

**NPL REPORT
DEPC-MPE 029**

**Experimental Aspects of
Small Punch Testing at
Elevated Temperatures**

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Experimental Aspects of Small Punch Testing at Elevated Temperatures

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ABSTRACT

Small punch testing, either at constant displacement rate or constant load is experimentally simple to perform. However care must be taken to ensure that the data obtained are reproducible as the results obtained are sensitive to the geometry of the test jigs used. The influence of the diameter of the indenting sphere and the receiving orifice has been investigated for both types of test.

A procedure for performing constant load small punch tests, which will ensure repeatable results is proposed.

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Approved on behalf of the Managing Director, NPL,
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authorised by Director, Engineering and Process Control Division

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1 INTRODUCTION

Although alloys are produced to satisfy a specification for their mechanical properties, invariably the properties of a particular cast vary from the mean values quoted and need to be measured. The common approach to material testing is to machine a fairly large sample from the available material and test this under uniaxial conditions. These tests are well established for tensile and creep properties of materials at high temperatures and testing standards are readily available [1,2]. However it is often impossible to obtain samples of a suitable size, either because the material is produced as thin sections or because the microstructure, and hence properties, vary spatially within the dimensions of a typical testpiece. In these cases some form of miniaturised testing is required.

One miniaturised testing technique that is receiving interest is the small punch (SP) test. The principle of the test is simple: a rigid spherical ball is pressed through a thin disc of material that is supported over a circular orifice. A schematic representation of the test is shown in Figure 1. Loading may be either at constant displacement rate or at constant load. A major benefit of the SP test is that it enables mechanical characterisation of the materials of in-service components in a minimally invasive, virtually non-destructive manner; i.e., component material removal and 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.

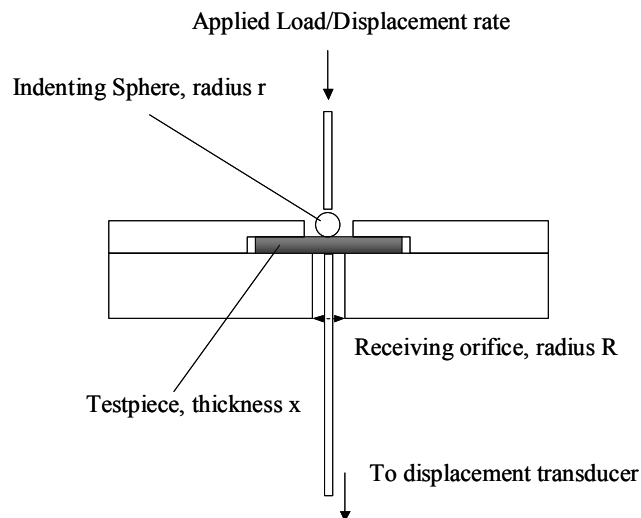


Figure 1 Schematic Representation of the Small Punch test

A current limitation of the SP test is that there is still no consensus on the optimum geometry of the test apparatus nor is there an unambiguous correlation between the data obtained from the test and from uniaxial tests. This report highlights some of the issues concerning SP testing and presents a recommended procedure to carry out the tests.

2 GENERAL CONSIDERATIONS

The results obtained from this type of test are critically dependent on the geometry of the test setup. It is therefore vital that the test jig is fully characterised before any test is started. The key geometric parameters have been identified as specimen thickness, and the diameters of the indenting sphere and receiving orifice.

A competent engineering workshop can produce specimens with a tolerance on thickness of ± 0.05 mm across both a single specimen and across a relatively large batch produced as a single job.

Silicon nitride or ruby balls, suitable for testing up to 700 °C can be purchased commercially with reproducible diameters. Figure 2 demonstrates the excellent consistency received from a batch of silicon nitride balls with a nominal diameter of 2.387 mm.

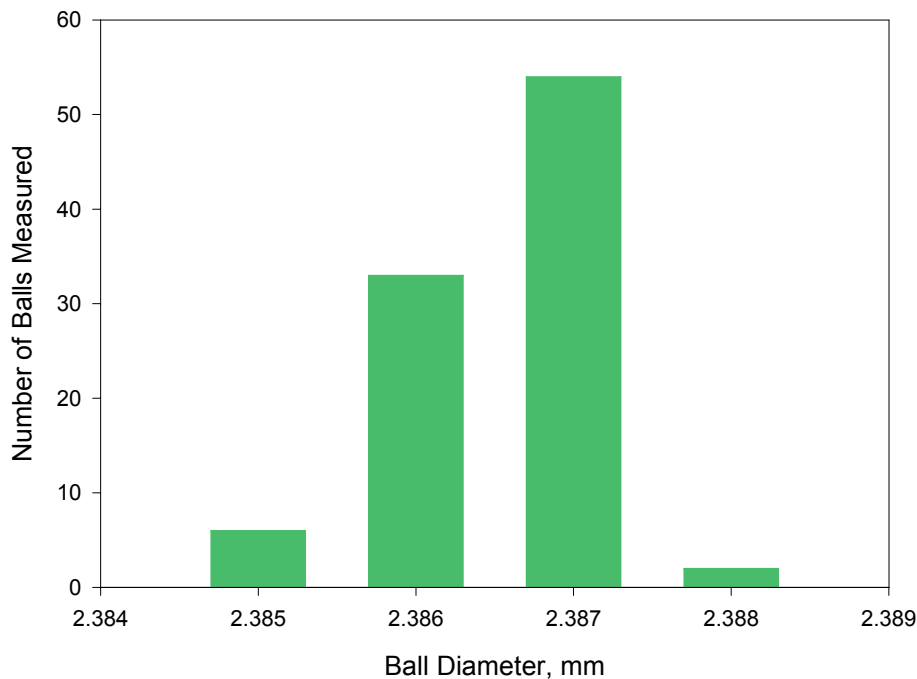


Figure 2 Diameter of silicon nitride balls measured on a single batch

The diameter of the receiving orifice can be produced by drilling with a tolerance of ± 0.05 mm. However this diameter is probably the most critical, as will be demonstrated in later sections, and must be measured prior to testing.

3 CONSTANT DISPLACEMENT RATE TESTING

This test is analogous to the uniaxial tensile test but is much more difficult to analyse. Load and displacement should be measured during the test and usually will give a curve similar to that shown in Figure 3.

Eskner and Sandstrom [3] divided the load/displacement curve into four regions:

1. Elastic bending
2. Plastic bending
3. Stretching
4. Instability

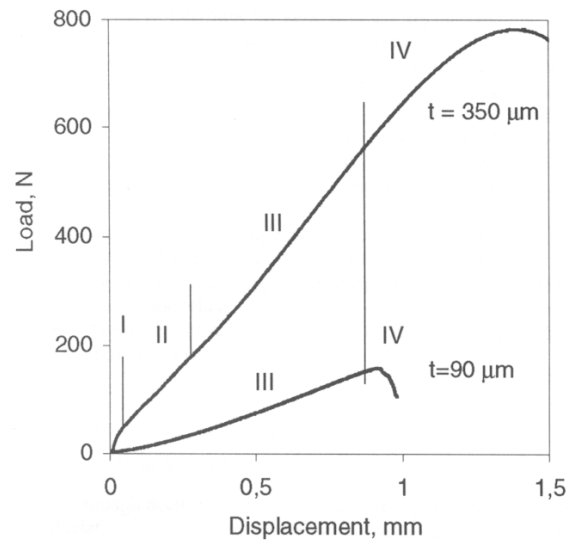


Figure 3 Load-Displacement Curve for Constant Displacement SP Test on 18Cr-Ni Steel (after Ref [3])

Currently the CEN TWA21 working group has proposed an alternative analysis method for constant displacement rate small punch test data [4]. The load-displacement curve is used to derive 4 parameters as shown in Figure 4.

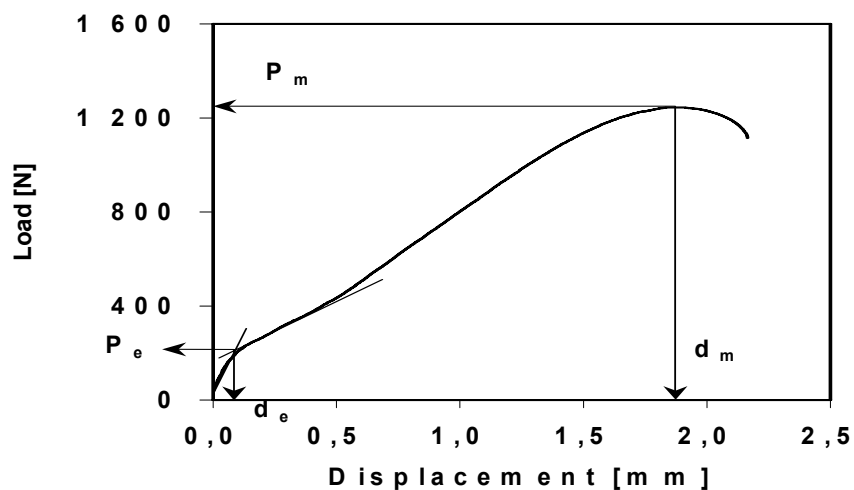


Figure 4 Analysis of load-displacement data (after [4])

Four parameters have been identified viz:

- P_m - the maximum load recorded during the test,
- P_e - the load characterising the transition from linearity to the stage associated with the spread of the yield zone through the specimen thickness
- d_m - displacement corresponding to maximum load F_m
- E^{SP} - SP fracture energy obtained from the area under the load – displacement curve up to fracture load or maximum displacement

Intuitively these parameters can be related to parameters measured during uniaxial testing. P_m corresponds to the Ultimate Tensile Stress and d_m to the elongation at failure in the uniaxial tensile test. In addition P_e can be taken as a measure of the uniaxial yield stress and E^{SP} as a measure of fracture toughness.

In reality the deformation behaviour is more complex than this. Initially the whole specimen will deform in an elastic manner. However after a small displacement the region directly under the crown of the indenting sphere will undergo plastic flow. From this point the region of yielded material under the indenting sphere will grow until it reaches a limit defined by contact between the sphere and the specimen. At the same time the shank of the specimen will still deform elastically as the total displacement increases. As the region under the indenting sphere reaches a saturation strain the material in the specimen shanks starts to yield. This then continues until plastic instability i.e. necking, occurs in the specimen shank. The local strain as a function of displacement for the crown and shank of the specimen is shown in Figure 5. It can be seen that the position of maximum principal strain, and hence onset of failure, changes with the total vertical displacement of the indenting sphere.

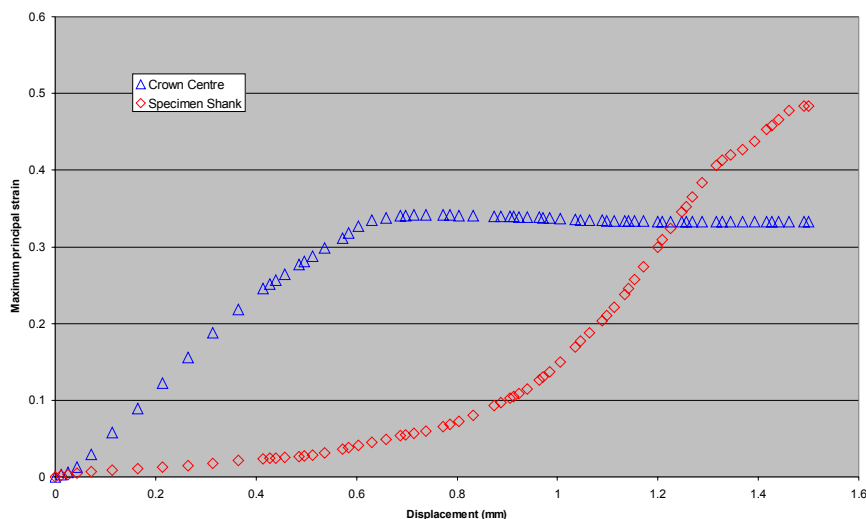


Figure 5 Local Strain as a function of Displacement for Specimen in Small Punch Test under constant Displacement Rate (arbitrary materials)

A consequence of the inhomogeneous deformation is that, in relatively brittle materials, cracking may occur at the crown of the specimen (Figure 6a) before yielding in the shanks of the specimen is fully established. This leads to a perturbation in the load-displacement curve as shown in Figure 6b.

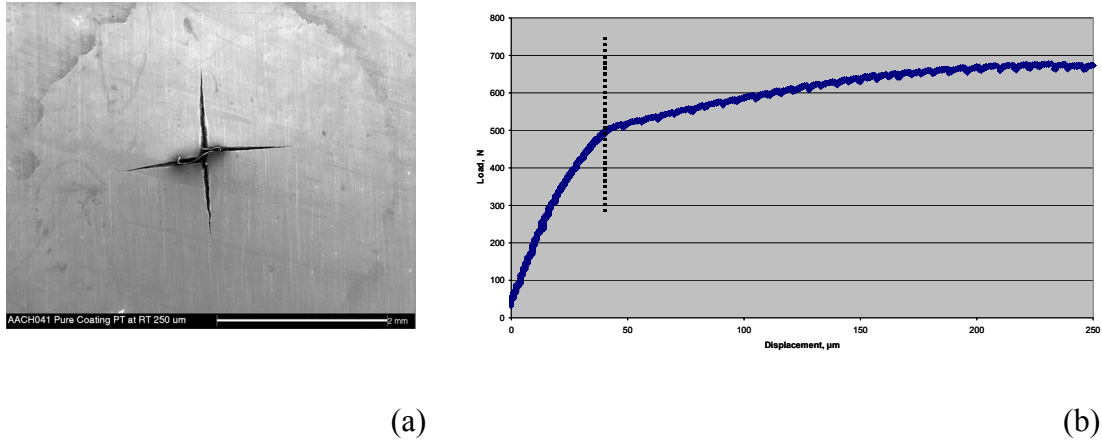


Figure 6 Small punch testing of brittle materials (a) image of cracking pattern (b) Influence of cracking on load-displacement curve

In comparison with the uniaxial tensile test the displacement rate and temperature of the test must be controlled within certain limits. Figure 5 shows the influence of changing the displacement rate by an order of magnitude. The difference in behaviour are similar to those observed in uniaxial tests ie the maximum load is greater at high displacement rates and the ductility is independent of strain rate.

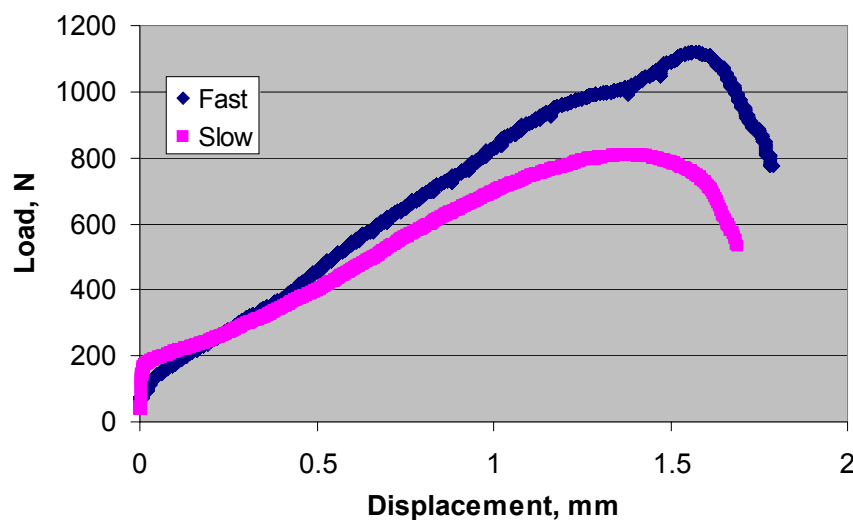


Figure 7 The influence of Applied Displacement Rate on Load/Displacement Behaviour of P12 Steel – Fast = 0.2 mm min^{-1} , Slow = 0.02 mm min^{-1}

Figure 8 demonstrates the influence of jig geometry on the load-displacement curves obtained during the test. Increasing the diameter of the indenting ball systematically

increases the maximum load obtained (Figure 8a) whilst increasing the diameter of the receiving orifice has little effect on the maximum load but seems to increase the maximum displacement for failure (Figure 8b). The magnitude of these effects are however dependent on the applied displacement rate.

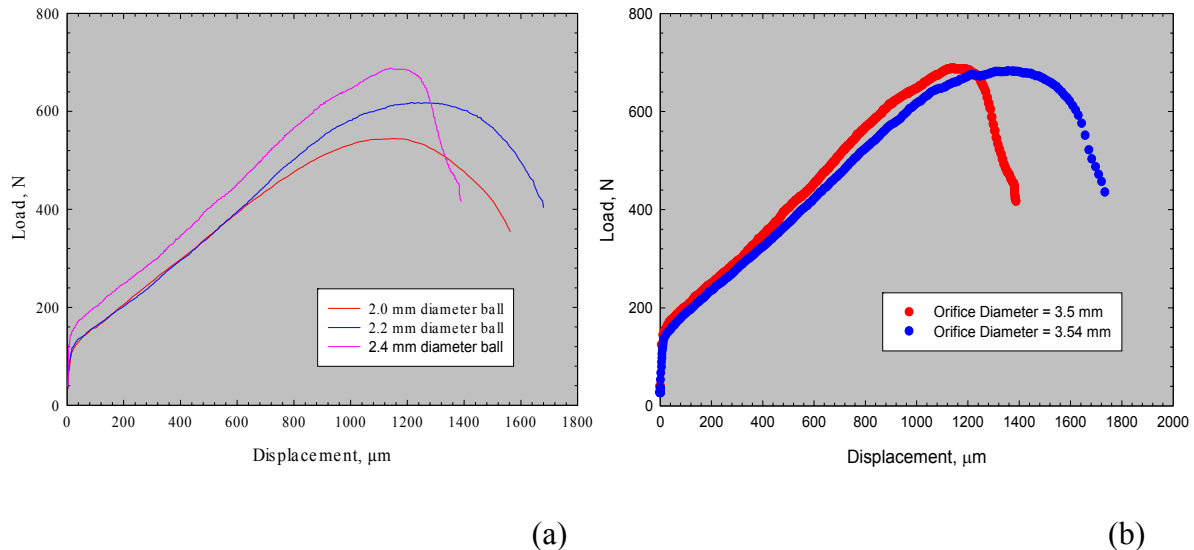


Figure 8 The influence of rig geometry on the load displacement curves obtained during SP testing of P12 at 600 °C at 0.2 mm min⁻¹ (a) varying ball diameter (b) varying orifice diameter

4 CONSTANT LOAD TESTING

Small punch testing under constant load produces a displacement-time trace that resembles that observed under uniaxial creep. Deformation is characterised by an extended period of ‘primary’ creep, followed by a region of approximately constant displacement rate with a final rapidly accelerating period leading to failure. Figure 9 shows a typical curve, obtained from P11 material at 580 °C.

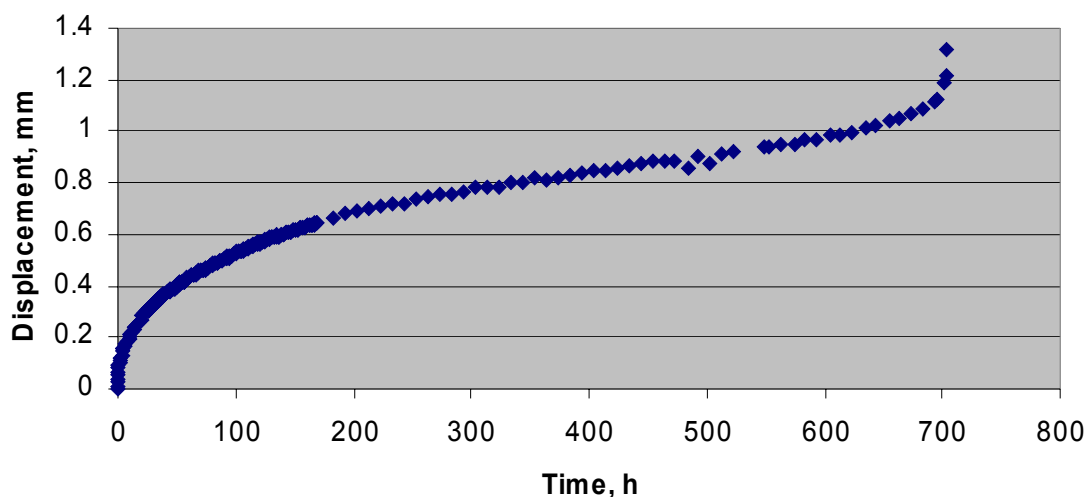


Figure 9 Displacement-time plot for constant load SP test of P11 at 580 °C and 330 N

This test is also extremely dependent on jig geometry and the influence of key parameters has been investigated by Evans and Evans [5]. Ball diameter and orifice diameter were key aspects of jig geometry, as well as other test parameters should as load, material condition and specimen thickness.

Figure 10 shows the influence of the orifice diameter on the time-displacement behaviour of service exposed P12 material tested at 600 °C and 320 N. The ball diameter was identical in each case at 2.39 mm. An increase in hole diameter of ~7% reduced the lifetime of the material by more than an order of magnitude.

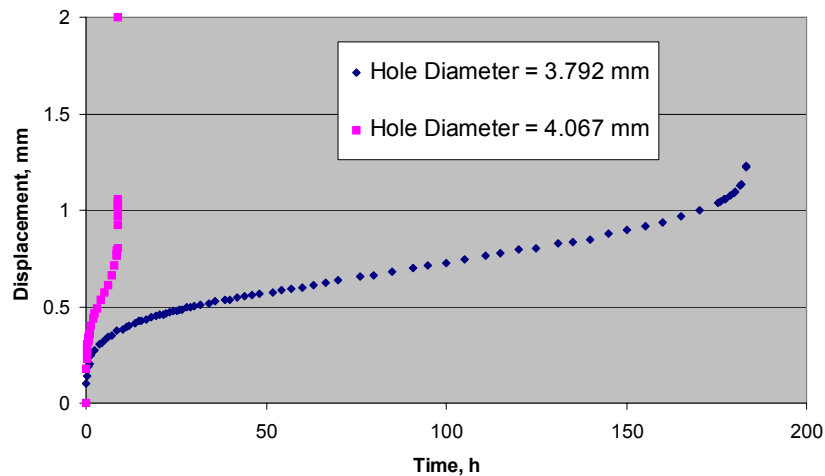


Figure 10 The influence of hole diameter on deformation behaviour in constant load SP tests on service exposed P12 at 600 °C and 320 N.

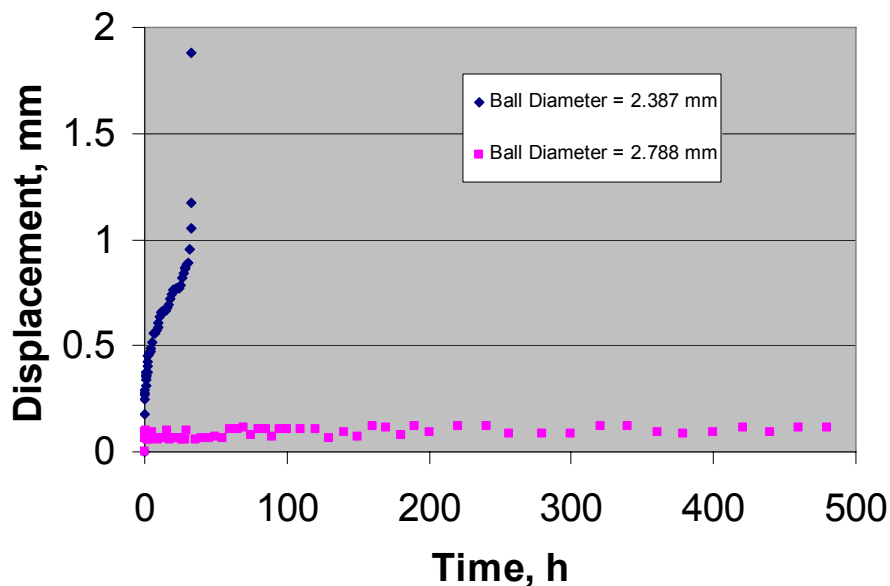


Figure 11 The influence of ball diameter on deformation behaviour in constant load SP tests on service exposed P12 at 600 °C and 320 N.

The influence of changing the ball diameter whilst keeping the hole diameter constant also has a significant influence on deformation behaviour. Figure 11 shows the dramatic effect of increasing the ball diameter by 16% - the projected influence on lifetime is many orders on magnitude.

The magnitude of both these effects has a complex interaction with material properties and must therefore be investigated for each material studied.

Several attempts have been made to correlate the data obtained from constant load SP tests to uniaxial creep tests. These normally take the form of a coefficient to convert the SP load to an equivalent uniaxial stress [6-8]: this coefficient being dependent upon both geometric and material parameters. However no single approach has been shown to be universally applicable and so at this stage no specific recommendation on conversion from small punch to uniaxial data can be made.

5 CONCLUSIONS

Small punch testing, either at constant displacement rate or constant load is experimentally simple to perform. However care must be taken to ensure that the data obtained are reproducible.

6 RECOMMENDATIONS

The following recommendations should be adopted in conjunction with those given in the CEN TWA21 documents [4,8]

1. For both forms of SP tests, temperature control should be equivalent to that for uniaxial testing
2. For both forms of SP tests, the geometry of the test jigs (ie ball diameter and hole diameter) should be measured prior to the start of the test programme
3. All tests in a series should ideally be carried out on a single test jig. Where this is not possible care should be taken that the dimensions of the jigs used are as close as possible. In order to produce comparable data the dimension should not differ by more than 1% between rigs.
4. If possible a small number of uniaxial tests should be performed on the same material in order to validate any expression used to correlate SP tests with uniaxial.

The procedure used at NPL for constant load small punch testing is given in Appendix 1 as an example of good practice for this type of testing.

7 ACKNOWLEDGEMENTS

The authors gratefully acknowledge the contribution of Dr L Crocker, who performed the finite element analysis to determine local strains during deformation.

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8 REFERENCES

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Appendix 1: NPL Internal Procedure for Constant Load Small Punch testing

1 PURPOSE

The purpose of this procedure is to document the actions necessary to carry out small punch creep testing of metals.

2 CONTENTS

3	SCOPE
4	PRELIMINARY
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7	ASSEMBLY OF CREEP TEST
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9	HOT LOADING
10	MONITORING OF CREEP DEFORMATION
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3 SCOPE

- 3.1 This procedure should be followed for all small punch creep tests carried out at NPL in the laboratory F9-L9.

4 PRELIMINARY

- 4.1 Before starting, the operator must be familiar with the test and the operation of the data logging system. They must also ensure that the machine, the extensometry and thermocouples are all within calibration. The calibration data sheets are to be filed in F9-L9 before commencing testing. The constant load testing machines are calibrated in accordance with BS 1610 : Pt 3.
- 4.2 Check that the machine has the required loading train assembly for the test (see Appendix 1). An image of the loading train assembly is shown in Figure 1.
- 4.3 Check that the loading train and pan have been weighed and their mass recorded.
- 4.4 Enter the Test Identification number and test details in the Computer Test Book, which is kept near the NPL Network terminal.

5 TESTPIECE DESCRIPTION AND MEASUREMENT

- 5.1. Testpieces used for small punch creep testing at NPL are normally circular discs with nominal dimensions 9 mm diameter and 0.5 mm thickness.
- 5.2 Diameter and thickness measurements are undertaken to an accuracy of better than 0.005 mm using a calibrated vernier gauge and 0-25 mm micrometer respectively.
- 5.3 Measure the diameter of the disc at three readings measured at equally spaced positions approximately 120° apart around the diameter. The diameter is taken as the mean of these 3 readings.
- 5.4 Measure the thickness of the specimen at the centre and at four points equidistant around the circumference towards the rim of the disc. The thickness is taken as the mean of these 5 readings.
- 5.5 All the readings shall be recorded on the creep data sheets and subsequently stored in F9-L9.

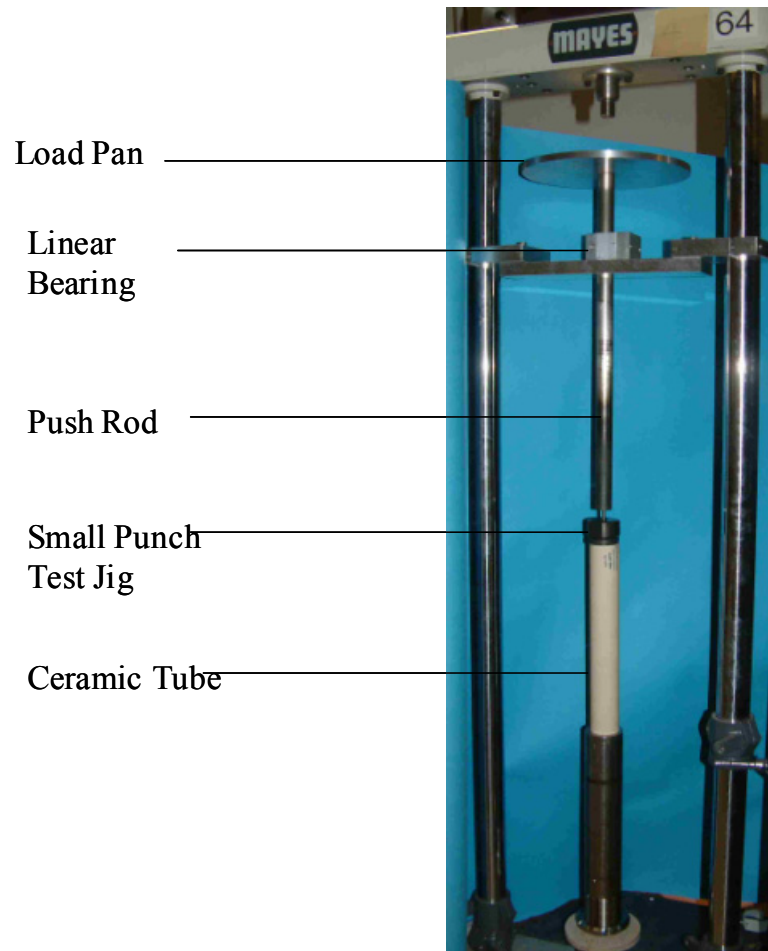


Figure 1 Loading Train Assembly for Small Punch Creep Test

6 OPERATION OF DATA LOGGING SYSTEM

- 6.1 Data logging is performed using custom software running the PC, Ionian. Users have personal login names and passwords. Users must be logged in before changes to test details are allowed.
- 6.2 Access to individual machines is obtained by double-clicking the mouse on the required machine.
- 6.3 Use the 'test set-up' feature to enter details of individual tests prior to starting the test set-up.
- 6.4 Back-up of data on the logging system is automated and uses the NPL network system.

7 ASSEMBLY OF CREEP TEST

- 7.1 Assemble the small punch testpiece in the appropriate jig (Figure 2) and tighten using the 41 mm AF spanner. Insert a spherical ball of the required size into the top recess followed by the punch.

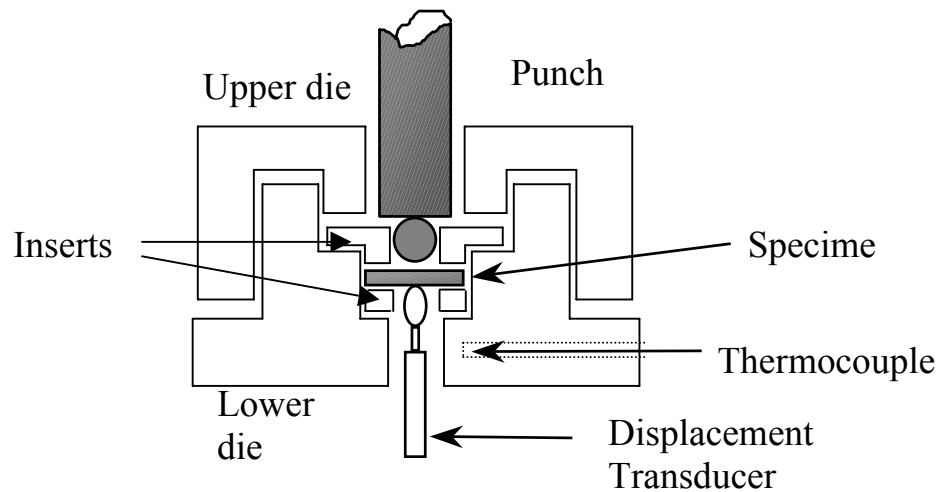


Figure 2 Details of Small Punch Test Jig Assembly

- 7.2 Set the jig on top of the ceramic tube on the creep machine, ensuring that the alumina rod make contact with the specimen within the jig and is free to move. The transducer reading on the data logger should now read ~5.0 mm.
- 7.3 Insert the control thermocouple into the hole in the test jig.
- 7.4 Lower the creep furnace to allow access to the top loading train. Insert the extension rod into the recess and lower the train until it makes contact with the punch. Raise the furnace and ensure that the extension rod and punch are aligned centrally. Finally lower the creep furnace and lock into position.

8 HEATING UP TO THE TEST TEMPERATURE

- 8.1 Pack the annular space at the bottom of the furnace with insulating fibre.
(NOTE: Protective mask and gloves must be used while handling this fibre.)
- 8.2 Switch on the furnace and set the test temperature on the digital controller.
- 8.3 The upper and lower temperature alarm limits on the data logging system are automatically set at ± 2 °C. However BS3500 Pt 3 and BS4A4 Pt 1 specifies the following tolerances on test temperature.

Test temperature °C	Over 10 h and up to 100 h	Over 100 h
Up to and including 600	± 2	± 3
Over 600 up to and including 800	$\pm 2\frac{1}{2}$	± 4
Over 800 up to and including 1000	± 3	± 6
Over 1000	By agreement	By agreement

*The tolerances include the allowable deviations from all sources.

- 8.4 The tolerance on the calibration of the thermocouples is ± 1 °C (QPDMM/B/107). Thus to ensure that prior warning is given of test temperatures deviating from the specified value, the following alarm limits should be used. Tighter alarm limits may be used for special purposes at the discretion of the operator.

Test temperature	Est. life less than 100 h	Est. life greater than 100 h
< 600 °C	± 0.5 °C	± 1.5 °C
600-800 °C	± 1 °C	± 2 °C
800-1000 °C	± 1.5 °C	± 3 °C
> 1000 °C	± 2 °C	± 4 °C

9 HOT LOADING

- 9.1 Add weights in turn to the top scale pan being careful not to introduce any impact loading. The total load applied should take the weight of the loading train into account.
- 9.2 Activate the strain monitoring on the data logger.

10 MONITORING OF CREEP DEFORMATION

10.1 Initial Checks

- 10.1.1 Check on the data logger that the machine has been activated. The data are being recorded if the 'temp' and 'strain' buttons for the machine are coloured green.

10.2 Daily/Weekly Checks

- 10.2.1 Check the temperature of the test every working day. Temperatures outside of the set limits are indicated as red text.

10.2.2 Data are logged at intervals determined by either time or change in displacement readings. These may be changed during the test using the test set-up function on the data logger.

10.2.3 As the displacement is negative graphical displays of any current test cannot be obtained on screen. Progress is monitored by converting the data to a *.csv file and subsequently exporting the data into a suitable spreadsheet package.

11 TERMINATING A TEST

11.1 When the testpiece has fractured or reached the required displacement to be shut-down, switch off the furnace and stop the logging functions for the particular machine.

11.2 After the furnace has cooled down, remove the packing from the furnace whilst wearing protective mask and gloves. Raise furnace, remove thermocouples and dis-assemble loading train.

11.3 On completion of test, enter the fracture lifetime in the “Computer Tests” book, which is kept near the data logger.

12 UNCERTAINTY OF MEASUREMENT

12.1 This test is extremely sensitive to the test jig geometry. Thus the uncertainty of measurement is dependent on several factors including ball diameter, hole diameter, specimen thickness and material parameters such as the stress index, n , in the Norton Creep Law, and the creep activation energy, Q . A definitive expression of the uncertainty of measurement is thus not available at the current time.

13 STAFF

13.1 Staff authorised to carry out this procedure are listed in the Word File, Staff Authorisations, in the folder D:\Creep Laboratory folder on the PC, Arafura.

14 REFERENCES

14.1 RELATED PROCEDURES

This procedure should be used in conjunction with the related procedures:

QPCMMT/B/106 Calibration of strain monitoring system in creep laboratory
 QPCMMT/B/107 Calibration of temperature monitoring system in creep laboratory
 QPCMMT/B/164 Calibration of weights for uniaxial creep testing

14.2 STANDARDS

There are currently no recognised standards for small punch creep testing, however CEN TWA21 is developing a Code of Practice for small punch creep testing. Staff should be familiar with the latest draft of this Code of Practice, which is available at <http://dominus.uni.com/livelink/livelink.exe>

APPENDIX 1 CREEP MACHINES CONVERTED FOR SMALL PUNCH TESTING

M/C Logger Channel	Transducer Type	Manufacturer	Capacity, kN	Comments
C1	ASL, 5 mm	Mayes	20	Small Punch Creep
C2	ASL, 5 mm	Mayes	20	Small Punch Creep
C3	ASL, 5 mm	Mayes	20	Small Punch Creep
C4	ASL, 5 mm	Mayes	20	Small Punch Creep
C5	ASL, 5 mm	Mayes	20	Small Punch Creep