



# **Determination of Secondary Creep Properties Using a Small Ring Creep Test Technique**

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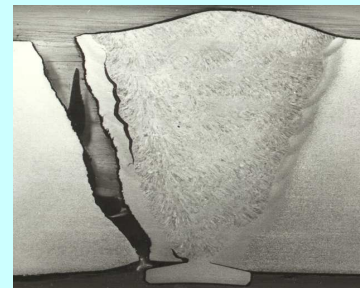
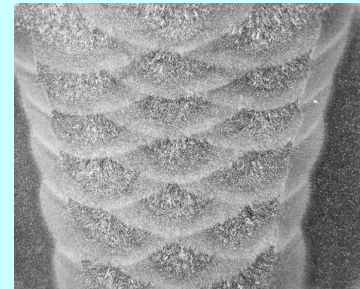
## Introduction

□ In this presentation, firstly, a brief description of three commonly used small creep specimen types and the test methods is given, i.e.

*Sub-size uniaxial creep test;*  
*Impression creep test; and*  
*Small punch creep test*

□ The performances of these test types are briefly described and their unique advantages and limitations, for specific practical applications, are briefly discussed.

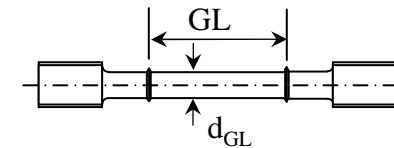
□ Following this, an alternative, recently developed small ring-type creep test method, and its applicability in determining the secondary creep properties is described in more details.





## Conventional Sub-Size Specimens

- ❑ Small cylindrical specimens, typically 1.5-3mm in diameter and 5-12mm in gauge length (GL). Electron beam welding may be used for specimen manufacturing.
- ❑ Data obtained (e.g. by EPRI/CEGB) compared very favourably with those of conventional full size creep tests.
- ❑ Provided grain sizes are not too large, specimen diameters as small as 1mm can be used to produce accurate “bulk” material creep properties.

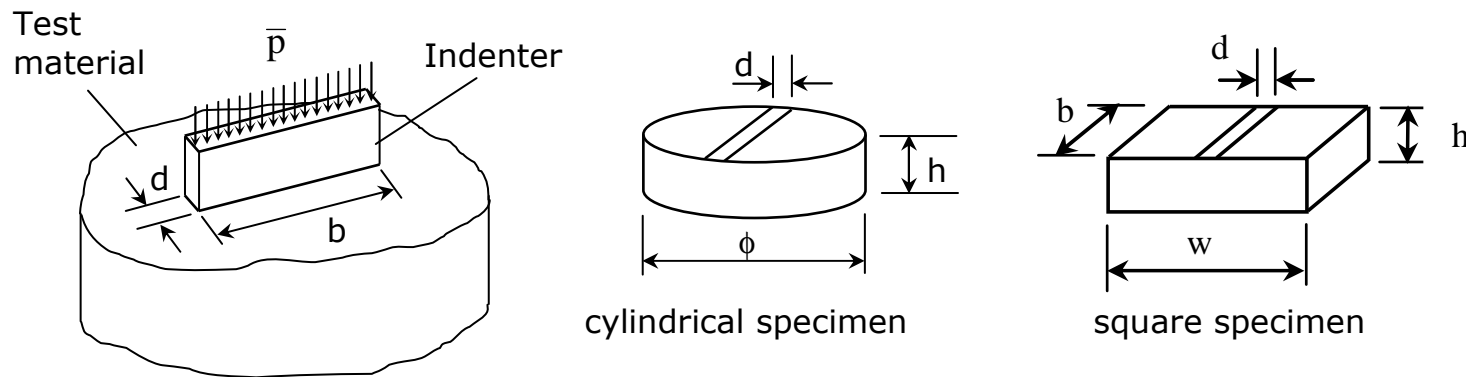


Conventional sub-size uniaxial specimen (GL ~ 5 – 12mm;  $d_{GL} \sim 1 - 3$ mm).

*Askins M. C. and Marchant K. D. (1987). Estimating the remanent life of boiler pressure parts, EPRI Contract RP2253-1, Part 2, Miniature specimen creep testing in tension, CEGB Report., TPRD/3099/R86, CEGB, UK.*



## Impression Creep Test

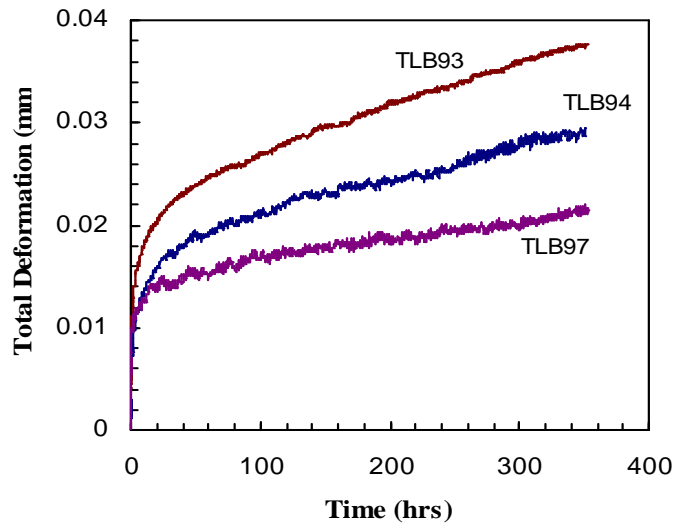


- ❑ The impression creep testing method with a rectangular indenter was introduced in 1996.
- ❑ It involves the application of a steady load to a flat-ended indenter, placed on the surface of a material at high temperature, and the measurement of very small deformations.
- ❑ Typical indenter/specimen dimensions:  $d = 1\text{mm}$ ,  $h = 2.5\text{mm}$ ,  $w = b = 10\text{mm}$ .
- ❑ Conversion relationships have been established based on the RSM:  $\sigma = \eta \bar{p}$  and  $\epsilon^c = \frac{\Delta^c}{\beta d}$
- ❑ The technique has been used extensively for welds, particularly for HAZs.
- ❑ The technique can be used for stepped-load and stepped-temperature situations.

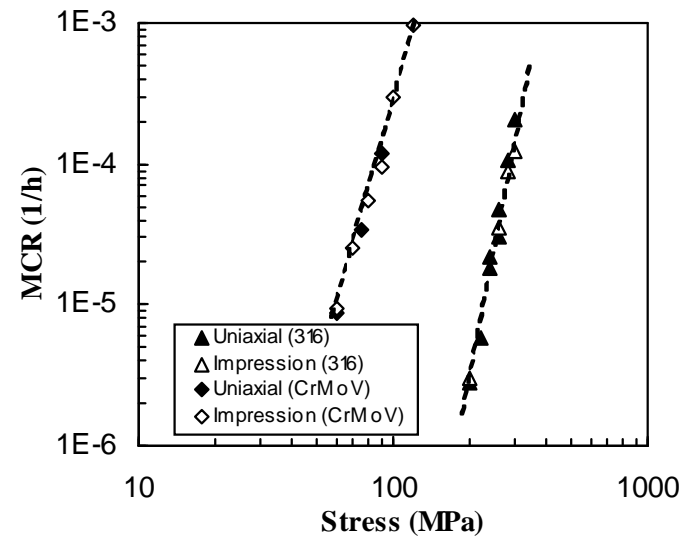
*Hyde, T. H., Sun, W. and Becker, A. A.*, Analysis of the impression creep test method using a rectangular indenter for determining the creep properties in welds, *Int. J. Mech. Sci.*, **38** (10), 1996, p. 1089-1102.



## Typical Results from Impression Creep Tests



Total impression deformations with time at 90 MPa and 600°C obtained from three different ex-service 1/2CrMoV steam pipe samples (d = 1mm, h = 2.5mm, w = 10mm).



Minimum creep strain rates for 316 stainless steel at 600°C and 2-1/4Cr1Mo weld metal at 640°C, obtained from uniaxial and impression creep tests.



## Small Punch Creep Test

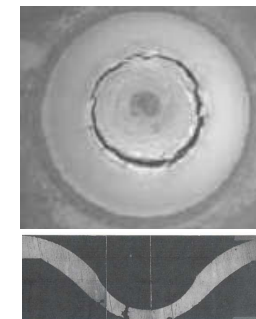
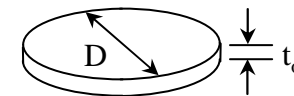
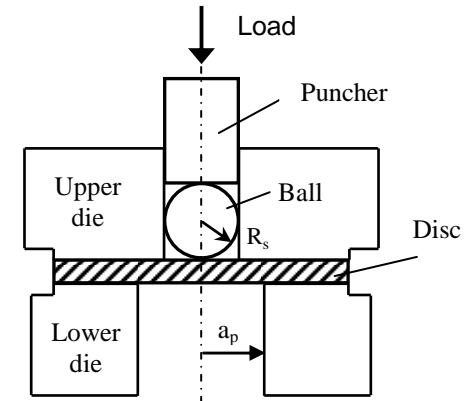
- ❑ A small punch creep test involves the application of a central load, through a spherical punch or a ball, to a thin disc (~ 0.5mm thick), at high temperatures
- ❑ The test involves the measurement of relatively large deformations; the creep curves till rupture can be obtained - particularly attractive for material testing for sub-regions, e.g. HAZ and weld metal
- ❑ Empirical relationships between the applied load,  $P$ , the “membrane stress”,  $\sigma$ , the strain at the edge of contact,  $\epsilon$ , and the total deformation,  $\Delta$ , are obtained, e.g.

$$P / \sigma = 1.72476\Delta - 0.05638\Delta^2 - 0.17688\Delta^3$$

$$\epsilon = 0.17959\Delta + 0.09357\Delta^2 + 0.00440\Delta^3$$

$$\sigma = \frac{0.3}{K_{sp}} \frac{Pa_p^{0.2}}{R_s^{1.2} t_o}$$

- ❑ Test procedures, specimen set-up, temperature control, etc, have all been established and a code of practice exists.



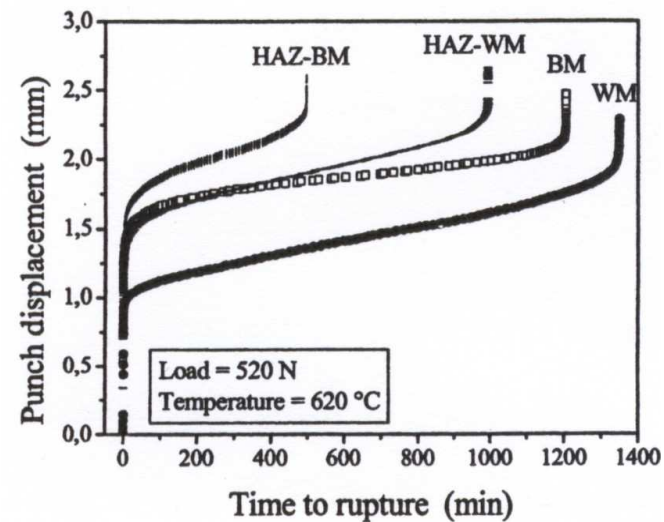
**Purmensky J. and Matocha K.** Latest developments in SPT. VITKOVICE Research & Development Ltd., Czech Republic, June 2007.

**Li Y. Z. and Šturm R.** (2008) Determination of creep properties from small punch test. *Proc. ASME Pressure Vessels and Piping Division Conference*. July 27-31, 2008, Chicago, Illinois, USA.

**CEN CWA 15627** Workshop Agreement: Small punch test method for metallic materials (Part A). December 2006, European Committee for Standardisation.



## Typical Results from Small Punch Creep Tests



Typical small punch test curves obtained using specimens from four different zones of a P91 welded joint.



## Small Ring-Type Creep Test Method

- ❑ A high sensitivity, ring type of small specimen creep test method, which can be used to obtain secondary creep data, has been developed recently.
- ❑ An analytical solution for the load line deformations of an elliptical ring was obtained based on the complementary strain energy approach.
- ❑ A reference stress approach is used to establish the conversion relationships between the applied load and the equivalent uniaxial stress and between the experimentally measured creep deformations and the equivalent uniaxial creep strains.
- ❑ Experimental validation of the test method is made using the results obtained from creep tests of (circular and elliptical) rings for a P91 steel at 650°C.





## Analytical Solutions

The steady-state creep solution for the load-line deformation rate of a diametrically loaded elliptical ring, obeying a Norton's law, has been obtained, based on the principles of virtual complimentary work and stationary complimentary energy:

$$\dot{\Delta}_V = \frac{2Bab}{(I_n)^n} \left( \frac{Pa}{2} \right)^n \text{Int}_2(n, \frac{a}{b}) \quad \text{for Norton's law: } \dot{\epsilon}^c = B\sigma^n$$

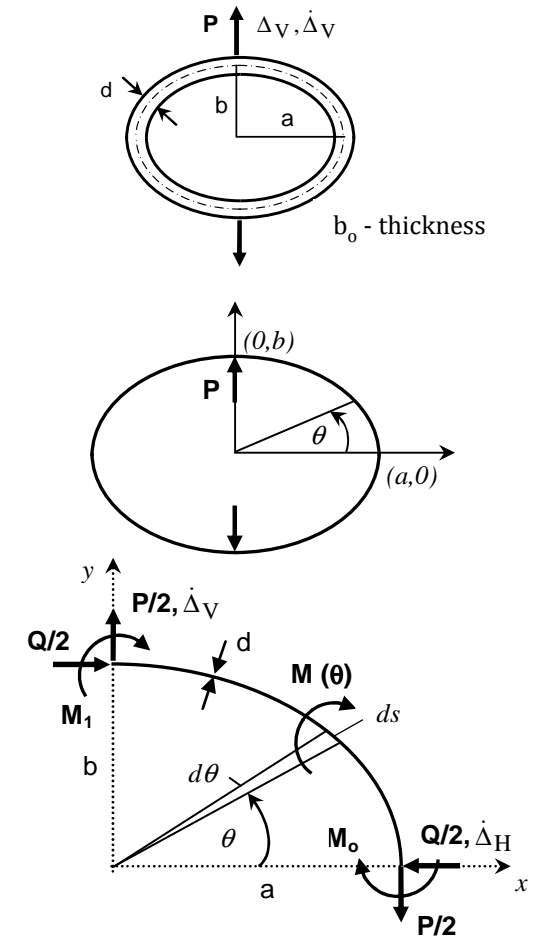
$$I_n = \int_A y^{1+\frac{1}{n}} dA$$

$$\text{Int}_2 = \left\{ -\int_0^{\theta'} (\cos \theta - \cos \theta')^n (1 - \cos \theta) \sqrt{\left(\frac{a}{b}\right)^2 \sin^2 \theta + \cos^2 \theta} d\theta \right. \\ \left. + \int_{\theta'}^{\frac{\pi}{2}} (\cos \theta' - \cos \theta)^n (1 - \cos \theta) \sqrt{\left(\frac{a}{b}\right)^2 \sin^2 \theta + \cos^2 \theta} d\theta \right\}$$

where  $\theta'$  is the solution of the following equation:

$$0 = \int_0^{\theta'} (\cos \theta - \cos \theta')^n \sqrt{\left(\frac{a}{b}\right)^2 \sin^2 \theta + \cos^2 \theta} d\theta - \int_{\theta'}^{\frac{\pi}{2}} (\cos \theta' - \cos \theta)^n \sqrt{\left(\frac{a}{b}\right)^2 \sin^2 \theta + \cos^2 \theta} d\theta$$

Hyde, T. H. and Sun, W. (2009) A novel, high sensitivity, small specimen creep test. *J. of Strain Analysis* 44 (3), 171-185.





## Conversion Relationships

For an elliptical ring with rectangular cross-section (thickness  $d$  and length  $b_0$ ):

$$I_n = \frac{2n}{2n+1} b_0 \left(\frac{d}{2}\right)^{\frac{2n+1}{n}}$$

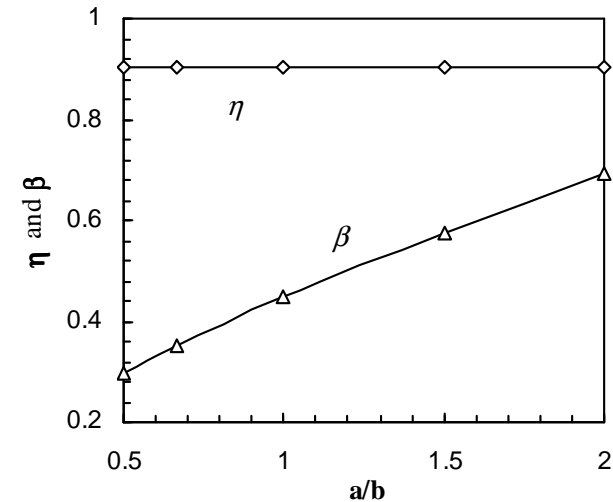
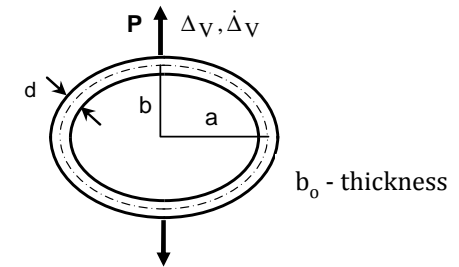
$$\dot{\Delta}_V = \left(\frac{2n+1}{n}\right)^n \text{Int}_2\left(n, \frac{a}{b}\right) \frac{4ab}{d} B\left(\frac{Pa}{b_0 d^2}\right)^n$$

Using a reference stress approach:

$$\dot{\Delta}_V = \beta \left(\frac{4ab}{d}\right) B(\sigma_{\text{ref}})^n$$

$$\beta = \left(\frac{2n+1}{n}\right)^n \frac{\text{Int}_2\left(n, \frac{a}{b}\right)}{\eta^n}$$

$$\sigma_{\text{ref}} = \eta \frac{Pa}{b_0 d^2} \quad \dot{\epsilon}^c(\sigma_{\text{ref}}) = \frac{d}{4ab\beta} \dot{\Delta}_V$$



Variations of the conversion parameters  $\eta$  and  $\beta$  with  $a/b$  for elliptical ring specimens.



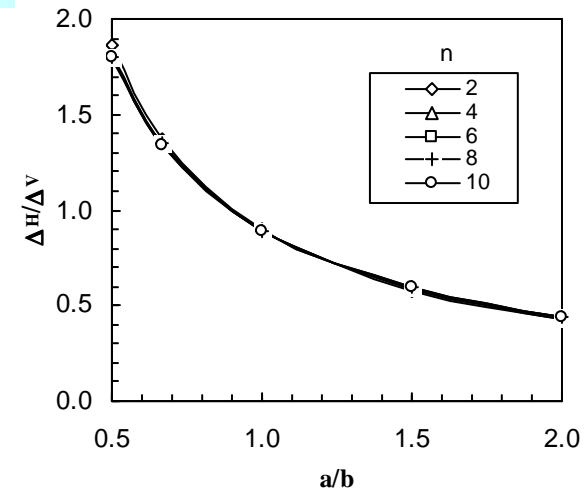
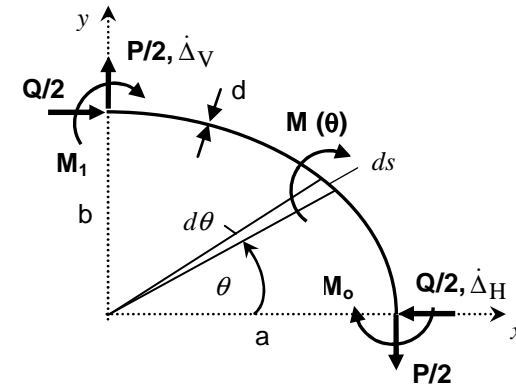
## Transverse Deformation

- An analytical solution for the transverse deformation,  $\Delta_H$ , was obtained in order to quantify its effect.
- As expected, the  $\Delta_H/\Delta_V$  ratios reduces significantly with increasing  $a/b$ .
- This indicates that the effect of geometry change can be minimised by using elliptical specimens with relatively large  $a/b$  ratios.

$$\dot{\Delta}_H = \frac{2Bb^2}{(I_n)^n} \left( \frac{Pa}{2} \right)^n \text{Int}_3(n, \frac{a}{b})$$

$$\frac{\dot{\Delta}_H}{\dot{\Delta}_V} = \frac{1}{a/b} \frac{\text{Int}_3(n, a/b)}{\text{Int}_2(n, a/b)}$$

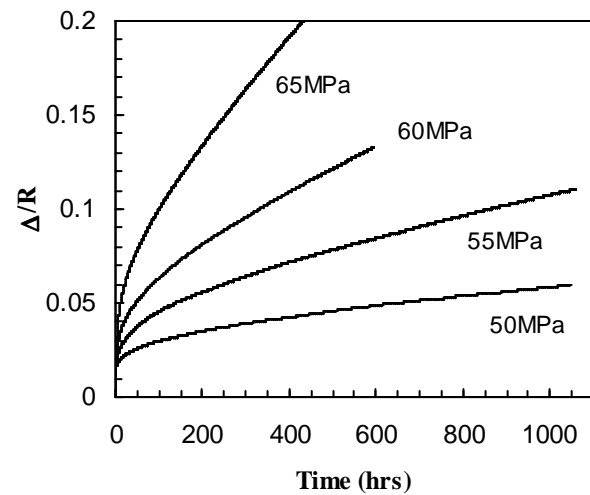
$$\text{Int}_3 = \left\{ -\int_0^{\theta'} (\cos \theta - \cos \theta')^n \sin \theta \sqrt{\left(\frac{a}{b}\right)^2 \sin^2 \theta + \cos^2 \theta} d\theta \right. \\ \left. + \int_{\theta'}^{\frac{\pi}{2}} (\cos \theta' - \cos \theta)^n \sin \theta \sqrt{\left(\frac{a}{b}\right)^2 \sin^2 \theta + \cos^2 \theta} d\theta \right\}$$



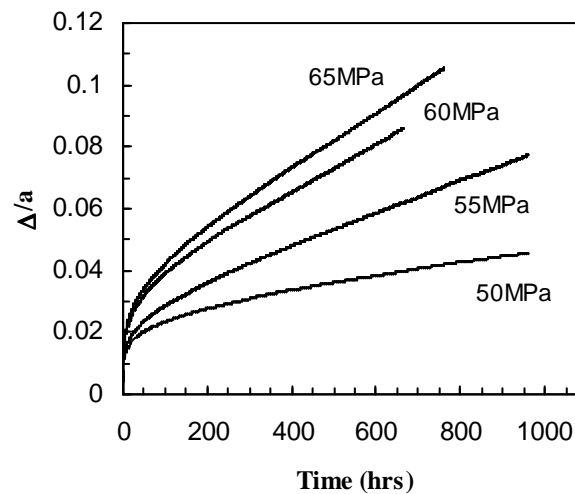
Variations of  $\Delta_H/\Delta_V$  with  $a/b$ , for a range of  $n$ , for elliptical rings.



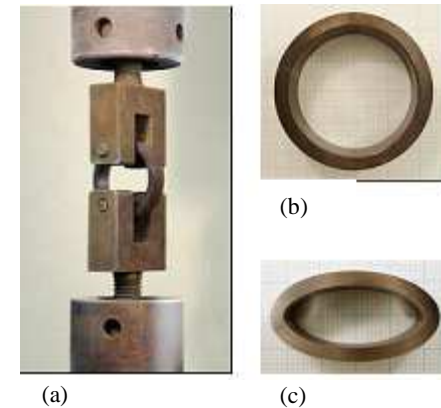
## Results from Ring Creep Tests for a P91 Steel at 650°C



Variation of  $\Delta/R$  with time for diametrically loaded P91 **circular** rings, at 650° C.



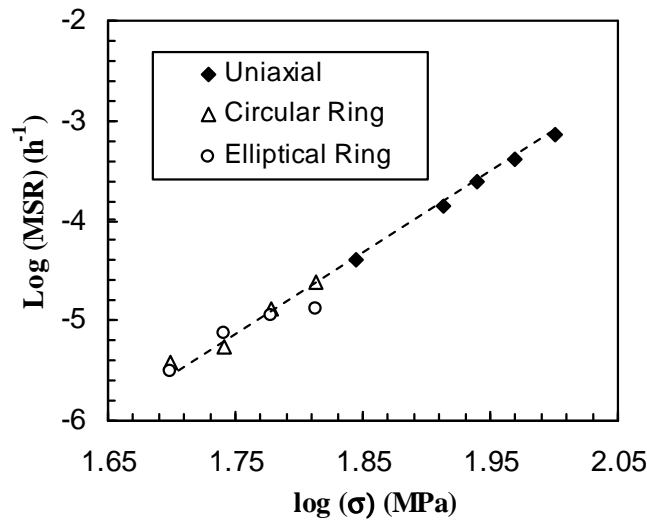
Variation of  $\Delta/a$  with time for diametrically loaded P91 **elliptical** rings, at 650° C.



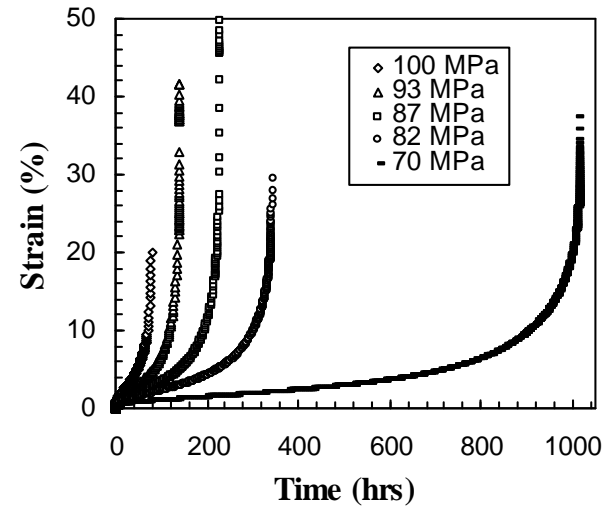
Ring test: (a) Load application; (b) Circular specimen; (c) Elliptical specimen.



## Results from Ring Creep Tests for a P91 Steel at 650°C ...



Minimum creep strain rate (MSR) data obtained from ring and uniaxial creep tests for P91 steel, at 650°C.



Uniaxial creep strain curves of P91 steel at 650°C.



## Equivalent Gauge Length (EGL)

□ For a conventional uniaxial creep test:  $\epsilon^c \approx \frac{\Delta}{GL}$

□ For non-conventional small creep test specimens:  $\epsilon^c \approx \frac{\Delta^c}{EGL}$

□ The creep strain and creep deformation may be given by:  $\epsilon^c(\sigma_R) \approx \frac{\Delta^c}{D}$

where  $D = EGL = \beta L$  and  $\sigma_R = \eta \sigma_{nom}$

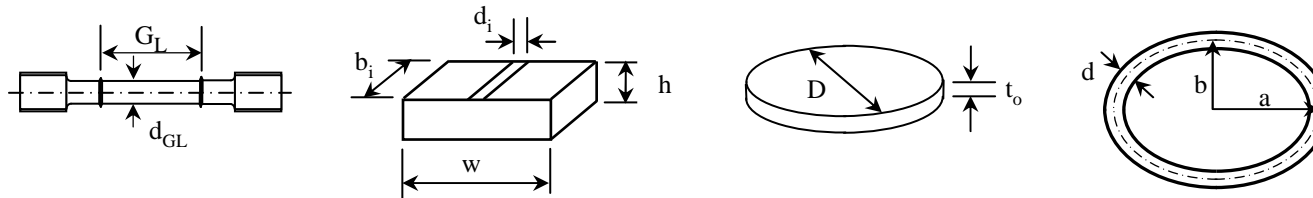
Equivalent gauge length (EGL) of small creep specimens (P is the applied load).

	Uniaxial	Impression	Small Punch*	Circular Ring	Elliptical Ring
$\sigma_{nom}$	$\frac{4P}{\pi d_{GL}^2}$	$\frac{P}{b_i d_i}$	$\frac{P}{2\pi R_s t_o}$	$\frac{PR}{b_o d^2}$	$\frac{Pa}{b_o d^2}$
$\eta$	1	~ 0.4	$\sim \frac{0.6\pi}{K_{sp}} \left( \frac{a_p}{R_s} \right)^{0.2}$	0.892	0.892
$\beta$	1	~ 2.0	----	0.448	~ 0.3 - 0.7
EGL	GL	~ 2d <sub>i</sub>	~ 2a <sub>p</sub>	$\frac{4R^2 \beta}{d}$	$\frac{4ab\beta}{d}$

\*It is difficult to define material and deformation independent parameters, due to the nature of the test.



## Equivalent Gauge Length (EGL)...



	Uniaxial	Impression	Small Punch	Circular Ring	Elliptical Ring
Dim s (mm)	$G_L = 10$ $d_{GL} < 3$	$b_i = 10$ $d_i = 1$ $h = 2.5$	$D \sim 8$ $a_p = 2$ $R_s = 1.25$ $t_o = 0.5$	$a = b = 5$ $d = 1$	$a/b = 2$ $a = 5$ $d = 1$
EGL (mm)	10	$\sim 2$	$\sim 5^*$	45	22.5

\* Estimated by the first term of the empirical ( $\epsilon$ - $\Delta$ ) relationship:

$$\epsilon = 0.17959\Delta + 0.09357\Delta^2 + 0.00440\Delta^3$$

$$P/\sigma = 1.72476\Delta - 0.05638\Delta^2 - 0.17688\Delta^3$$

**Li Y. Z. and Šturm R.** (2008) Determination of creep properties from small punch test. *Proc. ASME Pressure Vessels and Piping Division Conference*. July 27-31, 2008, Chicago, Illinois, USA.



## Main Features of the Ring Test

- ❑ The ring specimen is relatively “flexible”, i.e. it has a relatively “large” EGL;
- ❑ The method is suitable for testing at lower equivalent stresses – enabling low strains to be obtained from relatively large deformations;
- ❑ Specimens have simple geometries and the tests are easy to perform;
- ❑ The conversion relationships are material independent and are insensitive to the geometry changes which occur during deformation;
- ❑ It can be used to test materials whose creep strengths are similar to that of the loading pins, allowing some very strong high temperature materials, such as Nickel-based superalloys, to be tested;
- ❑ The ring specimens could be particularly suitable for determining the HAZ properties;
- ❑ Since measured creep deformations are relatively large, the test is not sensitive to the small thermal strains which results from unavoidable, small test temperature variations.



## **Impression, SPT and Ring Techniques**

- The impression creep test is suitable for determining minimum creep strain rate data, particularly at relatively high stresses. It has a relatively small EGL and therefore requires accurate measurement of very small deformations and high accuracy of temperature control. The measured behaviour is highly related to local properties.
- The SPT technique involves the measurement of relatively large deformations. Significant local plasticity and complicated deformation modes occur during the test. Due to this, it is difficult to accurately interpret the test data. The most attractive feature from SPT is that tertiary creep data can be obtained from the test.
- The small, ring-type specimen test has a large EGL, and is capable of obtaining relatively low strains from relatively large deformation. The method is suitable for determining minimum creep strain rate data, particularly at relatively low equivalent uniaxial stresses; it provides a useful addition to current small sample test methods.
- Each of the three techniques has its own unique features and applications. To the authors' point of view, none of them can be replaced completely by another one.