SMALL PUNCH TESTING FOR CREEP – PROGRESS IN EUROPE

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ABSTRACT

The small punch or disk bend test has particular value in life prediction of operating equipment since the test requires very small amounts of material (a common test specimen disk is 0.5 mm thick with a diameter of 6 to 10 mm), and usually the required volume of material can be acquired from operating equipment in a virtually nondestructive manner. The application of the small punch (SP) test for creep has gained significant interest in the last decade, primarily as a result of research in Europe. The CEN (one of three European standardization organizations recognized by the EC) has been working to develop a Code of Practice for the small punch test. The Code documents, very recently completed, focus on use of the test for creep rupture and tensile and toughness properties. This paper summarizes the European round-robin work leading to the Code of Practice and key aspects of the Code. Included is a description of the currently recommended semi-empirical interpretation of data from the multiaxially-loaded small punch test specimens, less straightforward than that from conventional uniaxial specimens. As the SP test sees more field use and as the specimen and test configurations achieve better uniformity, we can expect that its application to creep life prediction will increase.

INTRODUCTION

As industrial plant equipment ages, there is an increased emphasis on assuring its mechanical integrity. Mechanical integrity depends on many factors, not the least of which is the usage-related degradation of the material of construction. A common usage-related degradation mechanism in case of pressure-boundary components operating at elevated temperatures is one of creep. The key question for such operating equipment is what is its remaining creep life? Methods based on laboratory creep rupture testing of material removed from the equipment are considered most reliable since the material test results are component-specific and rely on fewer assumptions than are made by indirect tests and predictive methods. Conventional testing for rupture life is conducted on multiple uniaxial specimens, test times being accelerated by applied stresses or more often by temperatures, elevated over that being experienced in service. Much has been written on this subject (e.g., [1-4]), most all of which is based on application of the Robinson Life Faction rule [5]. The reader may refer to a summary paper [6] for reference to some of the relevant published work.

Standard specimens for conventional uniaxial testing are of the order of 12.5 mm (0.5 in.) in section diameter, and removal of adequate test material from an operating component inevitably requires component repair. The small punch or disk bend test, in contrast, utilizes disk specimens measuring 6 to 10 mm in diameter and 0.25 to 0.5 mm (0.010 to 0.020 in.) in thickness. Use of such specimens requires very little removal of material from a component, often without need for repair. First introduced in the US [7,8] and further developed in Japan and the US mainly for evaluation of time-independent material properties relating to uniaxial tensile behavior and toughness [9-12], the test has recently become more widely known and has begun to see practice in Europe, including for creep rupture life assessment [13-18].

Since the creep life prediction of operating equipment has been based on extrapolation of conventional, uniaxially loaded test specimen rupture times to the field application in question, the focus on development of the SP test for creep has been on use of the small punch test to predict the time to rupture of a
uniaxially loaded test specimen under specific conditions of applied load and temperature. In essence then, the current challenge with use and interpretation of small punch test data boils down to answering the question of what is the load that should be applied to the small punch test specimen to produce a rupture time equal to that which would be produced in a uniaxial test specimen under the load or initial applied stress condition of interest. For example, to estimate the remaining life of a pressure vessel operating at some stress and temperature, we need to small punch test the as-removed vessel sample material at some load that would give us rupture times equal to what a uniaxial test specimen would give us when subjected to the same stress as the pressure vessel. However, since the stress state in the SP test (biaxial) differs from that in a uniaxial test (uniaxial), and since the stress field in the small punch test varies through the test, interpretation is far from straightforward.

Following is a summary of some of the aspects of the European research and the results to date of European efforts to develop a Code of Practice for the small punch (SP) test for creep remaining life evaluation.

THE EPERC (EUROPEAN PRESSURE EQUIPMENT RESEARCH COUNCIL) ROUND-ROBIN

Following a questionnaire distributed to several EPERC (European Pressure Equipment Research Council) members, a number of laboratories volunteered participation in a SP Round Robin program [18] consisting of high temperature creep tests on disk specimens. The goal was to promote harmonization of the test procedures toward development of a Code of Practice that would be relatively standardized mainly with regard to geometric features and procedures of testing. This “standardization” document is viewed as essential for wide acceptance of the SP test as a tool for remaining life determination of operating components, including equipment operating in the creep range. The round-robin participating labs were CESI in Italy, Krakow Technical University in Poland, JRC (Joint Research Centre)-Institute for Energy of the EC (European Community) in the Netherlands, and The University of Wales, Swansea (UWS) in the UK. Following the results of this program, interested EC members, with limited US participation, have developed a Code of Practice for the SP test that includes creep testing and also low-temperature testing for the determination of tensile and toughness properties of metallic materials. The Code documents have been published as a CEN (Comité Européen de Normalisation) Workshop Agreement, as described later in this paper.

Testing

The round-robin test material was a CrMoV turbine rotor steel with composition as given in Table 1.

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<td>1.36</td>
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Table 1 Composition of CrMoV steel for SP testing

The SP test specimen was prepared as a disk of 8 mm (0.315 in.) diameter (D) and 0.5 mm (0.020 in.) thickness (t), clamped around its circumference, as shown in the schematic of Figure 1. The different clamping forces in the equipment of the different participating laboratories were assumed to have no significant effect on test results, although this merits further research. As shown, the load is applied to the specimen by a spherical ball-punch. Two sizes of ball were used by the participants, with radius, R = 1.0 and 1.25 mm. The deforming specimen-receiving die diameter, a = 4 mm.

Figure 1 Schematic of typical SP test configuration

The whole of the die/specimen/punch arrangement was enclosed in a cylindrical furnace, which kept the specimen at the desired temperature. In order to prevent excessive oxidation of the specimen, the tests were carried out in a protective argon gas atmosphere, with the exception of the Krakow team that conducted the tests in air.

The SP creep tests were run at a single load value, 300N (67.5 lbf), in a range of temperature from 560° to 660°C (1040° to 1220°F). The typical outcome of a SP test is the plot of punch or specimen displacement (vertical deflection) versus time, illustrated in Figure 2. The SP creep curve is comparable
to a uniaxial creep curve obtained on the same as-received material, at the same temperature and with similar rupture life. As in the conventional uniaxial creep test, the SP creep test also exhibits clear primary, secondary and tertiary creep phases.

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Consistent results are seen within each of two apparently different data groups. The difference in test results between the two groups can be explained, to a major extent, by the punch ball size used. The UWS and JRC participants used a 2 mm (0.08 in.), and the CESI and Krakow participants, a 2.5 mm (0.1 in.) diameter ball, resulting in higher applied stresses and consequent shorter failure times in the former set. As described earlier [18], the data from the two groups were normalized for the apparent effect of punch size and stress via two empirical correlations between applied load, $F_{SP}$, and membrane stress, $\sigma$:

$$F_{SP}/\sigma = \left[2\pi t(R + t/2) \sin \phi \right] \sin \phi$$  \[14\]  

$$F_{SP}/\sigma = \left[2\pi R \sin \phi \tan \phi \right] / \left[1 + \tan^2 \phi \right]^{1/2}$$  \[15\]

where $R$ is the ball punch radius, $t$ is the specimen thickness, and $\phi$ is the angle between the load axis and the normal to the specimen surface at the point of inflection, as shown in Figure 4.

Equations (1) and (2) indicate that for the two groups of data, if $\phi$ is assumed to be nearly independent of the punch ball size, $\sigma$ is inversely proportional to $R + t/2$, and $tR$, respectively. This proportionality indicates that the 2 mm-diameter punch test specimens experience roughly 1.2 and 1.25 times the stress, respectively, in the 2.5 mm-diameter punch tests, at the same load and deflection. With regard to creep, this stress ratio translates to a minimum creep rate ($\dot{\varepsilon}_{\min}$) ratio that is proportional to (1.2 or 1.25)$^n$ where $n$ is the Norton constant in:

$$\dot{\varepsilon}_{\min} \propto (\sigma)^n$$ \[3\]

Following the Monkman-Grant relationship between minimum creep rate and failure time, $t_{R}$, where failure time is inversely proportional to the minimum creep rate, gives:

$$t_R \propto (1/\sigma)^n$$ \[4\]
For a Norton constant of \( n = 6.5 \) considered representative for this material, the failure time ratio for the two data groups is 3.3 and 4.3 for Equations (1) and (2), respectively. Normalizing for the stress effect due to the punch size, using the 4.3 factor based on Equation (2), results in the data from the two groups converging into good agreement, as seen in Figure 5.

![Figure 5](image)

**Figure 5** Replot of the Figure 3 round-robin creep SP results, normalized for a punch ball diameter of 2.5 mm (0.1 in.) using the stress effect embodied by Equations (2), (3) and (4)

The convergence of data from the two groups with differing punch size provides reasonable quantitative assessment of the effect of punch size, although more work needs to be done to fully evaluate all of the variables involved in the test.

The significance of this inter-laboratory exercise is that the SP “iso-load” test method for creep appears reproducible enough for development into industrial applications, much like the SP test method for tensile and fracture properties has achieved wide use. For application to remaining life estimation, however, the appropriate selection of the load level equivalent to the stress applied in a conventional uniaxial creep rupture isostress test needs to be made. There follows a brief discussion of the round-robin test results in this regard.

**Correlating SP with conventional uniaxial test data**

Limited data obtained through conventional uniaxial creep testing were available on the steel chosen for the SP creep testing round-robin. This facilitated the specification of the load to be applied in the SP test. The lowest planned temperature for the SP testing was 580°C (1076°F) and in order to plan tests lasting between 1000 and 2000 hours (the longest of the planned round-robin tests), an “equivalent” stress of 200 MPa (29 ksi) was derived from the uniaxial testing results. The SP test load, \( F_{SP} \), which would cause failure of the disk specimen in the appropriate time scale was then deduced from short-term tests that suggested \( F_{SP}/\sigma = 1.5 \).

The three SP tests at 580°C did indeed fail between 1362 and 1825 hours (see Figure 3). From the uniaxial tests that were carried out at 575°C (1067°F) at stresses of 240, 223, 210 and 190 MPa, the interpolated lifetime for a stress of 200 MPa was calculated as 1814 hours (plotted in Figure 5) and agreed well with the SP data. The selected factor for \( F_{SP}/\sigma \) of 1.5 appeared to work well under the test conditions chosen. As described previously, to explore the suitability of using Eq. (1) and/or (2), a specimen, interrupted from the SP test just prior to failure at 605°C (1121°F) was examined. It was discovered from the examination that, given the deformation of the specimen, identifying the point of inflection in order to measure \( \phi \) (see Figure 4) is not straightforward. A selected inflection point coincident with the edge of the punch-disk face contact gives a \( \phi \) value that significantly overpredicts \( F_{SP}/\sigma \). On the other hand, choosing the point of inflection to coincide with the region of maximum thinning, inboard from the contact edge (making \( \phi \) smaller) provides \( F_{SP}/\sigma \) predictions closer to 1.5 that gave the best selection of the SP load for life testing.

The bottom line is that selection of the appropriate SP load is not straightforward and work needs to be done to establish a physical approach to determining \( F_{SP}/\sigma \). For a given application, this could involve short-term testing with examination of interrupted test specimens for identification of the inflection point and determination of \( \phi \). Alternatively, an empirical determination of \( F_{SP}/\sigma \) for a given material and for a range of temperature conditions could be developed. As the test and application experience grow, such empirical ratios would make application of the SP test for remaining creep life prediction of operating components relatively simple.

It is anticipated that development of the Code of Practice via the CEN Workshop agreement, as described below, will encourage more use of the SP test and help accelerate the development of the method and its interpretation.

**THE CEN CODE OF PRACTICE**

The CEN (the Comité Européen de Normalisation or European Committee for Standardization) is one of three European standardization organizations recognized by the EC, and whose members are the national standards bodies of the EC countries. The CEN, at the initiative and with the participation of interested organizations in Europe, has been working to develop a Code of Practice for the small punch test. The results of the EPERC round-robin provided foundation and technical input for The Code of Practice in regard to the creep testing application. The Code, intended to achieve a practical level of uniformity in implementation of the test method, includes material creep testing in addition to the more mature application of the test for tensile and toughness properties. The Practice documents have been recently completed and published as a Workshop Agreement [19]. The Workshop
The test specimen measures 8 mm (0.31 in.) in diameter and 0.5 mm (0.02 in.) in thickness with a tolerance of ±1% and ±0.5%, respectively. The final surface finish recommendation is for at least 200 grit. The recommended test environment is high-purity argon or other inert gas. The temperature control system should maintain a constant test temperature to within ±0.25% of the desired temperature in °K. Temperature monitoring thermocouples are to be located so as to provide reproducible indication of the specimen temperature.

Test Load

As mentioned earlier in this paper, the SP test load, \( F_{SP} \) selected should be one that produces a failure time equal to that which would be obtained in a uniaxial creep test at the same temperature and given stress of interest. Since the stress state in the SP test differs from that in a uniaxial test, and since the stress field in the small punch test varies through the test, interpretation is not straightforward. In development of the CWA, the proposed relationships between load applied in the SP test and SP specimen membrane stress (for example, Eqs. (1) and (2)) were examined within the context of the EPERC round-robin data. The considered relationships, including the one developed by Chakrabarty for stretch forming over hemispherical punch heads [20], are based on membrane stresses, with bending stresses neglected. In SP creep tests, punch deflection at failure is usually about 3-4 times the specimen thickness. At these levels of deformation, neglecting bending stresses is not unreasonable.

Recognizing from these relationships, that \( F_{SP}/\sigma \) is always proportional to specimen thickness, \( t \), and punch ball radius, \( R \), and that for a given punch displacement, angle \( \phi \) (see Eqs. (1) and (2) and Figure 4), varies with receiving die radius, \( r \), a general \( F_{SP}/\sigma \) correlation expression may be written as:

\[
F_{SP}/\sigma = b_1 R^{b_2} t^{b_3}
\]

where \( b_1, b_2 \) and \( b_3 \) are constants. The general expression was developed for ease of use in selection of test load. Using the membrane stretching-based relationships of reference [20] at any punch displacement:

\[
F_{SP}/\sigma = 2\pi R \sin^{2} \phi
\]

with \( t = t_0 \{(1+\cos \phi)/(1+\cos \phi_0)\}^2 \)

where \( \phi \) is the previously defined angle (see Figure 4) at the contact boundary, \( \phi_0 \) is the same angle at the clamped boundary, \( t_0 \) is the initial, undeformed specimen thickness, and \( t \), the thickness at the contact boundary.

The general expression of Eq. (5) was regressed for a set of computed \( F_{SP}/\sigma \) values over a range of \( R \) of 1-1.25 mm (0.04-0.05 in.), \( r \) of 2-2.5 mm (0.08-0.1 in.), and \( \phi \) of 0 to 90°, for \( t_0=0.5 \) mm (0.02 in.). Thus, the best-fit general formula to determine test load for the small punch test was developed as:

\[
F_{SP}/\sigma = 3.33 R^{0.2} t^{1.2}
\]

The undeformed specimen thickness is used in Eq. (8) for selection of test load.

To account for potential variability in applicability of Eq. (8) to various materials (with varying creep ductility, for example), stress and temperature conditions that govern deformation mode, and other yet unknown effects, the CWA recommends use of an empirical constant, \( k_{SP} \), in the equation:

\[
F_{SP}/\sigma = 3.33 k_{SP} R^{0.2} t^{1.2}
\]

Users are expected to develop an estimate of the constant, \( k_{SP} \), prior to full application of the test. Where \( k_{SP} \) is not known, the first tests may be set up assuming \( k_{SP}=1 \) and a series of a recommended minimum of 5 tests at one particular temperature carried out in order to evaluate \( k_{SP} \) through comparison with the stress rupture behavior defined from conventional uniaxial testing.

Application

The basic approach to using the small punch test for creep life prediction can follow the temperature-accelerated method popular with uniaxial testing; i.e., following establishment of
and with knowledge of the stress and temperature of the operating equipment in question, a series of small punch tests at temperatures elevated above the equipment operating temperature may be run, each at a constant load determined from the above equation. The small punch rupture times may then be extrapolated to the operating temperature of interest on a temperature – log (rupture time) basis (common with low alloy steels) or the 1/temperature - log (rupture time) basis (sometimes used with austenitic stainless steels). Alternative acceleration methods using a combination of elevated stress and temperature may also be used wherein extrapolation is performed using the Larson-Miller parameter, although the temperature acceleration method is considered more reliable.

As the SP test sees more field use and as the specimen and test configurations achieve better uniformity, we can expect that its application to creep life prediction will increase.

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REFERENCES