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Small Two-bars specimen creep testing of grad P91 steel at 650°C

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An abbreviated running title: Small TBS creep testing of grad P91 steel at 650°C

Abstract

Commonly used small creep specimen types, such as ring and impression creep specimens, are capable of providing minimum creep strain rate data from small volumes of material. However, these test types are unable to provide the creep rupture data. In this paper the recently developed Two-bar specimen type, which can be used to obtain minimum creep strain rate and creep rupture creep data, from small volumes of material is described. Conversion relationships are used to convert (i) the applied load to the equivalent uniaxial stress, and (ii) the load line deformation rate to the equivalent uniaxial creep strain rate. The effects of the specimen dimension ratios on the conversion factors are also discussed in this paper. This paper also shows comparisons between Two-bar specimen creep test data and the corresponding uniaxial creep test data, for grad P91 steel at 650°C.

Keywords: specimen dimensions; reference stress barometers; Two-bar spacemen; conversion relationships

1. Introduction

Many power plant and aerospace components operate at stresses and/or temperatures which are high enough for creep to occur[1]. Hence, the creep properties of materials are required in order to be able to obtain reliable component life estimations. Standard uniaxial creep test specimens (see Fig. 1) are usually used to determine creep properties. However, in many practical situations standard specimens cannot be produced without (i) compromising the structural integrity of the component from which they are removed, or (ii) requiring a major repairing operation for the tested components. Therefore, over approximately the last two decades, several small specimen creep test types have been developed and used to obtain material creep data from small volumes of material removed, for example, from a component surface using an in-situ sampling process (see Fig. 2) or from local heat-affected zones of welded joints, e.g.[2-4]. The small ring creep test method [4, 5]and the impression creep test technique [6-8], have been used to determine secondary creep rate data for materials but they are unable to provide tertiary creep data. Small, sub-sized uniaxial specimen tests have been used to obtain the full creep strain curves. However, electron beam welding may have to be used to join the gauge length section to the specimen ends, due to an insufficient volume of material being available, which makes the preparation of test specimens rather complicated [9, 10]. Alternatively, small punch creep tests e.g. [11-13]can be used to provide the creep deformation and rupture. However, interpretation of small punch creep test data, in relation to the corresponding uniaxial data, is difficult, and to date, a universally accepted interpretation procedure is not available [1, 13]. For these reasons, there is a strong desire for the development of miniature specimen types and the associated testing techniques which can be used to produce reliable creep deformation and creep rupture data. In this paper, a recently developed small-sized specimen (Two-bar specimen) type is described, which is suitable for use in obtaining both uniaxial minimum creep strain rate and creep rupture data [14].This specimen can be easily manufactured from the heat-affected zones (HAZ), weld metal (WM) zones of a weld [4, 15], or from small scoop samples removed from the surface of the component. Typical dimensions of a scoop sample are shown in Fig. 3. The specimen has simple geometry and can be conveniently machined and loaded (through pin-connections) and then tested under tensile loading. In this work grad P91 steel at 650^{o}Chas been used to assess the accuracy of the conversion relationships and to validate the testing technique. The conversion relationships are used to relate (i) the applied load, to the corresponding uniaxial stress; and (ii) the specimen deformation to the corresponding uniaxial strain. The minimum creep strain rate and creep rupture data obtained from the small Two-bar specimen are compared with those obtained from the corresponding uniaxial specimens.

2. The Small "Two-bar" Specimen creep testing

A Two-bar Specimen (TBS) [14] has a simple geometry and dimensions (see Fig. 4).The specimen dimensions are defined by b, d, $D_{i,}$ k and L_o, where b is the bar width, d is the specimen thickness, D_i is the diameter of the loading pins, k is the length of the loading pin supporting end and L_o is the "uniform bar" length, i.e. the distance between the centres of the loading pins. A tensile load is applied to the specimen through the loading pins to produce the required stress in the uniform part of the specimen (L_o).

The specimen load-line deformation is recorded throughout the test duration. Using the reference stress method in conjunction with finite element analyses (FE)[17-19],a conversion relationships have been obtained to convert the applied load (P) to the corresponding uniaxial stress (σ), i.e.,

$$\sigma_{ref} = \eta \sigma_{nom} \quad (1)$$

where σ_{ref} is the reference stress, σ_{nom} is the nominal stress in the specimen bars, i.e., $\sigma_{\mathrm{ref}} = \frac{P}{2A}$, where A is the bar cross section area and ηis the reference stress parameter. Anotherrelationship, i.e., Eq. 2, is used to convert the measured minimum load-line (pins) deformation rate ($\dot{\Delta}_{ss}$) to the corresponding uniaxial minimum creep strain rate(MSR), i.e.,

$$\dot{\varepsilon}^c \approx \frac{\dot{\Delta}_{ss}}{EGL} \quad (2)$$

where $\dot{\varepsilon}^c$ is the minimum strain rate, $\dot{\Delta}_{ss}$ is the minimum deformation rate and EGL is the equivalent gage length, i.e.,

$$EGL = L_o \beta \quad (3)$$

where β is the reference gauge length parameter for the particular TBSgeometr. Thereferenceparametersβ and ηare dependent on thespecimengeometry and dimension ratios,and are independent of material properties. The detailed derivations of these conversion relationships have been published in [14].

3. Determination of the Reference Stress Parameter for the TBS

Determining the accurate values of the conversion factors η and β, is the key factor to obtain accurate creep data, i.e. MSR and rupture data usingthe Two-bar specimen.Accurate determination of the reference stress parameters related to the corresponding uniaxial stresses allows (i) accurate determination of the applied load (P) for the specimen, (ii) accurate determination of the equivalent gauge length (EGL). The reference stress parameter η and β for the TBS have been obtained using FE analysis and aNorton material model, i.e.,

$$\dot{\varepsilon}^c = A\sigma^n \quad (4)$$

whereA and n are material constants.The loading pin steady-state deformation ratesfor the TBS were obtained, for a range of n values. The steady state deformation rates, $\dot{\Delta}_{SS}$, were normalised by dividing them by $L_o\, A(\alpha \frac{P}{2(bd)})^n$ [14],where P is the applied load. Several α values were considered for all of the n values. The value of α which made log β' , i.e. $log\left[\frac{\dot{\Delta}^{c}_{ss}}{L_o\ B(\alpha\frac{P}{2bd})^n}\right]$, practically independent of nis the reference stress parameter η for this particular TBS geometry and dimensions. This valuecorresponds to the solid line in Fig. 5.The value of β can then be obtained from the intercept of the horizontal or almost horizontal, solid line, inFig. 5. The procedure is described in more details in refs. [14, 20].

4. Effects of the TBSDimension ratioson the Conversion Factors and Recommended Dimension Ratios

4.1 Effects of L_o, k and bon the conversion factors

The specimen dimensions that can be used are not fixed,which allows the specimen to be manufactured from the different shapes and volumes of material samples that may be available. The specimen geometry is defined by three main dimension ratios, i.e. L_o/D_i, k/D_iandb/D_i(see Fig. 4). Since the conversion factors η and β are geometry dependent, the dimension ratios have an effect on the conversion factors. Consequently, making the most appropriate choice of specimen dimension ratios may affect the conversion factors, and lead to the most accurate interpretation of the MSR and rupture data [14]. Using FE analyses and a constant loading pin diameter the effects of the L_o/D_i, $k/D_i$and b/D_i(see Fig. 6to Fig. 8),on the reference stress parameter have been investigatedin [14], therefore the effects of thesefactors on the reference stress parameters will be briefly discussed in this paper.The FE analyses were carried out using the ABAQUS software package [21].

4.2 Effects ofd/$D_i$ratio on the conversion factors

The effect of TBS depth, d, on theη and β values was also investigated using FE analyses. The two extremes of behaviour, i.e. plane stress ($d \cong 0$) and plane strain conditions ($d \cong \infty$), were investigated using meshes consisting of 8-noded isoparametric elements for the plane stress, PS, and 8-nodedisoparametric elements, for the plane strain, PE, respectively. The intermediate behaviour was also investigated using meshes which consist of 20-noded, 3D brick elements,the model which is used for the 3D analyses shown in Fig. 11.The FE analyses were carried out using the ABAQUS software package [21]. Various values of d were used, while all other specimen dimensions were kept constant for the analyses. The 3D specimen model dimensions L_o, k, b and D_i were 20, 6, 2 and 5mm respectively, where the dvalues for the 3D analyses, were in the range 0.25 and 20 mm. The applied loads for the 3D analyses was increasing as the specimen depth, d, increases, in order to maintain the same nominal stress in the uniform part of the specimen, L_o, for all cases. The results presented inFig. 9 and Fig. 10indicate that, under plane strain conditions, where dis considered to be very large i.e. the d/D_i ratio is effectively infinite, β and η have the lowest values, which are 1.031 and 0.912, respectively. Whereas under plane stress conditions where d considered to be very small i.e. the d/D_i ratio is effectively close to zero, β and η have the highest values, which are 1.3066 and 0.993, respectively. The β values obtained from the 3D analyses are between those obtained from the plane stress and the plane strain conditions, but remain practically constant and close to those obtained from the plain stress condition for all practical $\frac{d}{D_i}$ values, i.e. $\sim \frac{d}{D_i} \leq 0.5$ as it can be seen from Fig. 9, and Fig. 10.

4.2.1 The effect of TBS depth, d, on the minimum strain rate and failure time

The precise volume and shape of the small sample of material available for testing dictates the specimen dimensions including the specimen depth. Therefore, theeffects of TBS depth, d, on the failure time and minimum strain rate have been investigated using FE analyses. The same 3D model as that shown in Fig. 11 was used to study the effects of the specimen depth on both the MSR and the failure time of the specimen. A damage model developed by Liu and Murakami [22] was used to obtain the TBS time to failure while Norton's model, was used to obtain the minimum deformation rates. Several values of d were included in the analyses while the rest of the specimen dimensions were kept constant, including the loading pin diameter. The applied load was increased with the d value in order to maintain the same nominal stress, (σ_{nom}),in the uniform part of the specimen, L_o, for all cases,where,$\sigma_{nom} = \frac{P}{2(b\times d)}$. The conversion relationship given by Equ. 2, was used to convert the TBS minimum deformation rates to the uniaxial minimum strain rates. Fig. 12 and Fig. 13, demonstrate that the effect of specimen thickness (d), on both the failure time and minimum strain rate, for constant nominal stress, is practically negligible.

4.3 Recommended specimen dimension ratio ranges

Unlike the impression creep test [23] where the creep properties are related to the small volume of material close to the contact region between the specimen and the loading device, the TBSwas designed to be able to obtain creep properties from the overall specimen creep deformation; not just from the localised deformation which occurs in the contact area between the loading pins and the loading pins supporting material. In order to make a suitable choice of specimen dimension ratios, with minimum localized deformation in the contact areas, the FE analyses results presented in Fig. 6 to Fig 10can be used as a guide. However, the specimen dimensions are normally dictated by the shape and size of the small sample of the material available for testing. It is recommended that specimen dimension ratios, i.e.,L_o/D_i, $k/D_i$and b/D_iwhich minimise the contribution of the deformation in the loading pins supporting material, should be used when it is possible. Theβ values are always dependent on the magnitude of the contribution of the deformation rate in the loading pins supporting material to the total specimen deformation rate, as indicated in Fig. 6 to Fig. 10, i.e.

$$\beta \propto \frac{\dot{\Delta}_k}{\dot{\Delta}_{total}}$$

where $\dot{\Delta}_k$ is the deformation rate in the loading pins supporting material, $\dot{\Delta}_{total}$ is the total TBS deformation rate measured at the loading pins. However, the η values, for the range of specimen dimension ratios, are close to unity and practically independent of the specimen dimensions. Hence the recommended ranges of specimen dimension ratios are given in Table 1.
The specimens which were tested experimentally had dimension ratios which fall in the range of the dimension ratios given in Table 1. Using the procedure described in section 3, the η and β values, for the tested specimens, were 0.9966 and 1.4557, respectively.

5. Experimental Creep Testing and Validation of the TBS Test Method

In this paper the validationof the TBS testing technique was carried out using the parent material (PM) of grad P91 steel [24].The material known, also as modified 9Cr steel, is a high strength, high ductility steel capable of operating at high temperatures. Therefore, this material is widely used in power plants pipe works. However, it is less creep resistance than typical P91 pipe material steel[25]. Table2 shows the chemical composition of the grad P91 steel.The material was used to manufacture five conventional uniaxial creep test specimens (see. Fig.1). Thespecimens were creep tested at 650^{o}C. The tests were carried out using stresses of 70, 82, 87, 93 and 100 MPa, respectively. The strains versus time curves obtained are shown in Fig. 14. The curves exhibit relatively small primary creep regions and comparatively long secondary and tertiary regions. Pronounced tertiary creep begins at a strain level of about 5.5%.

5.1 Two-bar SpecimensMachining and Loading Setup

The TBSs weremachined from the same materialgrad P91 steel usingElectrical Discharge Machining (EDM)[26,27]; it was convenient to use thismachining method to manufacture the specimens, because of the small dimensions of the TBS and the strong need to obtain identical bars with good finishing.The specific specimen dimensions used for L_o, k, b, d and D_i were 13.0, 6.5, 2.0, 2.0 and 4.974 mm, respectively. These dimensions were used becausethis size of specimen can easily be manufactured from small scoop samples of material (see Fig 3), removed from a component surface using thenon-destructive Surface Sampling System (SSam). In order to ensure high quality surface finishing, especially in the uniform part of the specimen (L_o), the specimens were carefully polished to the final dimensions. The loading fixtures generally have larger dimensions and have much higher stiffness, compared to the specimen (see Fig. 15).In addition, the loading pins and the loading pin holders are manufactured from a Nickel-base Superalloy (Nimonic 80A), which has much higher creep resistance than the tested material; this ensures that the deformation of the loading fixture is negligible.

5.2 Minimum Creep Strain Rates and Creep Rupture Data for the grad P91 steel at 650^{o}C

The TBSs were creep tested at 650^{o}C using a tensile load applied through the loading pins (see Fig. 15) with loads corresponding to uniaxial stresses of 70, 82, 87, 93 and 100 MPa, respectively. Equ. (1) was used to calculate the applied load for each stress. The deformation time curves obtained from the TBSs are shown in Fig. 16. As is the case for the uniaxial curves, the TBSs curves exhibit relatively small primary creep regions and relatively long secondary and tertiary regions.

The TBSs minimum creep strain rates were obtained using the TBSs minimum deformation rates and the conversion relationship given byEqu.2, the results are compared with the corresponding uniaxial minimum strain rates in Fig. 17, remarkably good agreement is found between the two sets of results. The TBSs time to failure are also compared with the corresponding uniaxial tests using (log-log scale) in Fig 18.Again, as with the MSR data,very good correlation between the uniaxial and the TBS rupture data was obtained.

The TBS creep testing techniquesis unlike the smallpunch creep testing (SPCT) [28, 29], where the specimen shape and dimensions change completely during the test; they change from having a flat surface disk to hemispherically ended, conicalshape. The changes in the overall TBS specimen shape and dimensions during the test are relatively small (see Fig 19). The tested specimen dimensions for all stresses levels used,were measured and theses are compared with the original specimen dimensions in Table 3. The conversion factors η and β for the Two-bar specimen, are specimen geometry dependent (see Fig. 6, Fig.7 and Fig.8), i.e. as the specimen dimension ratios (L_o/D_i ,b/D_i , k/D_i) change, the values of η and β change. If the values of the conversion factors change during the test, the results of the TBS creep tests will change accordingly, i.e. the TBS creep test results are very sensitive to the conversion factors. Therefore, the values of the conversion factors have to be constant or almost constant during the test duration. For this reason FE analyses was conducted in Section 4, in order to verify that the small changes in the TBS dimensions during the test, do not affect the conversion factors η and β significantly.

Table 3demonstrates that, the changes in the TBSs dimensions, i.e., k, d, b and L_o , is about0.06%, 6%, 4% and 27% respectively, also shows that the uniform part of the specimen, L_o, dictates the specimen deformation with elongation approximately 27% of the original length.The changes of L_o, is about 4.7 mm, which make the ratioL_o/D_i at failure ≈ 3.54, whereas L_o/D_i at the beginning of the test was 2.6, which makes the total change of theL_o/D_i ratio during the test is about 0.94. The data presented in Fig. 6, shows that between these twovalues of L_o/D_i, i.e. 2.6 and 2.54, both η and βfactors, remain practically constant.Since the changes in the overall specimen geometry and dimensions are insignificant during the test, it is reasonable to assume that the conversion factors remain practically constant throughout the test duration. Hence, the TBS deformationversus time curves presented in Fig. 16 can be conveniently converted to strain versus time curves using Equ. 5, i.e.

$$\varepsilon^c = \frac{\Delta^c}{\beta L_o} \quad (5)$$

where ε^c is the equivalent uniaxial creep strain, Δ^c is the TBS creep deformation , β is the reference stress parameter and L_o is the distance between the centres of the loading pins. The converted TBS strain-time curves are compared with the corresponding uniaxial curves in Fig. 20. Again remarkably good correlation between the uniaxial and the TBS curves is found.

6. Conclusions and future work

Small specimen creep testing techniques are useful in a number of practical engineering situations. They can be used to obtain the current creep strength of a service-aged material or to obtain the creep properties of HAZ / WM regions of a weld, or to obtain the relative creep properties of materials produced as part of an alloy development program, etc. This paper describes and demonstrates a recently developed small Two-bar specimen creep testing technique[14]. This testing technique displays many advantages compared to other small specimen creep test types; however the main advantages of the TBS testing method is that full strain versus time creep curves can be obtained. Unlike the impression creep test, the loading nature of the TBS (pin connections) allows highly creep resistant materials to be tested using loading pins with similar creep resistance to the tested material. Unlike the impression creep test method where the indenter must be made from a material which is 2^+ orders of magnitude more creep resistant than the specimen material. This greatly limits the materials which can be tested using this specimen type. Loading the specimen through pin connections produces an easy, self-centeringbehaviour of the specimen.The usefulness of a particular small Two-bar specimen test method depends on the ease with which specimens can be manufactured, tested and the ease with which the measured deformations can be converted to corresponding uniaxial creep strains.It should be noted that the conversion relationships, e.g. equations (1, 2, and 5) do not contain any material properties, i.e., the conversion process (from small specimen data to the corresponding uniaxial data) is material independent.In general, the small changes in the TBS shape and dimensions as a test progresseshave relatively insignificant effect on the reference stress parametersβ and η (see Table 3). The results shown in Fig. 17, Fig. 20 and Fig. 20 indicate that the experimental Two-bar specimen test data can beconverted to the corresponding uniaxial minimum and creep rupture data with remarkably good accuracy. The repeatability of the TBS testing method will be assessed in future publications.More creep tests using the Two-bar specimen will be carried out also in the future using different specimen dimensions made of different types of material.

Notation

ε^c , $\dot{\varepsilon}^c$	creep strain, minimum creep strain rate, respectively
Δ^c , $\dot{\Delta}_{ss}^c$	creep deformation, and minimum deformation rate, respectively
$\dot{\Delta}_k$	deformation rate in the loading pin supporting material
$\dot{\Delta}_{total}$	total Two-bar specimen deformation rate
β, η	reference stress parameters (conversion factors)
$\sigma, \sigma_{ref}, \sigma_{nom}$	stress, reference stress and nominal stress, respectively
α	reference stress scaling factor
A, n	material constants in Norton's law
EGL	equivalent gauge length
EDM	electrical discharge machining
HAZ, WM, PM	heat-affected zone, weld metal and parent material, respectively
FE	finite element
MSR	minimum strain rate
TBS	Two-bar Specimen
P	applied load
PS, PE	plane stress and Plane strain
SPCT	small punch creep test
3D	three dimensional
D_i, b, d, k, L_o	Two-bar specimen dimensions

Figures captions:

Fig. 1 Conventional uniaxial creep test specimen
Fig. 2 Photographs of scoop sampling in process on pipe-work (a), and typical scoop sample (b).
Fig. 3 (a) Photograph of a scoop sample, and (b) Dimensions of a typical scoop sample
Fig. 4 Two bar specimen geometry and dimensions.
Fig. 5 Determination of β and η for the TBS
Fig. 6 Variations of β and η parameters with various L_o/D_iratios; the ratio $k/D_i$for the specimens was 2 for all cases.
Fig. 7 Variations of β and η parameters with various k/D_i ratios; the ratio b/D_i for the specimens was 0.25 for all cases.
Fig. 8 Variations of β and η parameters with various b/D_i ratios; the ratio k/D_i for the specimens was 2 for all cases.
Fig. 9 The effects of d/D_i ratio on β values for specimen with L_o/D_i = 4, k/D_i = 1.3, b/D_i = 0.4 and D_i=5 mm.
Fig. 10 The effects of d/D_i ratio on η values for specimen with L_o/D_i = 4, k/D_i = 1.3, b/D_i = 0.4 and D_i=5 mm.
Fig.11 Finite element mesh and the boundary conditions for the TBS model
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Fig. 14 Creep strain versus time curves obtained from uniaxial tests for grad P91 steel at 650^o
Fig. 15 Photograph of the TBS loading setup, illustrates the loading method and the difference in the stiffness between the specimen and the loading fixtures
Fig. 16 The TBS Deformation times curves for grad P91 steel at 650^{o}C
Fig. 17 Minimum creep strain rate data for grad P91 steel at 650^{o}C, uniaxial and TBS
Fig.18 Creep rupture data obtained from TBS and uniaxial specimens for grad P91 steel at 650^{o}C.
Fig. 19 (a) Polished untested specimen; (b) Tested specimen
Fig. 20 Converted TBS creep strain curves together with the corresponding uniaxial creep strain curves for grad P91 steel at 650^{o}C, using 70, 82, 87, 93 and 100MPa

Tables captions:

Table 1 The recommended TBS dimension ratio ranges for a constant $D_{i.}$
Table 2 Chemical compositions for grad P91 steel (wt%)
Table3 the dimensions of the tested TBSs, made of grad P91 steel at 650^{o}C, all dimensions are in (mm)

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