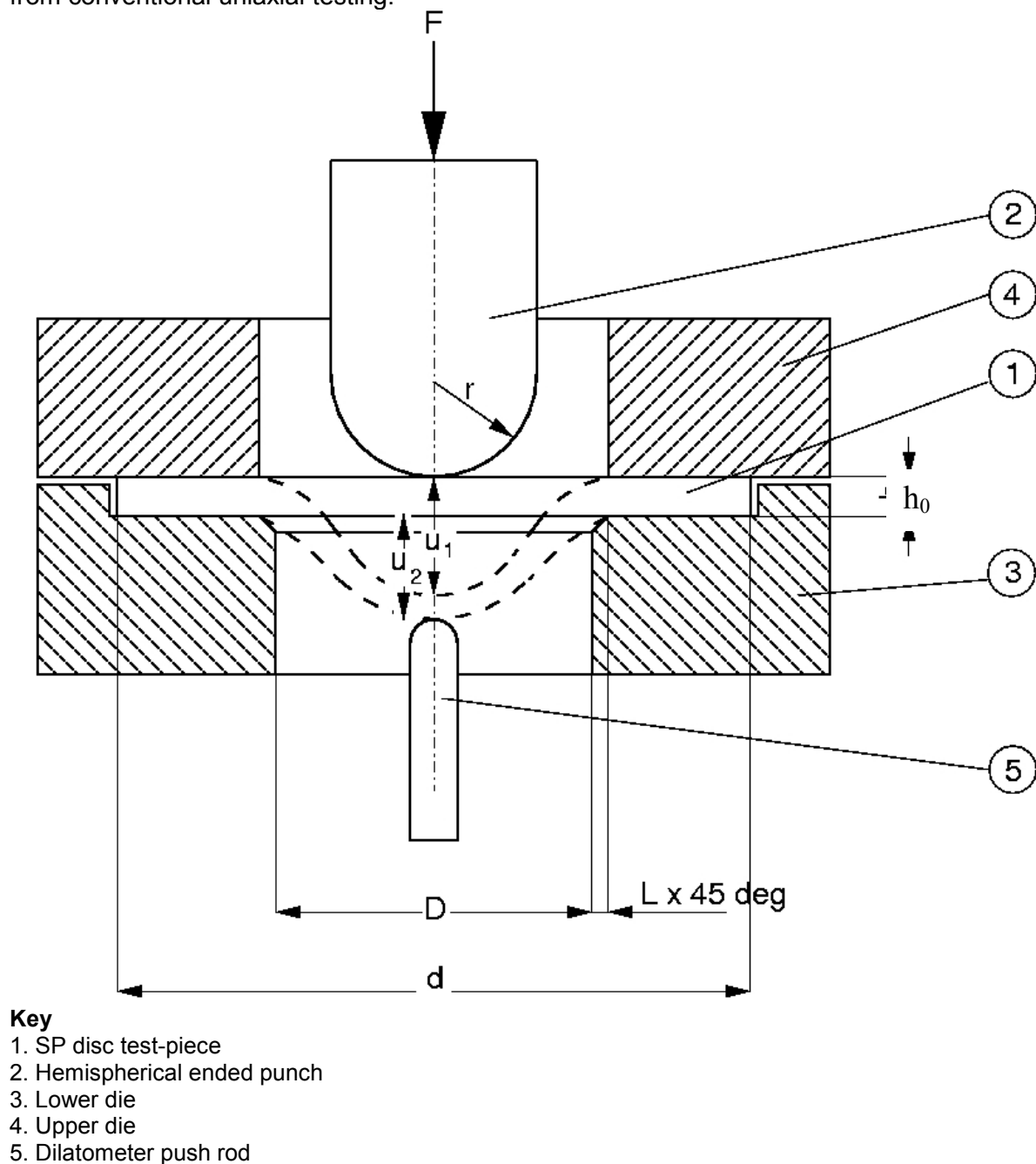


Figure 1 - Geometry of the SP Creep test installation

5.3 Application of load and temperature

The application of load and temperature should be as applied in a conventional uniaxial creep test as given by the European Creep Collaborative Committee (ECCC) and the draft EN/ISO standard for uniaxial creep testing of metallic materials. The temperature should be raised as quickly as possible after filling the chamber with inert gas however, for the Small Punch test, once the planned test temperature has been achieved and stabilised, the load should be applied immediately. Depending upon the material and test conditions, the effects of loading rate may be significant. In all cases the load should be increased smoothly to the test load and as rapidly as possible consistent with the load application system incorporated in the test machine. Should there be a marked difference between the thermal expansion coefficient of the punch and disc material, any effect of thermal loading on the test due to expansion coefficients should be carefully evaluated.

5.4 Monitoring and maintaining test conditions

The test conditions should be monitored continuously and maintained at the required levels as stated in Sections 3.1 and 3.3. This can be achieved by manual adjustment or fully automatic means. The monitoring and control systems should be checked and calibrated prior to each test and at regular intervals throughout the test period to ensure that the required test conditions are accurately maintained.

5.5 Test interruption and termination

Should the test be interrupted, it is recommended to restart the test in exactly the same way as the original starting procedure. It is not recommended to remove the test-piece for evaluation and then to re-introduce the same test piece to continue the test. The termination of the test equivalent to creep rupture failure of the test-piece can only be clearly defined through the observation of a sudden rise in the deflection rate. Unless there is a major fracture area developed, in most cases this rise in deflection rate will not be distinguishable from the rise due to advanced tertiary creep. Consequently it is proposed that the deflection at which the test should be terminated should be estimated before the test, based on experience with the material at the test load and temperature. This termination can be triggered automatically or manually and should be accompanied by switching off the furnace, allowing the test piece to return to ambient temperature.

5.6 Post test examination

After the test the test-piece should be photographed on both faces and also from the side to record a visual image of the total deflection. Measurements should be made of this total deflection and also of the diameter of the disc in order to assess the effectiveness of the clamping. Sectioning of the disc is recommended to analyse the variation in strain evidenced by thinning.

5.7 Data records

Accurate records should be kept of temperature, load, deflection and test duration. In addition, a record should be kept of all adjustments made to control or alter the test conditions and of any events that lead to interruptions in the test periods.

6. REPORT

6.1 Minimum Requirements

It is obligatory to cover the following items of information:

- a) Specific objective of the test,
- b) Reference to procedures including stress calculation methods adopted being in accordance with this Code of Practice,
- c) Test piece description, including (i) manufacturing procedures and finishing, (ii) initial measured dimensions and (iii) special features, if any,
- d) Test conditions, including (i) test temperature, (ii) test load, (iii) test environment,
- e) Description and relevant dimensions of testing equipment, including methods for controlling test conditions,
- f) Test results, including (i) total duration of the test, (ii) time to reach temperature and the soaking time prior to each loading, (iii) deflection measurements, if any, and (iv) final measured dimensions,
- g) The position of failure, cracking or major deformation,
- h) Report of any deviations from test conditions or from recommended procedures e.g. unscheduled interruptions or excursions in temperature or load.

6.2 Additional Information

Although not obligatory the following items should be reported whenever possible:

- a) Test piece details including processing route, metallurgical composition and characteristics, known creep properties for this class of material at this stress and temperature and service history, if applicable,
- b) Results of any post-test examination including fracture characteristics,
- c) Use of the test results in further analysis e.g. comparison with other data, incorporation in life time assessment methods etc.

Table 2 - Allowable Test Temperature Tolerances

Test Temperature		Tolerances $\pm$ °C	
°C	K	SP recommended $\pm 0.25\%K$	Draft EN/ISO standard
20	293	0.7	↑ 3
100	373	0.9	
200	473	1.2	
300	573	1.4	
400	673	1.7	
500	773	1.9	↓
600	873	2.2	↑
700	973	2.4	4
800	1073	2.7	↓
900	1173	2.9	↑
1000	1273	3.2	5
1100	1373	3.4	↓

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ANNEX A1

Relationship to uniaxial creep test properties

The basic idea for determination of the load which should be applied in a Small Punch creep test is to answer the question: “What is the load value to obtain the same time to rupture as in a uniaxial creep test?” However, this question is not so easy to answer as stresses are not maintained constant during the progression of creep deformation. Upon loading, deflections are very small, and the load balance is through shear stresses induced by bending moments. With further deflection, increasing the load balance is mainly through membrane stresses, which vary with deflection and current thickness. A practical way is to determine the membrane stresses at the steady state or stationary stage, which might be used to estimate the rupture time of the test.

As reported by Li and Sturm (2005) and others, several relations between load and stress are available and reviewed in the following paragraph. All of them are derived from equilibrium between load and membrane stresses with bending stresses neglected. In the Small Punch creep tests deflection at failure is usually about 3-4 times the specimen thickness or about 40%-60% of the disc support distance. When the test specimen undergoes such a large deformation, neglecting bending stresses is not unreasonable.

In total, four equations (a-d below) have been found in the literature, which are listed in the round robin report (Bicego et al, 2003) and quoted here. The argument which follows explains the reasons for choosing the equation (based on Chakrabarty 1970) governing load and stress given in the Code of Practice in Section 5.2. Chakrabarty's stretch membrane model is recommended as it is rigidly derived from elastic theory, and provides a complete set of relations. Regression analyses are carried out to give user-friendly general formula to determine the test load of small punch test. For the sake of clarity the symbols used from Chakrabarty and other authors cited hereafter are translated into the symbols adopted in this Code of Practice:

F – applied load on the SP specimen

h – current thickness of the disc (at the contact boundary)

h_0 – uniform initial thickness of the disc

R – radius of receiving aperture (die hole)

r – radius of the punch

d – radius of the contact boundary

σ – membrane stress

φ - angle made by the surface normal with the vertical axis

θ_0 – angle φ at the contact boundary ($\theta_0 = \varphi_{\max}$)

θ - angle φ at $d = R$ (clamped boundary)

u_1 – displacement of the punch ($\varphi = 0$)

a) The tensile radial (membrane) stress from the equilibrium (Bicego, 1998):

$$\frac{F}{\sigma} = [2\pi \cdot h \cdot (r + \frac{h}{2}) \sin \theta_0] \sin \theta_0 \quad (2.1)$$

where:

the angle θ_0 at the contact boundary could be empirically obtained from the comparison between uni-axial and SP testing. From the tests on steel X20 in the COPERNICUS project, $F/\sigma = 1.876$ and consequently $\theta_0 = \pi/4.6$.

b) A correlation based on the membrane stress equivalent concept was proposed by Dobes and Milicka (2001):

$$\frac{F}{\sigma} = [2\pi \cdot h \cdot r \tan \varphi] / [1 + \tan^2 \varphi]^{1/2} \quad (2.2)$$

This equation refers the situation at any point from the contact surface (here h should be considered the specimen thickness at the point examined). Adopting the simplification that the relevant stress is evaluated at the inflection point (contact boundary) of the SP specimen as in the previous model, equation (2.2) would reduce to:

$$\frac{F}{\sigma} = [2\pi \cdot h \cdot r \sin \theta_0 \tan \theta_0] / [1 + \tan^2 \theta_0]^{1/2} \quad (2.2a)$$

c). Tettamanti and Crudeli (1998) also put forward the second relation from the deflection process of the disc (applicable for large deflections):

$$\frac{F}{\sigma} = K [2\pi \cdot h \cdot r (\frac{D}{2r} - \chi)] \quad (2.3)$$

where:

D: receiving hole diameter equal to 2R, (typically 4 mm),

K: clamping coefficient, $K=0.5$ for unclamped condition where $K>0.6\sim 0.8$, if clamped

(: friction coefficient, $0.6\sim 0.7$, depending on temperature and the applied load

With this second relationship a value of $F/(\sigma = 1.95\sim 2.06$ is obtained, depending on test characteristics for the unclamped condition of the specimen.

In the first approximation, $F/(\sigma = 2$ is suggested by Tettamanti and Crudeli.

d) The formulation as proposed by Chakrabarty on stretch forming over hemispherical punch heads is also quoted as (Chakrabarty, 1970):

$$\frac{F}{\sigma} = 2\pi \cdot h \cdot r \cdot \sin^2 \theta_0 \quad (2.4)$$

$$h = h_0 \left\{ \frac{1 + \cos \theta_0}{1 + \cos \theta} \right\}^2 \quad (2.4a)$$

Where h is the specimen thickness at the contact boundary;

The relation between load and membrane stresses can be directly obtained if bending stresses are neglected. For example in Eqn. (2.1), the periphery of the contact boundary between punch header and the disc is taken as $2\pi \cdot (r + \frac{h}{2}) \sin \theta_0$, leads to a balance in the

load direction and considering the slope of membrane stresses, $(0, \theta)$, we have Eqn. (2.1) directly. In this case, $F/(\sigma h)$ is proportional to initial disc thickness h_0 or disc thickness h at the contact boundary. We notice that, in all equations mentioned above, $F/(\sigma h)$ is proportional to h_0 or h , i.e. all equations are based on a membrane model, while bending stresses are neglected. Therefore apart from subtle differences these equations are essentially the same.

Taking Eqn. (2.1) as example again and considering the radius of the contact boundary as $(r + h/2) \sin \theta_0$, the periphery of the contact boundary is taken as $2\pi \cdot (r + \frac{h}{2}) \sin \theta_0$, while the peripheries of the contact boundaries in other equations are taken as $2\pi \cdot r \sin \theta_0$. In Eqn. (2.1) there is no expression for disc thickness changes, although this is considered in other equations.

By using the above equations to determine test load for Small Punch creep test, a common problem is faced in determining the angle θ_0 at the contact boundary. In Eqns. (2.1) and (2.3), empirical values are suggested for a specific case. In order to set up a general user-friendly formula, regression analysis is needed.

Chakrabarty's stretch membrane model is recommended as it is rigidly derived from elastic theory, and provides a complete set of relations. The relation of load balance is already shown as Eqn. (2.4).

Meanwhile, Chakrabarty provided expressions for the central displacement of the punch, which equals u_1 at $\varphi = 0$ (Figure 1), as:

$$u_1 = R \sin \theta \ln \frac{\tan(\theta_0/2)}{\tan(\theta/2)} + r(1 - \cos \theta_0) \quad (3.1)$$

An equation relating θ and θ_0 is shown as:

$$\sin \theta = \frac{r}{R} \sin^2 \theta_0 \quad (3.1a)$$

In order to obtain a user friendly formula, regression analyses are used here (Zhen Yang, Zhiwen Wang, 2003). From Eqns. (2.4) and (3.1), a set of F/σ and u_1 values are computed by inputting the actual specimen sizes R and r and setting θ_0 to values in the range from 0 to 90° . Then fitting the values of F/σ and u_1 by a poly-nominal expression, a relationship between F/σ and u_1 (in unit of mm) is finally obtained. For the European round robin (Bicego et al 2003), $h_0 = 0.5$ mm, $R = 2.0$ mm and $r = 1.25$ mm. The relationship between F/σ and deflection (in unit of mm) is expressed in the form of

$$F/\sigma = 1.72476u_1 - 0.05638u_1^2 - 0.17688u_1^3 \quad (\text{for } u_1 > 0.8 \text{ mm}) \quad (3.2)$$

When deflection u_1 tends to zero, F/σ also tends to zero, i.e. the membrane stress σ tends to infinity. Thus the formula is not valid in the small deformation stage as the bending moment is neglected. According to an engineering judgment, the results for large deformation are

assumed valid if deflection is larger than 20% of the maximum structural dimension. Therefore, the stresses given by Eqn. (3.2) are valid, even in creep analysis, if deflection is larger than 20% of the receiving hole diameter, which for a typical diameter of 4mm would be 0.8 mm. According to Equation (3.2), the maximum value of $F/\sigma = 1.891$ at deflection $u_1 = 1.60$ mm. This value is very close to that suggested by Tettamanti and Crudeli in Eqn. (2.1). If deflection > 1.60 mm, F/σ decreases due to the reduction in thickness becoming faster (see Fig.2).

Regression analyses carried out by MATHCAD files can be also used to set up a general formula to determine test load for the Small Punch creep test. The purpose of the general formula is to find the relation between F/σ and specimen sizes R (radius of die hole) and r (radius of punch). Because F/σ is proportional to the disc thickness h_0 , the general formula can be written in the form of:

$$F/\sigma = b_1 R^{b_2} r^{b_3} h_0 \quad (4.1)$$

Taking logarithms on both sides, we have:

$$\log(F/\sigma) - \log(h_0) = \log(b_1) + b_2 \log(R) + b_3 \log(r) \quad (4.1a)$$

The unknown constants b_1 , b_2 and b_3 can be obtained by a multi-variables linear least square fitting. From Eqns.(2.4) and (3.1), a set of F/σ values are computed by inputting specimen sizes h_0 , R , and r , and setting θ_0 to values in the range from 0° to 90° . The ranges used in this calculation are 2 mm - 3 mm for the die hole radius, R , and 1 - 1.5 mm for the punch radius, r . Then the unknown constants b_1 , b_2 and b_3 are obtained by a multi-variables linear least square fitting. The general formula to determine test load for small punch test can be expressed in the form of:

$$F/\sigma = 3.332 R^{-0.202} r^{1.192} h_0 \quad (4.2)$$

Rounding of indices, for the purposes of this Code of Practice, this equation would become:

$$F/\sigma = 3.33 k_{SP} R^{-0.2} r^{1.2} h_0$$

where a SP creep test correlation factor (k_{SP}) is introduced in order to take into account the different creep ductilities of different materials and even for the same material at different temperatures and stresses.

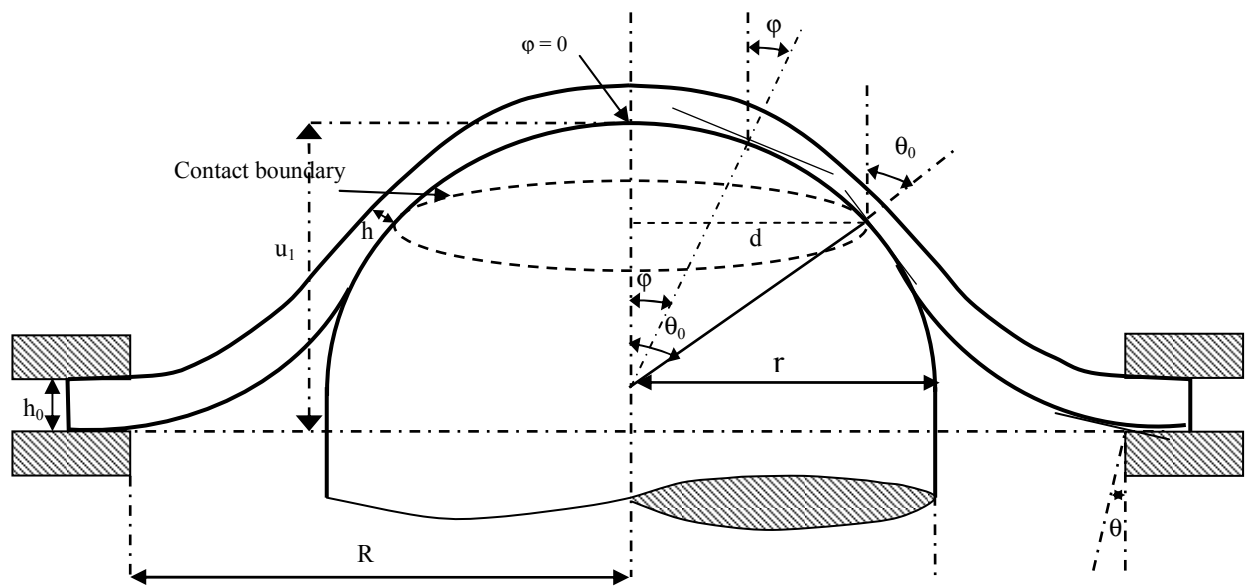


Figure 1 - Geometry of deformation (quoted from Chakrabarty, 1970)

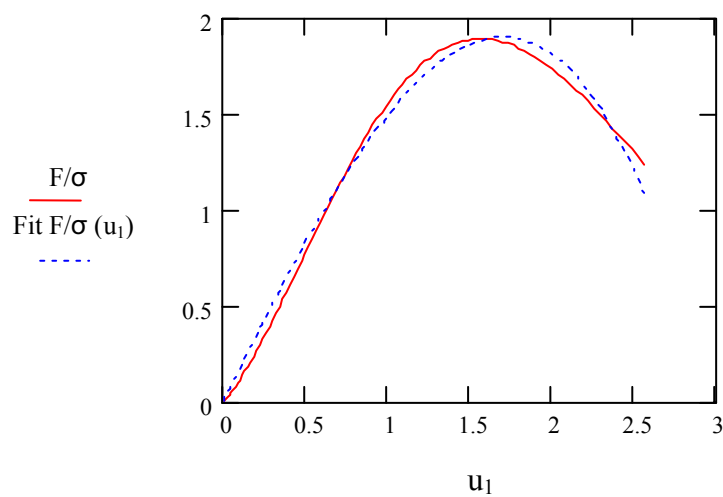


Figure 2 - Relation between F_{sp}/σ and punch displacement according to membrane stretch model (for $u_1 > 0.8\text{mm}$)

Annex A2

Guidance on Relevant Technological Issues: specimens sampling from components

Nomenclature in this Appendix A2

Boat samples: surface samples, cut from the component in two halves, usually leaving high stress concentration notches.

Core samples:

A2.1 INTRODUCTION

A major benefit of the small punch (SP) test is that it often enables mechanical characterisation of material from in-service components in a minimally invasive, virtually non-destructive manner; i.e., component material is removed for testing without necessarily a requirement for repair. The small volume of the SP test specimen requires that a minimum amount of component material be removed (sampled) for testing. Current standardised mechanical tests, on the other hand, require relatively large volumes of material that cannot be extracted from in-service equipment without repair after the material removal. This Appendix provides some guidance on material removal with a view to meeting current objectives of the SP test as noted in the preceding text of the Code of Practice. It is important to note at the outset, that the action of removing material from an in-service component requires approval of the owner/user and, in some instances, approval of the jurisdictional authority responsible for enforcing regulations intended to ensure safe operation. This document cannot provide guidance that encompasses such considerations, and the reader is cautioned that the feasibility of material sampling of operating components needs to be evaluated on a case-by-case basis within the context of future safe operation and pertinent regulation.

The following sections describe potential applications of the SP test; some available miniature sample removal technologies that have been used to generate material for SP testing; considerations in sample removal (selection of sample locations, amount of material, etc.); and preliminary guidance on the use of SP test data. The significant variability in the test methods and test data interpretation of the SP test prior to the adoption of this CWA precludes providing detailed guidelines on use of data. Therefore the information contained in this Appendix is to be considered preliminary.

A2.2 APPLICATIONS OF THE SP TEST

The SP test provides a direct means of mechanically testing material from a localised region of a component or structure, such as the heat-affected zone of a weldment, a coating, etc. The test potentially provides a more reliable means of characterisation than indirect methods based on laboratory simulations of the localised region or analytical predictions based on general models. Additionally, in many instances, the amount of material available is so limited as to preclude conventional testing using standard size specimens.

A2.2.1 In-Service Equipment

The primary need to characterise the mechanical properties of material removed from in-service components stems from a desire or requirement to assess the mechanical integrity of the component in order to establish its future fitness for service. The mechanical integrity

assessment depends crucially on, among other things, the material mechanical properties. Such properties include time-independent properties such as yield and tensile strength, ductile-brittle transition temperature, fracture toughness, etc., and time-dependent properties such as creep, and creep rupture strength, as outlined in the preceding Codes of Practice. These properties for a given situation may not be reliably known or estimated for a range of possible reasons including:

- Effects of material ageing, such as those at high-temperature, that can result in a reduction in fracture toughness and/or creep/creep rupture strength, etc. A well-studied example of sampling and SP testing application is the case of low alloy CrMoV steel, used for high-pressure steam turbine rotors, that exhibits temper embrittlement in service.
- Unknown pedigree of material, such as in the case of some older components where manufacturing records are not available or where the original specification for the material of construction did not include the relevant mechanical properties. Examples of these include cases where the original material specification did not include any requirement for fracture toughness, but where this property is now known to be critical to guard against unstable and catastrophic fracture from cracks that were either pre-existing or have developed during service.
- Properties of material at specific component locations are unknown as a result of fabrication or repair/refurbishment actions. The primary locations of interest in this case are weldments where properties of the weld and adjacent heat-affected zone (HAZ) are not known.
- Effects of abnormal loading conditions during operation that may have affected the as-manufactured properties. Examples of such loading would be short-term overload or periods of load (mechanical and thermal) beyond the design values.

A2.2.2 Laboratory Applications

In addition to the application of the SP test to in-service equipment, as noted above, the small specimen volume can be used to advantage of in other laboratory investigations where a minimal amount of relevant/representative material is available. Some examples of these include:

Failure analysis - where the amount of material available is often insufficient for a testing programme with conventional laboratory specimens. Furthermore, it is often the case that the failed part available for evaluation is of a configuration that precludes using standard test specimens and methods. The SP test often provides a vehicle to make measure properties with minimal destruction of the failed part and to focus on specific locations of interest.

In cases where the metal structure is, by design, of small section size (e.g., turbine blades), the limited available material in the aerofoil region makes the SP test a good choice.

Localised material damage, for example, characterisation of the root material in an ex-service turbine blade where damage from thermal fatigue and creep is localised to the near-surface region.

Localised microstructure, where the properties of the material are dependent on location e.g. microstructural regions of a weld - filler metal and especially the heat-affected zone (HAZ). A widespread problem presently under investigation is the unreliable characterisation (by the conventional large specimens) of the HAZ region in 9Cr steel weldments developing "Type IV" cracking. Most of the finite element modeling developments in the field of

creep life assessment of welded joints suffer from the limitation that HAZ properties are assumed, or measured from bulk "simulated HAZ" materials produced by heat treatment. There is a continuing lengthy debate and no general consensus over the relevance of the simulated materials.

Measurement of properties of coatings such as thermal barrier coatings. In this case, the small specimen thickness and loading configuration provides a means of testing coatings in an as-produced condition (coating plus portion of substrate). The application could involve assessing newer designs/processes or evaluating ex-service components for coating degradation. Preliminary feasibility of SP testing for coatings characterisation (such as strength and ductility) has been explored (e.g., [1, 2]).

The SP test has also found wide application in characterisation of polymeric materials, primarily for medical use. One form of the test, arising from research on polyethylene and polymethylmethacrylate or PMMA (e.g., [3, 4]), is now an ASTM standard for testing of ultra-high molecular weight polyethylene for surgical implants [5]. The advantage in this case is that medical implant product, pre- or ex-implant, is of limited section size and conventional mechanical test methods cannot be applied.

A2.3 MINIATURE SAMPLE REMOVAL TECHNOLOGIES

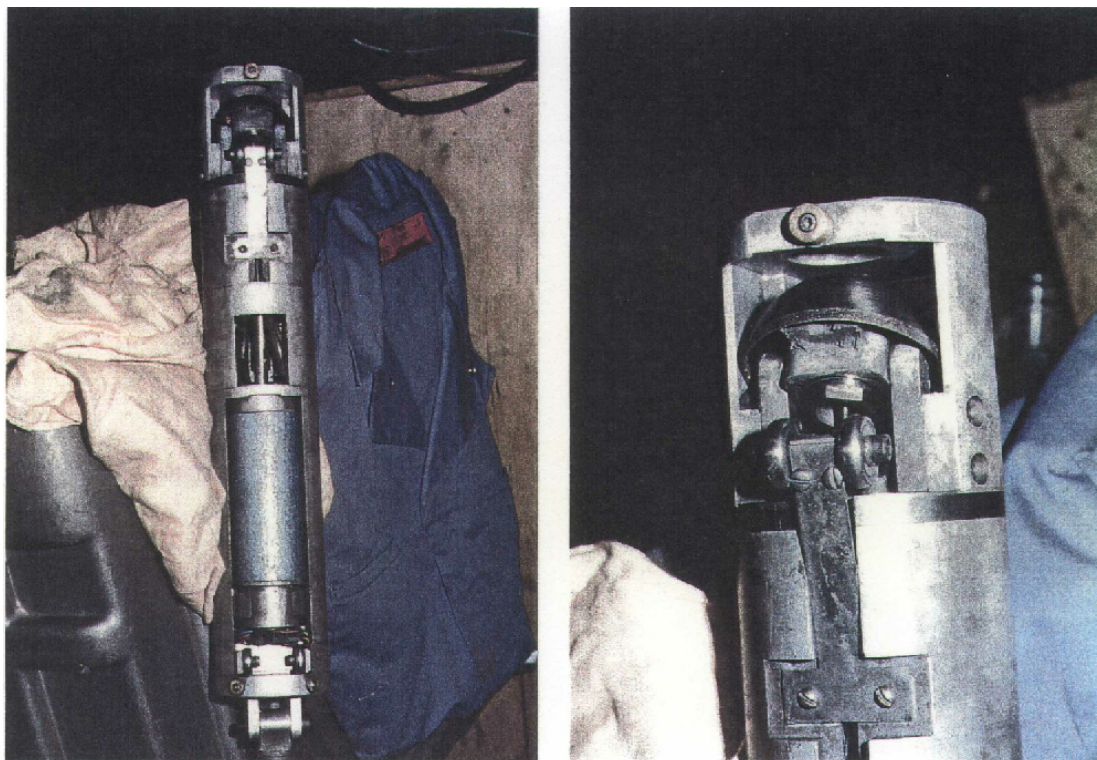
As stated earlier, the field application value of the SP test is closely tied to the ability to extract miniature samples from in-service equipment. Removal of relatively large samples, such as boat and core samples, is not of particular interest here, although material from such samples may be used to conduct SP tests.

In the last 15 years the electric power industry, and to a lesser extent the petrochemical process industry, have seen application of the miniature sample removal and SP testing approach to equipment condition assessment. The application has been driven by a need to assess the condition of aging equipment and their fitness for continued service. Below are examples of the technologies that have been applied and are currently available.

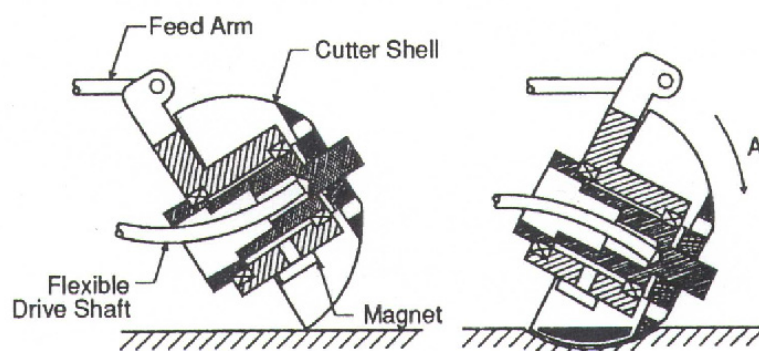
A2.3.1 Sampling Technologies

A.2.3.1.1 Scoop Cutter Sampling

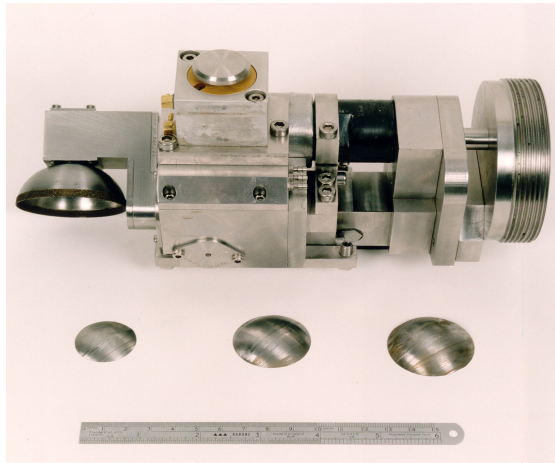
Scoop cutter sampling technology here refers to the method of sample removal whereby surface material is removed by mechanical cutting in a manner likened to an ice-cream scoop. Figure A2.1 shows such a miniature sample removal system [9]. The system uses a hemispherical cutter plated with cubic boron nitride (CBN) grit as an abrasive. A sample is removed by spinning the cutter about its axis of symmetry while slowly advancing it about a perpendicular axis to feed the cutter into the base material. During this feed the cutter is rotated e.g. the 25 mm-radius cutter shell follows the path that the leading edge of the cutter has cleared for it through the material. Coolant is introduced to the inside of the cutter to assist in clearing the swarf. The height of the cutter above the surface being sampled is adjusted by the operator to control the sample depth, usually 3-4 mm.



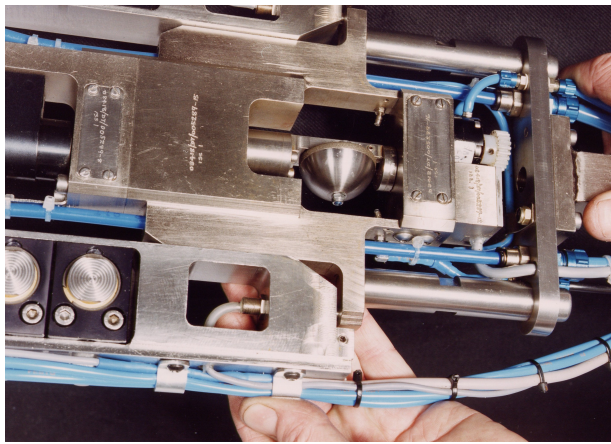
(a)



(b)



(c)



(d)

Figure A2.1 Photograph (a) and schematic (b) of abrasive-edged spinning cutter shell, in ref [9], and an example of (c) an underwater, and (d) a nuclear reactor pressure vessel sampler [10].

Figure A2.2 shows an example of a sample removed using this system together with SP test specimen blanks that have subsequently been electro-discharge machine (EDM)-machined from the miniature sample. A typical sample yields 2 to 5 small punch specimens, depending on the shape of the surface being cut and the depth of cut.

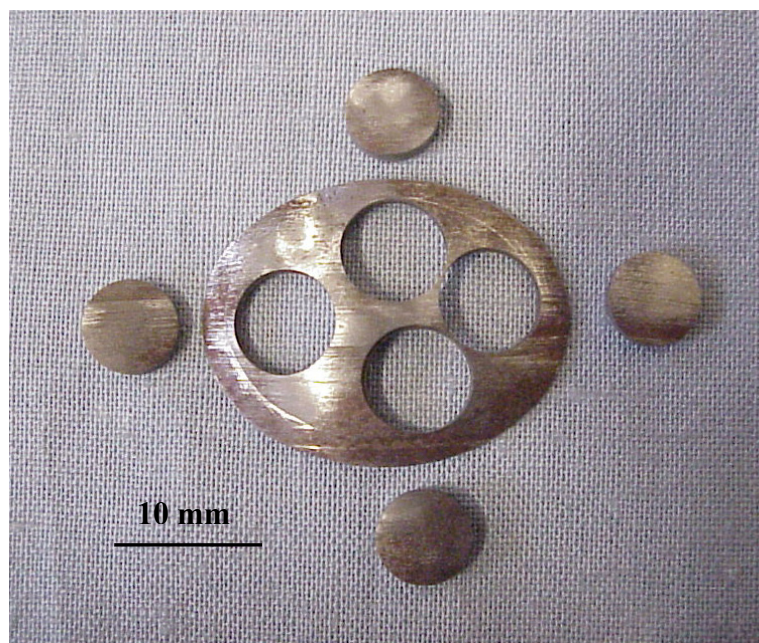


Figure A2.2 Example of a miniature sample removed with the scoop system, with SP test specimen blanks subsequently machined using EDM.

A.2.3.1.2 Electro-Discharge Machining (EDM) Sampling Systems

EDM (spark-erosion) sampling systems have been used for nearly a decade, particularly in underwater applications such as for relatively large boat sample removal from nuclear reactor pressure vessel internals (e.g., [11, 12]). Figure A2.3 shows a miniature version of that concept [13], along with an example of an as-removed sample. Typical samples have a maximum depth of 6 mm and 30 mm maximum surface dimension. Here the electrodes are made from a special alloy (depending on the type of alloy to be sampled), shaped in the form of a ring sector. During cutting, this tool rotates about its diametrical axis so the sampled material is a spherical segment. Good characteristics of the spark erosion system are: minimal specimen residual stresses generated in material removal, low cost and easy to replace cutting consumables, and a cutting profile (depth and surface area) that can be tailored to specific sampling needs. Sample sizes and SP specimen sizes are similar to above in paragraph 2.4.1.

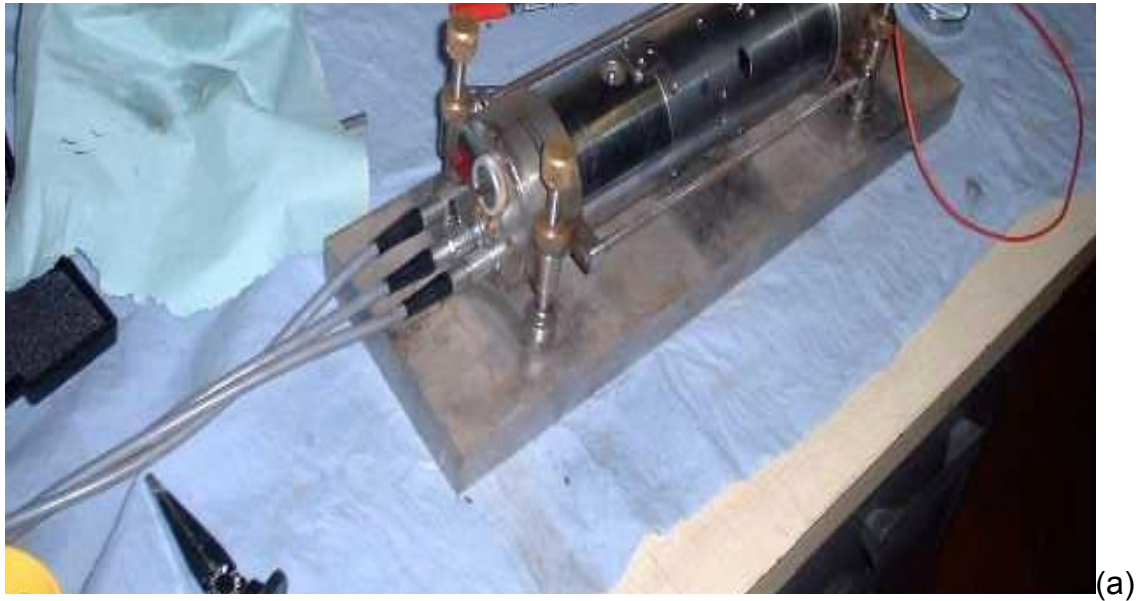


Figure A2.3 (a) An electro-discharge machining sample removal system [13] and (b) example of a sample removed with the system.

A2.4 CONSIDERATIONS IN SAMPLE REMOVAL

As described in previous sections, the value of the SP test in field applications is closely tied to the ability to extract miniature samples from in-service equipment. The equipment owner/operator and relevant regulatory approvals notwithstanding, there are several considerations associated with the steps in the decision process, including:

- What is the primary damage or failure mode being addressed?
- Which properties are of interest?
- Which are the component locations of interest?
- How will the SP test data be used?
- To what extent will sample removal compromise future component integrity?

A2.4.1 Damage/Failure Modes and Properties of Interest

Table A2.1 summarizes the various properties and related damage/failure modes that may be derived from the SP test: also included in the table is guidance on number of test specimens required. This latter guidance is important as the amount of sample material to be removed depends on the number of SP tests needed, this in turn depends on the properties being sought, therefore particular attention should be paid to the specific damage/failure mode being addressed and relevant properties required.

The most common and widely studied application of the SP test is the measurement of time-independent properties. These include yield and tensile strength; toughness in terms of fracture initiation toughness (K_{IC} , J_{IC}); and the ductile-brittle transition temperature or fracture appearance transition temperature (FATT) for carbon and low alloy (body-centered cubic) steels. The strength measurements directly address the load-bearing capacity of the component and margins against overload failure and yielding or plastic collapse. This is generally not a primary objective of the SP test, but can be determined as part of other SP tests properties determinations. In case of the FATT determination, the number of specimens required would generally translate to more than one miniature sample being removed. In this case, particular attention needs to be paid to ensuring that the miniature samples are removed from locations where the material is expected to be in the same condition. For example, in case of high-pressure steam turbine rotors where the temper embrittlement of the rotor bore material varies with position along the rotor, sample locations should be selected to represent one particular level of embrittlement.

In case of creep rupture behavior determination, general guidelines for number of specimens, form of acceleration (temperature elevation), test duration, minimising specimen oxidation effects, etc. have been published for standard test specimens (e.g., [REF]), and may be used. As for the case of FATT determination, the number of test specimens is such that generally more than one miniature sample will be required. Again, care should be taken to ensure that the sampled material in all cases is representative of the single condition of interest. This may be particularly challenging in case of specific weldment zones within in-service equipment, where removing more than one sample from the same weldment may not be advisable (due to compromising future integrity, for example).

Table A2.1 - Summary of Damage/Failure Modes and Relevant SP-Derived Properties and Specimen Needs

<u>Damage/Failure Mode</u>	<u>SP-Derived Properties</u>	<u>Minimum Number of SP Test Specimens</u>	<u>Comments</u>
Overload, Yielding, Plastic Collapse	Yield Strength, Tensile Strength	2	Properties typically measured as part of some other measurement, such as toughness.
Creep/Creep Rupture	Rupture Strength	5(*)	Methods for acceleration may be as used for standard test specimens (e.g., [14])
Time-Independent Fracture	FATT (or DBTT)	7(*)	Applicable to carbon and low alloy (body-centered cubic) steels
	Fracture Initiation Toughness, K_{Ic} , J_{Ic}	2	Tests at desired temperature; empirical and semi-empirical approaches available [Matocha]

(*) Depending on the analysis method to be used.

A2.4.2 Locations of Interest and Use of SP Test Data

Generally, a specific location in a component is of interest because it has been determined by analysis, experience, or inspection, that it represents a critical life-limiting region. A stress/thermal analysis, for example, may indicate that a particular area of the component or structure sees the highest stresses and/or temperature and is therefore expected to accumulate damage more rapidly than other locations. Similarly, experience with a comparable or identical piece of equipment might point to a particular area being prone to a certain damage or failure mode. Often, non-destructive inspections provide indications of damage such as cracks, and the region of cracking becomes one of prime importance. What is noteworthy is that application of the SP test and any pre-test sample removal is typically driven by a need to measure properties at a specific location. Some examples of applications that affect where samples would be removed include:

- Regions of age-related embrittlement such as a particular location in the high-pressure steam turbine rotor bore, nuclear reactor vessel, petroleum refinery hydrocracker vessel, etc. In addition to embrittlement, certain material types may be identified as being susceptible to age-related damage; for example, the Type IV cracking-susceptible HAZ of 9Cr steel weldments is a zone of particular interest.
- Location in a structure known to have experienced overheating or overstress, such as where equipment may have experienced fire damage, or where there has been transients in stress and/or temperature above the design values.
- Location in a structure known to generally have the greatest susceptibility to damage and failure, such as regions with the poorest properties and/or highest stresses, for example the near-hub region of the low-pressure steam turbine

shrunk-on disk, the blade attachment region of a high-pressure steam turbine rotor, etc.

- Locations where inspections show cracks, and there is a need to know whether such cracks will lead to catastrophic fracture. In such a case, the SP test may be used to measure toughness of material in the near-vicinity of the cracks, and to establish a critical crack size and whether catastrophic fracture risk is significant.

The loading configuration in the SP test is such that the material is tested in a predominantly biaxial stress state. Furthermore, the configuration is axisymmetric. The test therefore differs significantly from a standard tensile or creep rupture test, where loading is uniaxial, and from a standard fracture mechanics test (bend bar, compact tension, center-cracked panel, etc.), where loading is via a single, in-plane bending moment or a uniaxial applied load. Thus, while specimen orientation with respect to certain material characteristics (such as grain shape, texture) can be defined in case of standard tests, the SP test specimen orientation selection is not as straightforward. Below are some considerations with regard to SP test specimen orientation.

- Where the material mechanical response is expected to be isotropic, specimen orientation is not considered important.
- Where material mechanical response is anisotropic, such as may be the case with high grain aspect ratios (e.g., rolled product), textured microstructure (including directionally solidified material), composites, etc., the following should be considered:
 - For uniaxial properties in a direction that is in-plane isotropic with a second orthogonal direction (as may be the case for the plane transverse to the rolling direction of rolled product), the SP test specimen should be oriented so the specimen disk plane is coincident with the isotropic plane (i.e., transverse plane of rolled product). Other SP test specimen orientations may not yield representative results.
 - For uniaxial properties where the material is anisotropic without a plane of isotropy, there are no firm options for selection of the SP specimen orientation. However, since the SP specimen disk plane will see peak tension in bending (radial or hoop), it is recommended that specimen orientation be chosen so that the uniaxial direction of primary interest is in the SP specimen disk plane. In this situation the detailed specimen orientation should be recorded in order that the accumulated data can be analysed in any future enhancements of SP testing interpretation.

Where the SP test is to be conducted in determination of fracture properties, the following additional points should be noted:

- For standard bend-type fracture specimen equivalence, the SP specimen disk plane is normal to the direction of crack advance in the fracture specimen; i.e., in XYZ coordinates, a fracture specimen of Y-Z orientation (see for e.g., [8] for definitions; the crack advances in the Z direction, within the X-Z plane) implies an SP specimen configured with the disk plane being X-Y (i.e. normal to Z direction).
- For uniaxially loaded fracture specimen equivalence (e.g., center-cracked panels), it is recommended that the SP specimen is again oriented so that the disk plane is normal to the primary crack growth direction of the fracture specimen.

- The effects of anisotropy on fracture are difficult, if not impossible, to capture with the SP test. However the user should always record specimen orientation within the context of the anisotropy of the material being tested.

The selection of material sampling and SP testing locations also depends on the subsequent use of SP test data. A common application problem is the extrapolation of the test results to regions of the component away from the sampled location. Sampling locations should always be selected in the context of an overall plan for how the data will be used and to what extent the larger issue of component integrity prediction will be satisfactorily addressed. The localised character of the SP test application, while an advantage in many respects, can present the user with an extrapolation challenge. In the case of in-service equipment, the material tested is near-surface and may not represent the bulk. In other instances, the material tested at one location can differ significantly from that at another location, with the latter limiting the lifetime.

A2.4.3 Sample Removal and Future Component Integrity

Perhaps the greatest deterrent to material sample removal from in-service equipment is the concern for whether the sample removal operation will compromise the future integrity of the component, and if so, to what extent. The answer depends on the specific sampling process used and the design and operation of the sampled component. Following are some considerations regarding future integrity, together with comments on the effects of available sampling technologies described in this document.

A2.4.3.1 Local Stresses

Two potential effects of sample removal need to be considered:

- any change in the near-surface geometry of the component that can result in local intensification of stress, and
- creation of near-surface residual stresses from the sample removal operation or subsequent repair

In both cases the through-thickness gradient in any effect is expected to be steep; i.e., the stresses developed as a result of the sample removal decay rapidly from the surface into the interior. The stress concentration factor varies with the geometry of the depression left behind. For example, the stress concentration factor at the surface under uniform tension is predicted to range from nearly 1.5 for a 25 mm-radius cut (this factor is estimated to drop off to below 1.2 at about 2 mm from surface) to significantly lower values for larger cut radii. More benign radius cuts can be achieved with increased radius cutters. Care should be taken to ensure that this stress concentration does not compromise future integrity. Where local near-surface stresses govern damage, an evaluation should be made against future damage in the region around the sample removal position. On the positive side, the sample removal process may result in removal of surface-damaged material; i.e., the post-sampled surface may be considered to be partially “renewed.”

There is no concise information available on residual stresses that may be generated from a given miniature sample removal process. Nevertheless, the user should take note of whether the surface being sampled has a deliberately imposed stress condition, such as compressive residual stresses from peening. In this case, sample removal will also remove this deliberately imposed condition to the possible detriment of future integrity. Alternatively, sample removal may reduce an otherwise undesirable near-surface condition, such as residual tensile stress from welding. With regard to the suitability of the sampled material for SP testing, methods for SP test specimen removal may be used so that the actual material

tested is well below the as-cut surface of the sample to eliminate cutting effects that could compromise the test data. (e.g. [15]).

A2.4.3.2 Material Degradation from Sampling

Two main aspects of surface material degradation from sampling are generally of concern:

- surface roughness
- damage from heating

Both the mechanical cutting process, which currently use a 120-grit or finer abrasive, and the EDM methods produce relatively smooth as-cut surfaces that are generally smoother than the as-found component surface in the case of most industrial equipment.

It is recommended that sample temperatures during cutting and subsequent specimens machining remain below a level that alters material state (microstructure and internal stress): 50°C for the case of steels is a conservative value. Experiments with temperature measurement immediately below a mechanical cut [16] indicate that virtually right at the cut surface, peak temperature for typical low alloy steels increases by less than 10°C above ambient during the cutting process. For the EDM technique, a peak temperature less than 35°C has been reported [13].

Therefore the current indications are that existing sample removal technologies are unlikely to degrade component material significantly during the cutting process. Naturally, this assumes that the cutting process goes smoothly and that the equipment functions as intended.

A2.4.3.3 Future Inspectability

As sample removal (and subsequent repair) alters the component surface geometry, inspection methods that require a relatively flat surface can become ineffective at the sampled location. An example of this is ultrasonic testing (UT) inspection where the geometry of the depression left behind by the sampling methods previously described is such that near-surface flaws in the depression cannot be detected. In such cases, sample location selection should be carefully evaluated. This is even more relevant where sampling is used to extract a flaw for detailed laboratory examination; in this case, the near-surface material left behind may have the remnant of the flaw or possibly other flaws that may be difficult to detect. Naturally, where only surface-connected flaws are of interest, surface inspection techniques (e.g., penetrant testing) remain viable options for future inspections.

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Part B: A Code of Practice for Small Punch Testing for Tensile and Fracture Behaviour

0 INTRODUCTION

Safety margins of a component or structure provided in the design are reduced throughout a service life by ageing. It 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 ageing mechanism or a combination of several ageing mechanisms.

The term „safety margin“ is used in a broad sense meaning the safety state (i.e. integrity and functional capability) of components in excess of their normal operational requirements [2].

Determination of actual mechanical properties (yield stress, tensile strength, ductile to brittle transition temperature, fracture toughness) of structural components is hence necessary for optimisation of operating procedures and inspection intervals as well as for repair strategies and residual lifetime assessment.

Current standardised mechanical tests require relatively large volumes of test material that cannot be extracted from in service equipment without post-material removal repair [3].

The determination of the actual mechanical properties of components without a need for post-material removal repair has led to the development of small punch (SP) test techniques based on penetration tests of miniature (often disk-shaped) test specimens [4]. It can be considered as a non-destructive technique because of the very limited amount of testing material to be sampled. It is an efficient and cost effective technique and has the potential to enable measurement of the real 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.

It enables the determination of mechanical properties of non-uniform materials such as welds, especially those having narrow beads such as electron beam or laser beam welds, and metal coatings. The test technique provides potentially more reliable means of material properties characterisation than indirect methods based on laboratory simulations of the localised regions or analytical predictions based on general models.

It was developed at MIT for radiation embrittlement studies, first reported in 1981 [5] and extensively developed in Japan particularly at Tohoku University [6]. The first collaborative efforts in SP standardisation were reported by Japanese Atomic Energy Research Institute (JAERI) in 1988 [7]. In the US, further work by EPRI and Failure Analysis Associates (FAA, now Exponent) since the late 1980s [8] led to the introduction of the technique into Europe from 1992 by Swansea University [9] and ERA in the UK and CISE (now CESI) in Italy [10].

Its development was enabled by the high precision of computer controlled servo mechanical testing facilities. While results obtained so far seem well encouraging, new good ideas for improving the results by adding FE modelling [11], local approach theory and special equipment (video cameras, holography) have been developed quite recently [12].

The testing technique is limited by the fact that an agreed standard procedure for such tests does not exist. The harmonisation of current SP testing practices is the main task of this Code of Practice.

1 SCOPE

This Code of Practice gives guidance on the procedure to be followed when carrying out Small Punch tests. The objectives of such tests are to evaluate the tensile and fracture behaviour of materials exposed in operating plant components in order to provide data needed for plant life and integrity assessment. The Code of Practice primarily addresses metallic materials but can also be used for other materials.

The scope of the Code of Practice covers the following:

Test Piece

Test pieces are discs of specified dimensions procured from components or any other source. They may be homogeneous or contain manufacturing features such as for example joints, weldments, defects or coatings.

Load

The load may be applied to the disc from a screw driven, hydraulic or any other mechanical source. The Code of Practice particularly addresses the usual situation where the punch displacement rate (punch velocity) is maintained constant throughout the test.

Temperature

The Small Punch Test will usually be carried out at room temperature but the general principles apply also to tests where the temperature is reduced or elevated. The Code of Practice specifically addresses the usual situation where the temperature is maintained constant throughout the test.

Environment

The test pieces will usually be tested in a natural (air) environment. However, the general principles should also apply when other environments are used. Although special precautions will be necessary where hazardous or corrosive environments are used, these are not detailed in this document.

2 DEFINITIONS AND SYMBOLS

For the purpose of this Code of Practice, the symbols and designations are as given in Table 1 and the following definitions apply.

2.1 Small Punch test

A mechanical test carried out on a small disc shaped test piece by means of the application of a mechanical load applied to one surface of the test piece by means of a shaped punch in order to investigate its response to the load.

2.2 Small Punch Bulge test

As 2.1 above but under the condition that the perimeter of the disc is clamped and does not displace during the test.

2.3 Small Punch Drawing test

As 2.1 above but under the condition that the perimeter of the disc may displace during the test.

2.4 Load

The force applied to the test piece from the punch. This load includes all weights of equipment, which act on the punch.

2.5 Displacement

The displacement of the punch tip.

2.6 Deflection

The displacement of the point at the centre of the specimen on the opposite site of the punch.

2.7 Load Punch Displacement Curve

The continuous record of the load (see 0) and displacement (see 0) during the whole small punch test.

2.8 Load Specimen Deflection Curve

The continuous record of the load (see 0) and deflection (see 0) during the whole small punch test.

2.9 Test Piece

The disc under investigation independent of its material, its composition, its structure and its manufacturing route.

2.10 Test Piece Environment

The environment which is in contact with all surfaces of the test piece.

2.11 Symbols and Designation

The following Table 1 gives an overview about the symbols and their designation, which are used in this code of practice and in its annexes.

Table 1 Symbols and Designations		
Item	Unit	Designation
d_1	mm	disc diameter
d_2	mm	bore diameter of receiving die
r	mm	punch tip radius
h	mm	height of specimen
l	mm	length of receiving die edge chamfer
F	N, kN	punch force
u_1, u_2	mm	displacement, deflection
v	m/s	punch velocity
t	s	time
T	K	temperature
E_{SP}	J, kJ	small punch energy
ε	-	strain
$\dot{\varepsilon}$	1/s	strain rate
σ	Pa, MPa	stress

E	Pa, MPa, GPa	Youngs modulus
D	-	ductility factor
J_{Ic}	N/mm	ductile fracture toughness
K_{Ic}	N/mm	brittle fracture toughness
K	-	geometrical factor
S	-	standard deviation
R	-	regression coefficient
n	-	power law hardening coefficient
σ_1	Pa, MPa	power law hardening coefficient
α, β	-	coefficients
k	-	coefficient for ductile fracture toughness
C	-	coefficient for brittle fracture toughness
m	-	slope of a line
b	-	interception of a line

3 APPARATUS

3.1 Testing Rig

0 illustrates schematically a cross-sectional view of the specimen holder with a spherical tipped punch and the test specimen. The receiving die bore diameter $d_2 = 4$ mm and a punch tip radius $r = 1.25$ mm are recommended for the case of $d_1 = 8$ mm discs. For discs having a different diameter an appropriate receiving bore diameter and punch radius should be used. The chamfer edge of the receiving die is recommended to be $l = 0,2$ mm.

The test rig shall have a spherical tipped punch capable of forcing the central portion of the test specimen through the hole in the receiving die, until the end point of the test occurs. The spherical portion of the punch shall have a hardness to be sufficiently rigid so as not to be deformed during the test (55 HRC is sufficient for most steels). Punch tip ovality has to be controlled and documented as well.

The clamping surfaces of the specimen holder in contact with the test specimen shall be plane and parallel to each other. Both surfaces shall be clean, free from oxide build-up, corrosion and dirt and sufficiently rigid not to be deformed during the test (a hardness of 55 HRC or higher is recommended).

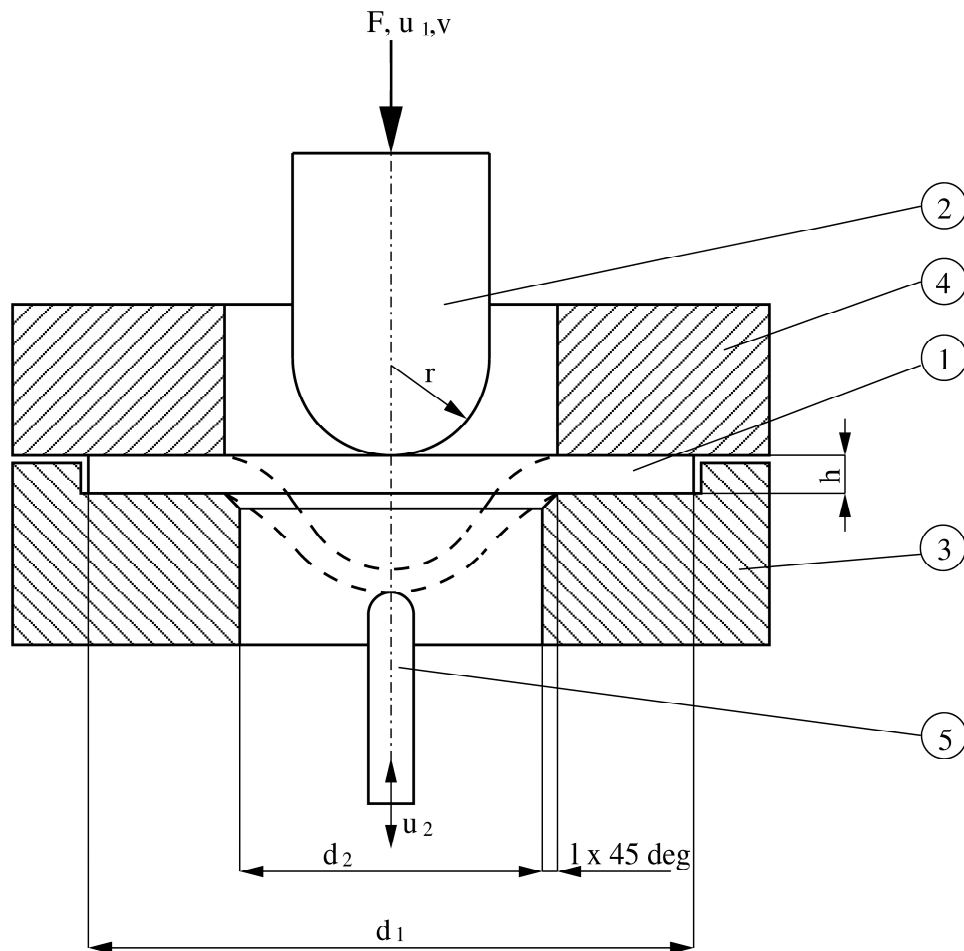


Figure 1 – Cross-sectional scheme of the testing apparatus (1 – specimen, 2 – punch, 3 – receiving die, 4 – clamping die, 5 – deflection measurement rod)

3.2 Loading System

A screw-driven testing machine is usually used for SP tests. It shall be equipped with a test rig for holding and loading the test specimen and with a load and a displacement measuring system. The percent error for the force measurement system within the range of forces of the testing machine shall not exceed $\pm 1\%$ of the actual measured force agreeing with the latest recommendations for tensile testing provided by EN 10002. The loading system should be calibrated for accuracy using a proving ring or similar certified device and the results recorded at least once per annum.

3.3 Displacement Measurement System

Any method of displacement measuring may be used. The displacement indicator shall monitor the punch movement with an accuracy of at least $\pm 1\%$ of the disk thickness h .

3.4 Deflection Measurement System

Any method of displacement measuring may be used. It might be convenient to measure the deflection of the specimen in an indirect way by monitoring the displacement of a measuring rod as indicated in 0. The displacement indicator shall monitor the deflection with an accuracy of at least $\pm 1\%$ of the disk thickness h .

3.5 Heating or Cooling System

The heating or cooling system should provide a uniform temperature distribution throughout

the test section of the disc. In the case of a clamped perimeter in the Small Punch Bulge test, the section beneath the clamp is not considered as part of the test section.

A temperature measuring system is to be supplied comprising thermometers, usually thermocouples, appropriately located to determine that the full test section remains within the temperature limits prescribed for the test. The thermocouples should be of a type and composition suitable for the test temperature regime selected for the test and calibrated in accordance with the EN 10002 standard.

The temperature control system should be capable of maintaining the temperature within a range of ± 3 K of the designated test temperature, by automatic means throughout the test according to the uniaxial tensile testing standard EN 10002.

3.6 Test Environment

Usually the Small Punch Test is carried out in a natural air environment. For studies where the effect of the environment is of specific interest, other environments may be employed but this must be clearly stated in the test report and the publication of the test results. For all environments the composition should be known and, if necessary, strictly controlled within specified limits.

3.7 Additional Measurements

Other test parameters may be monitored such as crack initiation or growth or displacement field measurements either by continuous or discontinuous methods. These additional measurements may not be allowed to affect the results of the Small Punch test itself. Any additional measurement made should be reported with the test results.

3.8 Data Recording

Equipment should be provided which will record the test parameters automatically with a resolution which matches that of the measuring instruments and should be accurate to within $\pm 1\%$ of full scale deflection at least and preferably within $\pm 1\%$ of the measured signal, when all sources of error are taken into account.

4 TEST SPECIMEN PREPARATION

The test piece is to be procured from standard test material, e.g. bar or sheet or from engineering components prior to or during operation. Methods for extracting material from components are detailed in Annex B2. In order to minimise work hardening in the surface of the test piece, the disc should be machined to a thickness of approximately $1,1 \cdot h$ 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 $\pm 1\%h$.

Disc shaped test specimens with $d_1 = 8$ mm in diameter and $h = 0,5$ mm in thickness are recommended. The thickness of the test piece should be measured at four positions around the perimeter at 90° intervals and at the central position. The diameter should be measured in two positions at 90° .

4.1 Specimen for Small Punch Bulge Test

Since the outer section of the specimen is clamped rigidly in this test, different specimen shapes are allowed. Both disc and square test specimens may be used. This method applies also to test specimen with a thickness between $h = 0,2$ to $0,6$ mm.

4.2 Specimen for Small Punch Drawing Test

Here, the whole specimen is deformed during the test, therefore the dimensions given in section 4 are recommended. The disc diameter should be manufactured with an accuracy of $\pm 1\%d_1$.

4.3 Identification and documentation

Test pieces should be permanently marked on the curved edge with a unique identifier. The position of the identifier should also enable the position of the four thickness measurements to be traced.

A written record of each test piece should be kept, listing:

- Identification
- Material composition and cast
- Material condition and original location
- Test piece manufacturing route
- Test piece original dimensions

This information should be transferred to the test documentation to form a complete test record.

5 TEST TEMPERATURE CONSIDERATIONS

Testing temperature affects significantly the nature of load punch displacement curve. For this reason it shall be maintained constant throughout the test. Any method of cooling or heating may be used. The provided temperature of the specimen immediately prior to the test is the same as the test temperature. The method of temperature measurement must be sufficiently sensitive and reliable to ensure that the temperature of the test specimen is within the limits specified above.

6 TEST PROCEDURE

6.1 Installation of the Test Specimen

Small Punch Bulge Test

Insert the test piece centrally into its position below the punch. Clamp the specimen rigidly between receiving die and counter die. Follow the general procedure given in section 0.

Small Punch Drawing Test

Insert the test piece centrally into its position below the punch. Here, the specimen is positioned loosely between receiving die and counter die. The size of the gap between specimen and counter die shall not exceed $1\%h$. The counter die shall maintain its position throughout the test. Follow the general procedure given in section 0.

Further General Procedure

Locate the punch displacement system and, if desired, the deflection measurement system below the centre of the test piece.

For the case of testing at different temperatures or in other environments close the chamber

system and set up the required conditions.

6.2 Test Speed

The test speed should be chosen so that the stress and strain rates are within the bounds given in the EN 10002 standard for tensile testing.

Because of the geometry of the small punch test the specimen strain and stress rates are not constant during the small punch test even for a constant punch displacement rate. For the geometry recommended in section 4, the following formula gives a good estimation of the maximum small punch strain rate $\dot{\epsilon}_{SP}^{\max}$ measured in $[s^{-1}]$ depending on the punch velocity v measured in $[m \cdot s^{-1}]$:

$$\dot{\epsilon}_{SP}^{\max} \approx 1000 \cdot m^{-1} \cdot v$$

Example:

The required maximum strain rate in a small punch test should be $\dot{\epsilon}_{SP}^{\max} = 0.008 \cdot s^{-1}$, which is equal to the allowed maximum strain rate for tensile strength measurement according to EN 10002. Then the punch velocity should be set as:

$$v = \frac{\dot{\epsilon}_{SP}^{\max}}{1000 \cdot m^{-1}} = \frac{0.008 \text{ m}}{1000 \text{ s}} = 0.48 \frac{\text{mm}}{\text{min}}.$$

In general, a displacement rate of the punch (punch velocity) in the range between 0,2 – 2 mm/min is recommended and should be documented.

6.3 Test Record

Accurate records should be kept of load, punch displacement, specimen deflection and temperature over the whole test duration. In addition, a record should be kept of all adjustments made to control or alter the test conditions and of any events that lead to interruptions in the test periods.

The objective of the test is to produce a load punch displacement (load specimen deflection) record, which contains information about the elastic-plastic deformation and strength properties of the material. The following characteristics of a load punch displacement curve are used for determination of tensile and fracture behaviour (see 0):

F_m [N] – maximum load recorded during SP test,

F_e [N] – load characterizing the transition from linearity to the stage associated with the spread of the yield zone through the specimen thickness (plastic bending stage) (see Sec. 7),

d_m [mm] – displacement corresponding to maximum load F_m ,

E^{SP} [J] – SP fracture energy obtained from the area under the load punch displacement curve up to fracture (see Sec. 7).

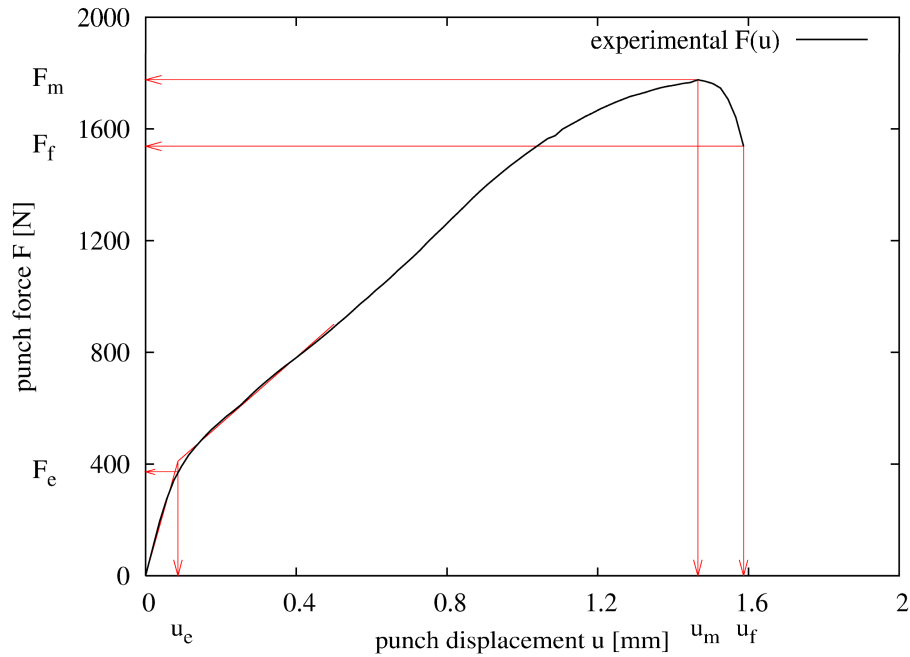


Figure 2 – Load punch displacement curve recorded during a small punch test.

7 POST TEST EXAMINATION

7.1 Determination of the elastic plastic transition load

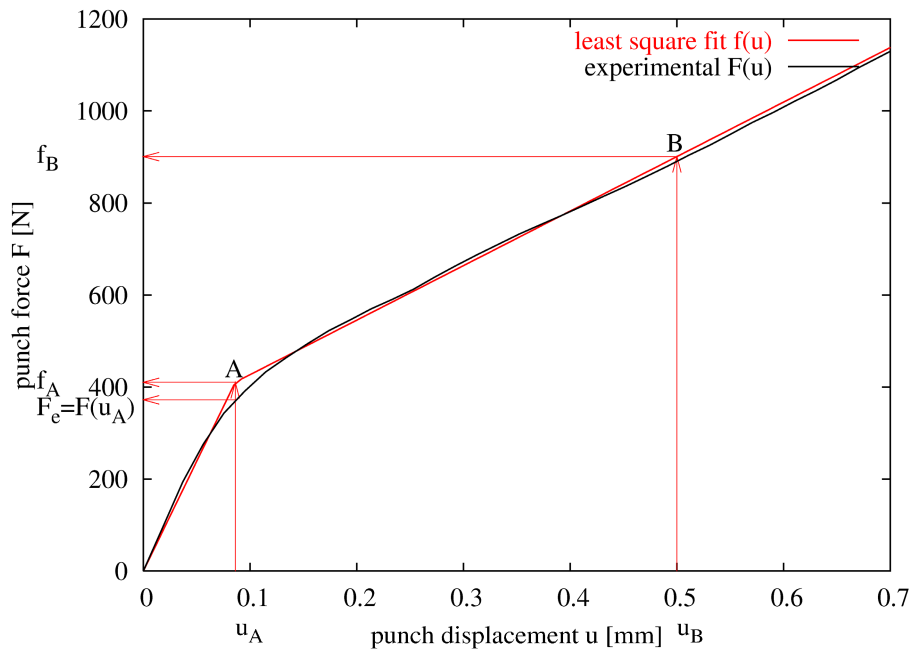


Figure 3 – Experimental load punch displacement curve $F(u)$ and least square fit $f(u)$

The elastic plastic transition load F_e can be correlated with the yield strength obtained by tensile tests and is therefore of specific interest. The following procedure describes how to obtain F_e .

A load punch displacement curve $F(u)$ is obtained from a Small Punch Test.

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

$$f(u) = \begin{cases} \frac{f_A}{u_A} u & \text{for } 0 \leq u < u_A \\ \frac{f_B - f_A}{u_B - u_A} (u - u_A) + f_A & \text{for } u_A \leq u \leq u_B \end{cases}$$

Minimisation of the error:

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

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

Then, the yield displacement $u_e = u_A$ and the load F_e can be obtained from the experimental load punch displacement curve as $F_e = F(u_A)$.

The only free parameter in this optimisation is the value for u_B . Here, we recommend a value between 0.3 and 0.5 mm at the end of the characteristic plateau of the load punch displacement curve. A good choice is $u_B = h$.

7.2 Determination of the SP Fracture Energy

The SP fracture energy E^{SP} is defined by the area under the load punch displacement curve:

$$E^{SP} = \int_0^{u_f} F(u) du$$

up to the displacement at onset of fracture/failure u_f , which is defined as the punch displacement at 20% load drop after maximum load.

$$F_f = 0.8 \cdot F_m$$

7.3 Determination of the Effective Fracture Strain

The effective fracture strain is defined as:

$$\varepsilon_f = \ln(h_0/h_f),$$

where h_0 is the original thickness of the test specimen and h_f is the final thickness adjacent to the area of failure. Therefore, the specimen has to be sectioned through the position of fracture after the test as can be seen in 0.

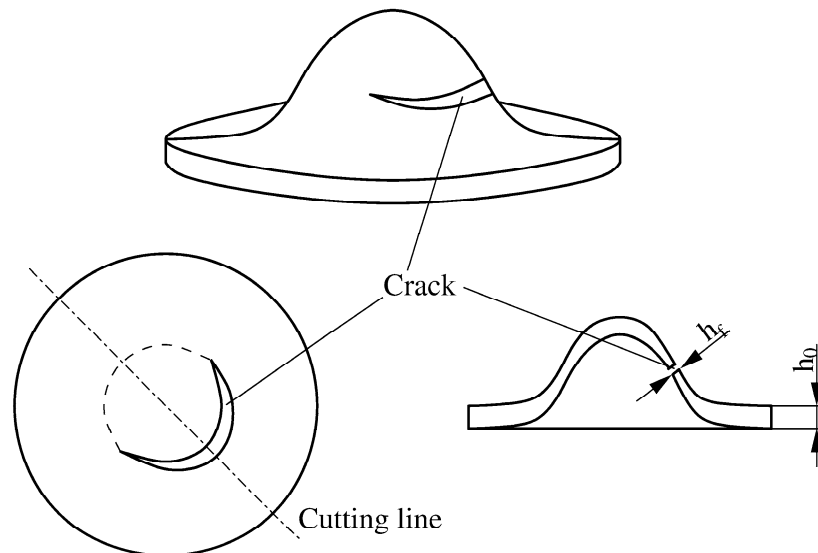


Figure 4 - (top) schematic drawing of a cracked small punch specimen, (left) top view to the cracked small punch specimen with the line indicated where to cut the specimen, (right) cross sectional view to the cracked small punch specimen with the positions indicated where to measure h_0 and h_f

8 TEST REPORT

8.1 Minimum Requirements

It is obligatory to cover the following items of information:

- Specific objective of the test.
- Reference to procedures adopted being in accordance with this Code of Practice.
- Test specimen description, including (i) manufacturing procedures and finishing, (ii) initial dimensions and (iii) special features, if any.
- Test conditions, including (i) test temperature, (ii) loading rate, (iii) test environment.
- Description of testing equipment, including methods for controlling test conditions.
- Test results, including (i) load displacement / deflection curve, (ii) SP test parameters (F_e , F_m , u_m), (iii) final measured dimensions and (iv) position of failure
- Fracture mode
- Report of any deviations from test conditions or recommended procedures e.g. unscheduled interruptions or excursions in temperature or load.

8.2 Additional Information

Although not obligatory the following items should be reported whenever possible:

- Test specimen details including processing route, chemical composition and metallurgical characteristics of material and service history.

- b) Results of any post-test examination including failure mode analysis.
- c) Use of the test results in further analysis e.g. comparison with other data, incorporation in life time assessment methods etc.

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ANNEX B1

Derivation of tensile and fracture material properties

B1.1 Introduction

The basic idea for performing SP tests is to get experimental information on material mechanical strength. When the SP tests are performed under nominally time-independent conditions, as in the objective of this Part B of the SP testing practice, these tests are aimed at two possible objectives:

- a) to provide a measure of a technological characteristic, being a practical criterion of material strength judgement, i.e. for fulfilling minimum acceptability criteria with respect to some specification in a material code or standard,
- b) to provide a method, equivalent but in alternative to the traditional full size specimen standard practices, by which the parameters defining the relevant mechanical properties (such as the tensile and the fracture toughness) can be evaluated.

However, none of the above scopes have reached a full development for the SP tests. The scope (a) would be similar, in a sense, to the common use of impact tests or of hardness tests: materials are currently compared, assessed, accepted or rejected based on experimentally determined Vickers or Rockwell hardness, Charpy Energy, NDTT (Nihil Ductility Transition Temperature) or FATT (Fracture Appearance Transition Temperature) values, as compared to code requirements for materials. This is used both for material production, welds qualifications, and components residual life and fitness for service studies. It is noted that ASTM has also developed a SP test standard on plastics (PMMA, ref. [1]), just in line with this type of application. It is believed that, until such SP material characteristics for metals will not be reported in materials codes, a long step still to go, the SP tests will not be applicable for this purpose.

Therefore, the objective (b) is currently the more important issue. SP testing provides SP load displacement records, and any quantities which are taken from such data are dependent on punch radius r , the hole diameter d_1 and the specimen thickness h . A method to estimate tensile or toughness properties from SP test records should therefore include consideration on how such test parameters do affect the process of derivation. As no current method has yet reached a wide state of consensus, validated on broad classes of alloys, this Annex B1 is not meant to recommend any preferred method; instead, a list of existing methods, with their essential nature, scopes and complexities (i.e. ready-to-use self-consistent method, methods requiring ad hoc parameters adjustments by additional non-SP testing, and methods requiring modelling analysis) is presented in the following section of this Annex B1, with the appropriate references in the literature.

B1.2 Tensile properties

There are two significantly different approaches to the derivation of tensile properties from SP load displacement records.

B1.2.1 Phenomenological correlations between SP and standardised tensile tests results

The nature of the load punch displacement curve varies with the punch radius r , the hole diameter d_1 and the specimen thickness h . Reasonable best fit correlations at ambient temperature of some SP data determined at key positions along the load – displacement curve of SP tests, as identified in this CoP (F_e , F_m , u_m), with the tensile properties as determined from the standard tensile tests (yield stress, ultimate tensile strength) were demonstrated in [2-6]. Two concerns should be considered.

- In order to apply such correlations to the SP results, to estimate the tensile properties of the material tested according to this SP procedure, the explicit values of those correlation coefficients would be needed, which were not openly reported in all the references above (curves with defined coefficients are in refs. 3 and 5).
- It should be realised that any best fitting method between SP and standard test data is in principle only valuable for the material for which the cross experimentation was carried out. Any use beyond this domain, though using material class similarity concepts, should be considered with caution, and discussed (justified) thoroughly in the SP test report using such a correlation taken from a different material.

B1.2.2 Methods requiring modelling: Neural Networks and Finite Element methods via Ramberg-Osgood modelling

The experimentally determined load punch displacement curve obtained during a small punch test, which contains information about the elastic plastic deformation behaviour and strength properties of the material, is transferred according to ref.[7-9] to a neural network, which is trained using load punch displacement curves generated by finite element simulations of the small punch test and the corresponding material parameters. The simulated material behaviour of the specimen is based on a ductile elastic plastic damage theory. During a training process the neural network generates an approximated function for the inverse problem relating the material parameters to the shape of the load punch displacement curve of the small punch test.

A further method developed by Failure Analysis Associates [10] is based on purely analytical material independent interpretation of the SP test results. It consists of matching the observed small punch test load punch displacement curve (up to the point of observed crack initiation) to a curve from a database of curves corresponding to a range of stress strain constitutive behaviour, therefore no finite element analyses are required. Such a database may be generated via small punch experiments on materials with known stress-strain behaviour. The constitutive stress-strain model used here is a Ramberg-Osgood model, with also possible modification to accommodate the dual yield observed in several low alloy steels [11].

B1.3 Embrittlement: Transition Temperature

The evaluation of transition behaviour of ferritic steels is based on the temperature dependence of small punch related parameters, ref. [12]. For a certain temperature the values for E^{SP} , u_m and F_m show a sudden decrease. This temperature is assumed to correspond to the point where ductile-to-brittle transition occurs. The test method for determination of DBTT (measured by FATT and/or 41J absorbed energy TT) is empirical, and based on standard Charpy tests. The transition temperature T_{SP} obtained by small

punch testing is often correlated with the DBTT obtained by Charpy using the following equation:

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

between DBTT and the corresponding SP transition temperature T_{SP} , measured in a series of SP tests typically ranging from -196°C to 25°C , ref. [6, 12, 13]. The SP specimen orientation is such that the normal to the punch disk plane is parallel to Charpy specimen crack propagation direction; the minimum number of SP tests needed for deriving a reliable correlation is discussed in ref. [5]. T_{SP} is determined as the temperature where E^{SP} has its mean value of the highest and the lowest values in the transition region, by intersecting the smooth curve fitted from the energy versus temperature data.

B1.4 Fracture Toughness

There are three approaches to estimate the material fracture toughness (K_{Ic} and J_{Ic}) by SP tests. Two of them are material dependent and based on empirical correlations, refs. [14-18]. The third one is based on purely analytical interpretation of the test results, its material independent and requires no prior knowledge of mechanical material properties [2, 10, 19].

B1.4.1 Two-step method of determination of K_{Ic} .

The derivation is made of:

- a correlation between T_{SP} and FATT as above,
- the traditional correlation between FATT and K_{Ic} (Merkle Corten)

Scatter bound using this method was reported being about 50% [10].

B1.4.2 Empirical, direct correlations from SP to K_{Ic} .

In the ductile case, J_{Ic} can be linearly correlated with ε_f using:

$$J_{Ic} = k \cdot \varepsilon_f - J_0,$$

where k and J_0 are empirically determined constants. $\varepsilon_f = \ln(h_0/h_f)$ is the effective fracture strain. In the brittle or predominantly elastic case K_{Ic} was proposed to be related to the small punch fracture stress σ_f^{SP} by the equation:

$$K_{Ic} = C \cdot [\sigma_f^{SP}]^{2/3},$$

where C is an empirically determined constant [18].

B1.4.3 EPRI-FAA “Innovative Approach”.

In this approach [10] the criterion used for fracture is the strain energy density (strain energy absorbed per unit volume) required to produce crack initiation in a solid uncracked specimen. This criterion is then applied (as a crack initiation criterion) to the crack tip of a standard test specimen loaded via computer simulation.

The procedure used to determine material fracture toughness from a single small punch test is as follows:

- Recording the load punch displacement curve during SP test and monitoring of the bulged specimen surface for identification of crack initiation.
- Determination of uniaxial tensile stress-strain constitutive behaviour from the load punch displacement curve.
- Determination of the strain energy density corresponding to crack initiation in the small punch test.
- Determination of fracture toughness J_{Ic} from estimation of the load level at which the critical strain energy density is expected to be met at the crack tip of a large standard geometry fracture test specimen.

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Annex B2

Guidance on Relevant Technological Issues: specimens sampling from components

Nomenclature in this Appendix B2

Boat samples: surface samples, cut from the component in two halves, usually leaving high stress concentration notches.

Core samples:

B2.1 Introduction

A major benefit of the small punch (SP) test is that it often enables mechanical characterisation of material from in-service components in a minimally invasive, virtually non destructive manner; i.e., component material is removed for testing without necessarily a requirement for repair. The small volume of the SP test specimen requires that a minimum amount of component material be removed (sampled) for testing. Current standardised mechanical tests, on the other hand, require relatively large volumes of material that cannot be extracted from in-service equipment without repair after the material removal. This Appendix provides some guidance on material removal with a view to meeting current objectives of the SP test as noted in the preceding text of the Code of Practice. It is important to note at the outset, that the action of removing material from an in-service component requires approval of the owner/user and, in some instances, approval of the jurisdictional authority responsible for enforcing regulations intended to ensure safe operation. This document cannot provide guidance that encompasses such considerations, and the reader is cautioned that the feasibility of material sampling of operating components needs to be evaluated on a case-by-case basis within the context of future safe operation and pertinent regulation.

The following sections describe potential applications of the SP test; some available miniature sample removal technologies that have been used to generate material for SP testing; considerations in sample removal (selection of sample locations, amount of material, etc.); and preliminary guidance on the use of SP test data. The significant variability in the test methods and test data interpretation of the SP test prior to the adoption of this CWA precludes providing detailed guidelines on use of data. Therefore the information contained in this Appendix is to be considered preliminary.

B2.2 Applications of the sp test

The SP test provides a direct means of mechanically testing material from a localised region of a component or structure, such as the heat-affected zone of a weldment, a coating, etc.

The test potentially provides a more reliable means of characterisation than indirect methods based on laboratory simulations of the localised region or analytical predictions based on general models. Additionally, in many instances, the amount of material available is so limited as to preclude conventional testing using standard size specimens.

B2.2.1 In-Service Equipment

The primary need to characterize the mechanical properties of material removed from in-service components stems from a desire or requirement to assess the mechanical integrity of the component in order to establish its future fitness for service. The mechanical integrity assessment depends crucially on, among other things, the material mechanical properties. Such properties include time-independent properties such as yield and tensile strength, ductile-brittle transition temperature, fracture toughness, etc., and time-dependent properties such as creep, and creep rupture strength, as outlined in the preceding Codes of Practice. These properties for a given situation may not be reliably known or estimated for a range of possible reasons including:

- Effects of material ageing, such as those at high-temperature, that can result in a reduction in fracture toughness and/or creep/creep rupture strength, etc. A well-studied example of sampling and SP testing application is the case of low alloy CrMoV steel, used for high-pressure steam turbine rotors, that exhibits temper embrittlement in service.
- Unknown pedigree of material, such as in the case of some older components where manufacturing records are not available or where the original specification for the material of construction did not include the relevant mechanical properties. Examples of these include cases where the original material specification did not include any requirement for fracture toughness, but where this property is now known to be critical to guard against unstable and catastrophic fracture from cracks that were either pre-existing or have developed during service.
- Properties of material at specific component locations are unknown as a result of fabrication or repair/refurbishment actions. The primary locations of interest in this case are weldments where properties of the weld and adjacent heat-affected zone (HAZ) are not known.
- Effects of abnormal loading conditions during operation that may have affected the as-manufactured properties. Examples of such loading would be short-term overload or periods of load (mechanical and thermal) beyond the design values.

B2.2.2 Laboratory Applications

In addition to the application of the SP test to in-service equipment, as noted above, the small specimen volume can be used to advantage in other laboratory investigations where a minimal amount of relevant/representative material is available. Some examples of these include:

Failure analysis - where the amount of material available is often insufficient for a testing programme with conventional laboratory specimens. Further, it is often the case that the failed part available for evaluation is of a configuration that precludes using standard test specimens and methods. The SP test often provides a vehicle to make measure properties with minimal destruction of the failed part and to focus on specific locations of interest.

In cases where the metal structure is, by design, of small section size (e.g., turbine blades), the limited available material in the aerofoil region makes the SP test a good choice.

Localised material damage, for example, characterisation of the root material in an

ex-service turbine blade where damage from thermal fatigue and creep is localised to the near-surface region.

Localised microstructure, where the properties of the material are dependent on location e.g. microstructural regions of a weld - filler metal and especially the heat-affected zone (HAZ). A widespread problem presently under investigation is the unreliable characterisation (by the conventional large specimens) of the HAZ region in 9Cr steel weldments developing "Type IV" cracking. Most of the finite element modelling developments in the field of creep life assessment of welded joints suffer from the limitation that HAZ properties are assumed, or measured from bulk "simulated HAZ" materials produced by heat treatment. There is a continuing lengthy debate and no general consensus over the relevance of the simulated materials.

Measurement of properties of coatings such as thermal barrier coatings. In this case, the small specimen thickness and loading configuration provides a means of testing coatings in an as-produced condition (coating plus portion of substrate). The application could involve assessing newer designs/processes or evaluating ex-service components for coating degradation. Preliminary feasibility of SP testing for coatings characterisation (such as strength and ductility) has been explored (e.g., [1, 2]).

The SP test has also found wide application in characterisation of polymeric materials, primarily for medical use. One form of the test, arising from research on polyethylene and polymethylmethacrylate or PMMA (e.g., [3, 4]), is now an ASTM standard for testing of ultra-high molecular weight polyethylene for surgical implants [5]. The advantage in this case is that medical implant product, pre- or ex-implant, is of limited section size and conventional mechanical test methods cannot be applied.

B2.3 Miniature sample removal technologies

B.2.3.1 General

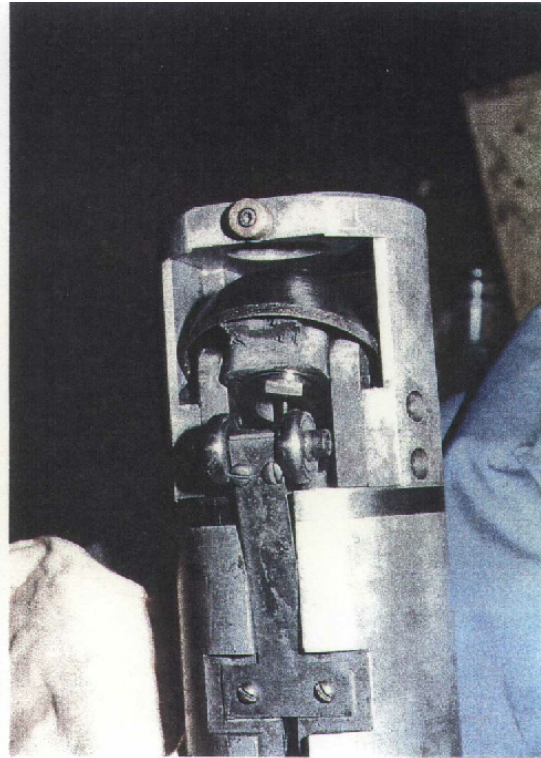
As stated earlier, the field application value of the SP test is closely tied to the ability to extract miniature samples from in-service equipment. Removal of relatively large samples, such as boat and core samples, is not of particular interest here, although material from such samples may be used to conduct SP tests.

In the last 15 years the electric power industry, and to a lesser extent the petrochemical process industry, have seen application of the miniature sample removal and SP testing approach to equipment condition assessment. The application has been driven by a need to assess the condition of aging equipment and their fitness for continued service. Below are examples of the technologies that have been applied and are currently available.

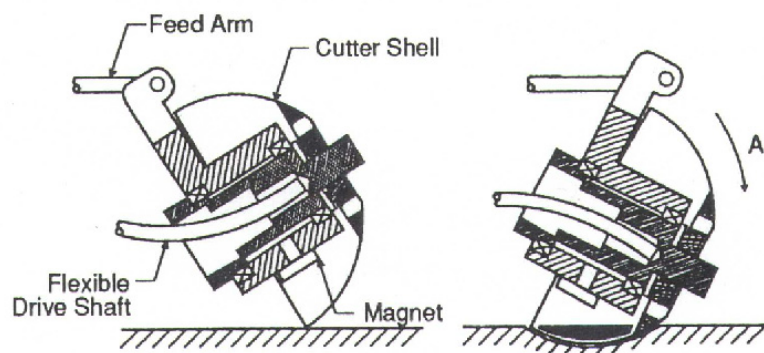
B2.3.2 Sampling Technologies

B2.3.2.1 Scoop Cutter Sampling

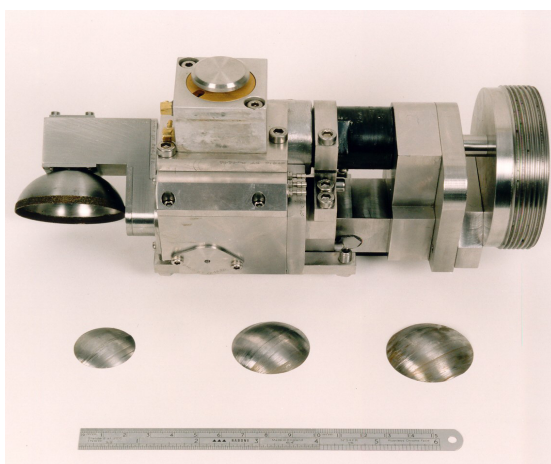
Scoop cutter sampling technology here refers to the method of sample removal whereby surface material is removed by mechanical cutting in a manner likened to an ice-cream scoop. Figure B2.1 shows such a miniature sample removal system [9]. The system uses a hemispherical cutter plated with cubic boron nitride (CBN) grit as an abrasive. A sample is removed by spinning the cutter about its axis of symmetry while slowly advancing it about a perpendicular axis to feed the cutter into the base material. During this feed the cutter is rotated e.g. the 25 mm-radius cutter shell follows the path that the leading edge of the cutter has cleared for it through the material. Coolant is introduced to the inside of the cutter to assist in clearing the swarf. The height of the cutter above the surface being sampled is adjusted by the operator to control the sample depth, usually 3-4 mm.



(a)



(b)



(c)

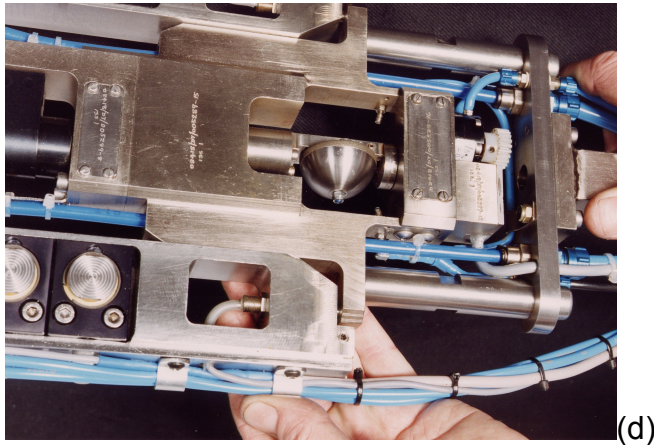


Figure B2.1 Photograph (a) and schematic (b) of abrasive-edged spinning cutter shell, in ref [9], and an example of (c) an underwater, and (d) a nuclear reactor pressure vessel sampler [10].

Figure B2.2 shows an example of a sample removed using this system together with SP test specimen blanks that have subsequently been electro-discharge machine (EDM)-machined from the miniature sample. A typical sample yields 2 to 5 small punch specimens, depending on the shape of the surface being cut and the depth of cut.

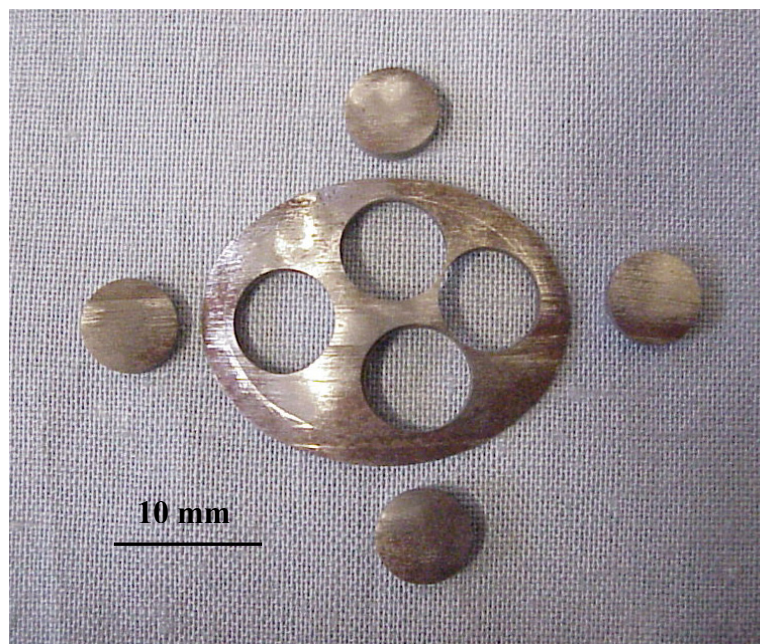


Figure B2.2 Example of a miniature sample removed with the scoop system, with SP test specimen blanks subsequently machined using EDM.

B2.3.2.2 Electro-Discharge Machining (EDM) Sampling Systems

EDM (spark-erosion) sampling systems have been used for nearly a decade, particularly in underwater applications such as for relatively large boat sample removal from nuclear reactor pressure vessel internals (e.g., [11, 12]). Figure B2.3 shows a miniature version of that concept [13], along with an example of an as-removed sample. Typical samples have a maximum depth of 6 mm and 30 mm maximum surface dimension. Here the electrodes are made from a special alloy (depending on the type of alloy to be sampled), shaped in the form of a ring sector. During cutting, this tool rotates about its diametral axis so the sampled material is a spherical segment. Good characteristics of the spark erosion system are: minimal specimen residual stresses generated in material removal, low cost and easy to replace cutting consumables, and a cutting profile (depth and surface area) that can be tailored to specific sampling needs. Sample sizes and SP specimen sizes are similar to above in paragraph 2.4.1.

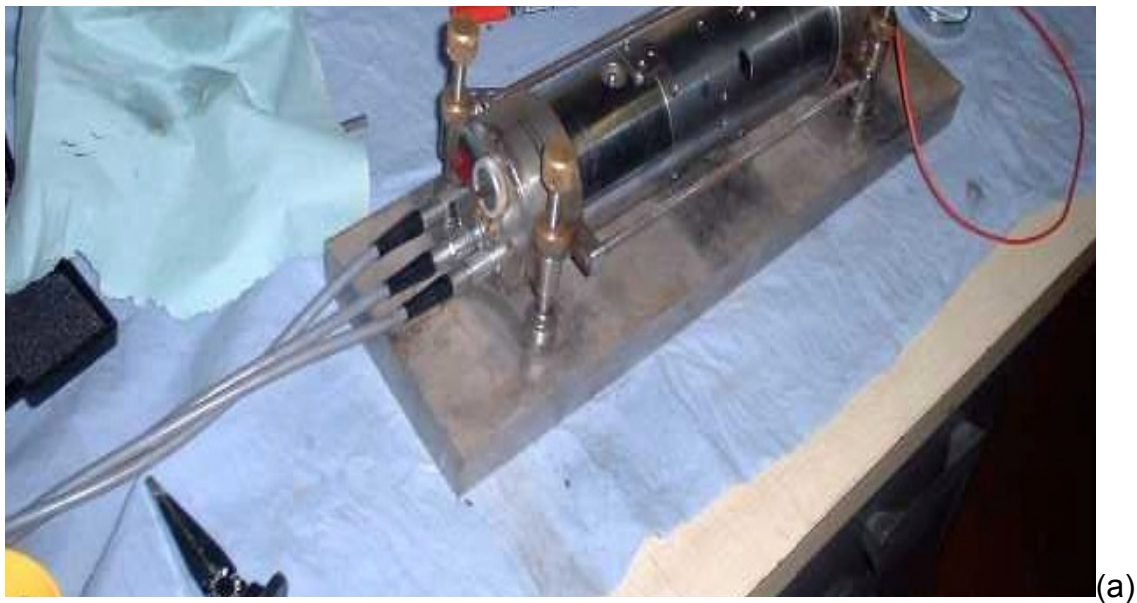


Figure B2.3 (a) An electro-discharge machining sample removal system [13] and (b) example of a sample removed with the system.

B2.4 CONSIDERATIONS IN SAMPLE REMOVAL

As described in previous sections, the value of the SP test in field applications is closely tied to the ability to extract miniature samples from in-service equipment. The equipment owner/operator and relevant regulatory approvals notwithstanding, there are several

considerations associated with the steps in the decision process, including:

- What is the primary damage or failure mode being addressed?
- Which properties are of interest?
- Which are the component locations of interest?
- How will the SP test data be used?
- To what extent will sample removal compromise future component integrity?

B2.4.1 Damage/Failure Modes and Properties of Interest

Table B2.1 summarizes the various properties and related damage/failure modes that may be derived from the SP test: also included in the table is guidance on number of test specimens required. This latter guidance is important as the amount of sample material to be removed depends on the number of SP tests needed, this in turn depends on the properties being sought, therefore particular attention should be paid to the specific damage/failure mode being addressed and relevant properties required.

The most common and widely studied application of the SP test is the measurement of time-independent properties. These include yield and tensile strength; toughness in terms of fracture initiation toughness (K_{Ic} , J_{Ic}); and the ductile-brittle transition temperature or fracture appearance transition temperature (FATT) for carbon and low alloy (body-centered cubic) steels. The strength measurements directly address the load-bearing capacity of the component and margins against overload failure and yielding or plastic collapse. This is generally not a primary objective of the SP test, but can be determined as parts of other SP test properties determinations. In case of the FATT determination, the number of specimens required would generally translate to more than one miniature sample being removed. In this case, particular attention needs to be paid to ensuring that the miniature samples are removed from locations where the material is expected to be in the same condition. For example, in case of high-pressure steam turbine rotors where the temper embrittlement of the rotor bore material varies with position along the rotor, sample locations should be selected to represent one particular level of embrittlement.

In case of creep rupture behaviour determination, general guidelines for number of specimens, form of acceleration (temperature elevation), test duration, minimising specimen oxidation effects, etc. have been published for standard test specimens (e.g., [REF]), and may be used. As for the case of FATT determination, the number of test specimens is such that generally more than one miniature sample will be required. Again, care should be taken to ensure that the sampled material in all cases is representative of the single condition of interest. This may be particularly challenging in case of specific weldment zones within in-service equipment, where removing more than one sample from the same weldment may not be advisable (due to compromising future integrity, for example).

Table B2.1
Summary of Damage/Failure Modes and Relevant SP-Derived Properties and Specimen Needs

<u>Damage/Failure Mode</u>	<u>SP-Derived Properties</u>	<u>Minimum Number of SP Test Specimens</u>	<u>Comments</u>
Overload, Yielding, Plastic Collapse	Yield Strength, Tensile Strength	2	Properties typically measured as part of some other measurement, such as toughness.
Creep/Creep Rupture	Rupture Strength	5(*)	Methods for acceleration may be as used for standard test specimens (e.g., [14])
Time-Independent Fracture	FATT (or DBTT)	7(*)	Applicable to carbon and low alloy (body-centered cubic) steels
	Fracture Initiation Toughness, K_{Ic} , J_{Ic}	2	Tests at desired temperature; empirical and semi-empirical approaches available [Matocha]

(*) Depending on the analysis method to be used.

B2.4.2 Locations of Interest and Use of SP Test Data

Generally, a specific location in a component is of interest because it has been determined by analysis, experience, or inspection, that it represents a critical life-limiting region. A stress/thermal analysis, for example, may indicate that a particular area of the component or structure sees the highest stresses and/or temperature and is therefore expected to accumulate damage more rapidly than other locations. Similarly, experience with a comparable or identical piece of equipment might point to a particular area being prone to a certain damage or failure mode. Often, non-destructive inspections provide indications of damage such as cracks, and the region of cracking becomes one of prime importance. What is noteworthy is that application of the SP test and any pre-test sample removal is typically driven by a need to measure properties at a specific location. Some examples of applications that affect where samples would be removed include:

- Regions of age-related embrittlement such as a particular location in the high-pressure steam turbine rotor bore, nuclear reactor vessel, petroleum refinery hydrocracker vessel, etc. In addition to embrittlement, certain material types may be identified as being susceptible to age-related damage; for example, the Type IV cracking-susceptible HAZ of 9Cr steel weldments is a zone of particular interest.
- Location in a structure known to have experienced overheating or overstress, such as where equipment may have experienced fire damage, or where there has been transients in stress and/or temperature above the design values.
- Location in a structure known to generally have the greatest susceptibility to damage and failure, such as regions with the poorest properties and/or highest

stresses, for example the near-hub region of the low-pressure steam turbine shrunk-on disk, the blade attachment region of a high-pressure steam turbine rotor, etc.

- Locations where inspections show cracks, and there is a need to know whether such cracks will lead to catastrophic fracture. In such a case, the SP test may be used to measure toughness of material in the near-vicinity of the cracks, and to establish a critical crack size and whether catastrophic fracture risk is significant.

The loading configuration in the SP test is such that the material is tested in a predominantly biaxial stress state. Furthermore, the configuration is axisymmetric. The test therefore differs significantly from a standard tensile or creep rupture test, where loading is uniaxial, and from a standard fracture mechanics test (bend bar, compact tension, center-cracked panel, etc.), where loading is via a single, in-plane bending moment or a uniaxial applied load. Thus, while specimen orientation with respect to certain material characteristics (such as grain shape, texture) can be defined in case of standard tests, the SP test specimen orientation selection is not as straightforward. Below are some considerations with regard to SP test specimen orientation.

- Where the material mechanical response is expected to be isotropic, specimen orientation is not considered important.
- Where material mechanical response is anisotropic, such as may be the case with high grain aspect ratios (e.g., rolled product), textured microstructure (including directionally solidified material), composites, etc., the following should be considered:
 - For uniaxial properties in a direction that is in-plane isotropic with a second orthogonal direction (as may be the case for the plane transverse to the rolling direction of rolled product), the SP test specimen should be oriented so the specimen disk plane is coincident with the isotropic plane (i.e., transverse plane of rolled product). Other SP test specimen orientations may not yield representative results.
 - For uniaxial properties where the material is anisotropic without a plane of isotropy, there are no firm options for selection of the SP specimen orientation. However, since the SP specimen disk plane will see peak tension in bending (radial or hoop), it is recommended that specimen orientation be chosen so that the uniaxial direction of primary interest is in the SP specimen disk plane. In this situation the detailed specimen orientation should be recorded in order that the accumulated data can be analysed in any future enhancements of SP testing interpretation.

Where the SP test is to be conducted in determination of fracture properties, the following additional points should be noted:

- For standard bend-type fracture specimen equivalence, the SP specimen disk plane is normal to the direction of crack advance in the fracture specimen; i.e., in XYZ coordinates, a fracture specimen of Y-Z orientation (see for e.g., [8] for definitions; the crack advances in the Z direction, within the X-Z plane) implies an SP specimen configured with the disk plane being X-Y (i.e. normal to Z direction).
- For uniaxially loaded fracture specimen equivalence (e.g., center-cracked panels), it is recommended that the SP specimen is again oriented so that the disk plane is normal to the primary crack growth direction of the fracture specimen.
- The effects of anisotropy on fracture are difficult, if not impossible, to capture with the SP test. However the user should always record specimen orientation within the context of the anisotropy of the material being tested.

The selection of material sampling and SP testing locations also depends on the subsequent use of SP test data. A common application problem is the extrapolation of the test results to regions of the component away from the sampled location. Sampling locations should always be selected in the context of an overall plan for how the data will be used and to what extent the larger issue of component integrity prediction will be satisfactorily addressed. The localised character of the SP test application, while an advantage in many respects, can present the user with an extrapolation challenge. In the case of in-service equipment, the material tested is near-surface and may not represent the bulk. In other instances, the material tested at one location can differ significantly from that at another location, with the latter limiting the lifetime.

B2.4.3 Sample Removal and Future Component Integrity

Perhaps the greatest deterrent to material sample removal from in-service equipment is the concern for whether the sample removal operation will compromise the future integrity of the component, and if so, to what extent. The answer depends on the specific sampling process used and the design and operation of the sampled component. Following are some considerations regarding future integrity, together with comments on the effects of available sampling technologies described in this document.

B2.4.3.1 Local Stresses

Two potential effects of sample removal need to be considered:

- any change in the near-surface geometry of the component that can result in local intensification of stress, and
- creation of near-surface residual stresses from the sample removal operation or subsequent repair

In both cases the through-thickness gradient in any effect is expected to be steep; i.e., the stresses developed as a result of the sample removal decay rapidly from the surface into the interior. The stress concentration factor varies with the geometry of the depression left behind. For example, the stress concentration factor at the surface under uniform tension is predicted to range from nearly 1.5 for a 25 mm-radius cut (this factor is estimated to drop off to below 1.2 at about 2 mm from surface) to significantly lower values for larger cut radii. More benign radius cuts can be achieved with increased radius cutters. Care should be taken to ensure that this stress concentration does not compromise future integrity. Where local near-surface stresses govern damage, an evaluation should be made against future damage in the region around the sample removal position. On the positive side, the sample removal process may result in removal of surface-damaged material; i.e., the post-sampled surface may be considered to be partially “renewed.”

There is no concise information available on residual stresses that may be generated from a given miniature sample removal process. Nevertheless, the user should take note of whether the surface being sampled has a deliberately imposed stress condition, such as compressive residual stresses from peening. In this case, sample removal will also remove this deliberately imposed condition to the possible detriment of future integrity. Alternatively, sample removal may reduce an otherwise undesirable near-surface condition, such as residual tensile stress from welding. With regard to the suitability of the sampled material for SP testing, methods for SP test specimen removal may be used so that the actual material

tested is well below the as-cut surface of the sample to eliminate cutting effects that could compromise the test data. (e.g. [15]).

B2.4.3.2 Material Degradation from Sampling

Two main aspects of surface material degradation from sampling are generally of concern:

- surface roughness
- damage from heating

Both the mechanical cutting process, which currently use a 120-grit or finer abrasive, and the EDM methods produce relatively smooth as-cut surfaces that are generally smoother than the as-found component surface in the case of most industrial equipment.

It is recommended that sample temperatures during cutting and subsequent specimens machining remain below a level that alters material state (microstructure and internal stress): 50°C for the case of steels is a conservative value. Experiments with temperature measurement immediately below a mechanical cut [16] indicate that virtually right at the cut surface, peak temperature for typical low alloy steels increases by less than 10°C above ambient during the cutting process. For the EDM technique, a peak temperature less than 35°C has been reported [13].

Therefore the current indications are that existing sample removal technologies are unlikely to degrade component material significantly during the cutting process. Naturally, this assumes that the cutting process goes smoothly and that the equipment functions as intended.

B2.4.3.3 Future Inspectability

As sample removal (and subsequent repair) alters the component surface geometry, inspection methods that require a relatively flat surface can become ineffective at the sampled location. An example of this is ultrasonic testing (UT) inspection where the geometry of the depression left behind by the sampling methods previously described is such that near-surface flaws in the depression cannot be detected. In such cases, sample location selection should be carefully evaluated. This is even more relevant where sampling is used to extract a flaw for detailed laboratory examination; in this case, the near-surface material left behind may have the remnant of the flaw or possibly other flaws that may be difficult to detect. Naturally, where only surface-connected flaws are of interest, surface inspection techniques (e.g., penetrant testing) remain viable options for future inspections.

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