Associated conference: 5th International Small Sample Test Techniques Conference

Conference location: Swansea University, Bay Campus

Conference date: 10th - 12 July 2018

How to cite: Brett, S.J. 2018. The impression creep Monkman Grant relationship. *Ubiquity Proceedings*, 1(S1): 7 DOI: https://doi.org/10.5334/uproc.7

Published on: 10 September 2018

The impression creep Monkman Grant relationship

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Abstract

Impression creep testing is an established small-scale testing technique in which the indentation rate of a rectangular indenter can be converted into equivalent creep strain rate. It is a versatile technique in that, once a stable indentation rate is established, either the stress, temperature, or both, can be varied to provide data under multiple test conditions on the same specimen. It does not however produce a specimen failure. In order to overcome this limitation, use can be made of an empirical relationship between the creep strain rate obtained in the impression test and the rupture life obtained in a conventional uniaxial creep test at the same stress and temperature. This relationship, termed the Impression Monkman Grant relationship, has been applied successfully to grade 91 steel where it has been shown that rupture life predicted from impression testing is in good agreement with actual rupture life obtained by conventional uniaxial testing. The relationship has proved particularly useful for plant application in situations where mis-heat treated grade 91 pipework with lower than expected creep strength has been encountered, requiring an estimate of creep strength to justify continued operation in service.

Keywords: Small Scale Creep Testing; Impression Creep Testing; Grade 91 Steel; Monkman Grant Relationship; Mis-heat Treatment

1. Introduction

Impression creep testing was originally developed at Nottingham University in the UK primarily to obtain creep data from different microstructural regions within weldments to be used in finite element modelling. As a result, the technique is supported by a substantial body of theoretical work and full details about specimen preparation and the testing technique are available [1]. In recent years it has become a useful method of evaluating the creep strength of grade 91 materials in high temperature steam pipework and headers, particularly where routine inspection/on-site metallography has indicated the possible presence of materials with inadequate properties [2][3].

As illustrated in Fig.1, the impression creep test uses a nickel base superalloy rectangular indenter of width **d** to load the specimen of dimensions **w** x **w** x **h** at high temperature. The most commonly used specimen dimensions are **w** = 10mm, **h** = 2.5mm, for which **d** = 1mm, or **w** = 8mm, **h** = 2mm, for which **d** = 0.8mm. Where, as is often the case, the material to be tested needs to be obtained from a plant component using a small-scale on-site sampling technique such as scoop sampling, the smaller size is often preferred, requiring as it does, less material removal.

Once the impression creep indenter is fully embedded in the specimen, the test generally achieves constant, or near constant, rate of indentation with time within a test time of 350-400 hours. The measured indentation rate, typically over the last 100 hours of the test, can then be converted into an equivalent creep strain rate using conversion factors calculated from a finite element model developed by Nottingham University (dividing by 2.180 for 10x10x2.5mm specimens or by 1.744 for 8x8x2mm specimens [4]). A useful advantage of this test method is that, after the creep strain rate has been obtained in this way, either the stress, temperature, or both, can be altered to provide additional creep strain rates at alternative test conditions. This means that creep strain rate data which might be obtained from a conventional uniaxial multi-specimen iso-stress or iso-thermal creep test programme can be obtained from a single impression creep specimen.

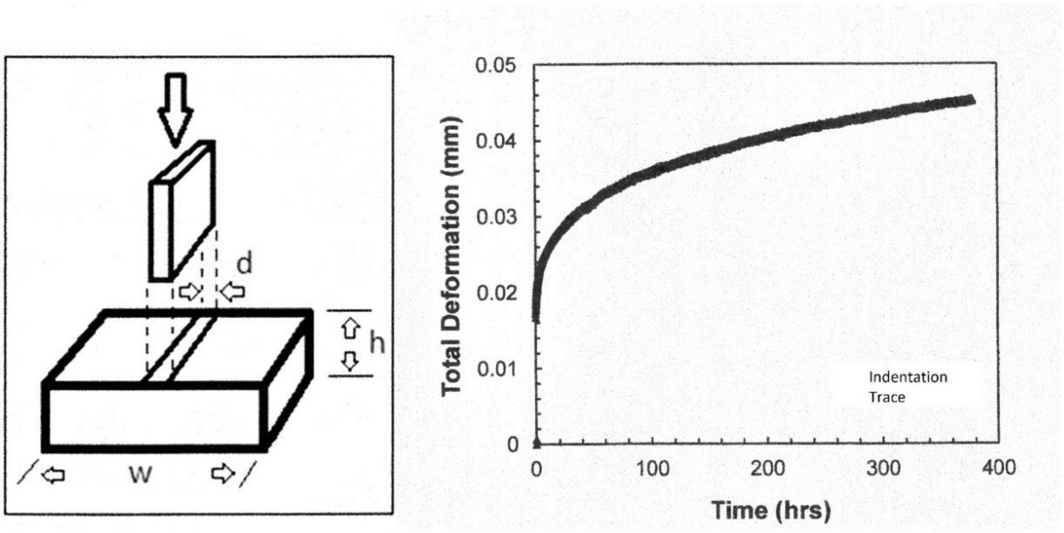

Figure 1. Geometric set-up of the impression creep test with a typical indentation trace.

2. Rupture Life Prediction using Impression Data and the Conventional Monkman Grant Relationship.

A potential disadvantage of the impression creep test is that it does not produce a specimen failure. However, the equivalent uniaxial rupture life corresponding to each impression creep strain rate measured can be estimated via an empirical relationship between creep strain rate and uniaxial rupture life, such as Monkman Grant. The requirements for this approach to be valid are: (a) that the uniaxial minimum creep strain rate and impression creep strain rate should be interchangeable and (b) that the material uniaxial minimum creep strain rate and the uniaxial rupture life must obey the particular Monkman Grant equation adopted.

A first attempt at this approach was made using the Monkman Grant relationship for P91 material derived by Parker [5]. Based on data produced by Spigarelli, Kimura and Ellis, this relationship was adopted because it was also found to provide a good fit to the present author's P91 uniaxial data:

$$\mathbf{MCR = 0.1\ t_f^{-1.16}} \tag{1}$$

where MCR is the minimum creep strain rate (per hour) and t_f is the rupture life (in hours) in conventional uniaxial creep testing.

A study looked at three different grade 91 materials with a wide range of creep strengths. For all three materials the rupture life predicted from impression creep data in combination with the Parker Monkman Grant relationship and the uniaxial rupture lives actually measured were found to be in good agreement [6].

3. Limitations to the use of the Conventional Monkman Grant Relationship

A limitation to the approach was however identified in that uniaxial minimum creep strain rates and impression creep strain rates were found to diverge at the highest stress levels. This is illustrated in Fig.2 below for one of the materials, Bar 257, a weak forging material which had been subjected to substantial investigation. It can be seen that the two measurements of strain rate are in good agreement, and arguably interchangeable, in the stress range 75-135MPa at 600°C. This is not necessarily so at higher stresses however, where the single impression strain rate obtained in this range falls significantly below the equivalent uniaxial minimum creep rates.

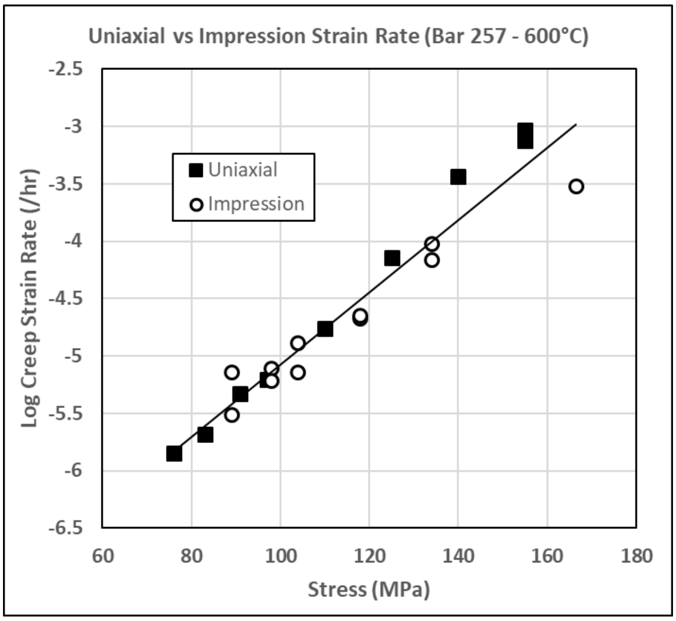

Figure 2. Uniaxial minimum creep strain rate and impression creep strain for Bar 257.

This region corresponds to the uniaxial tests with the highest elongations at fracture and is found to be a more generally observed effect when testing materials with high ductility. Two other examples of materials exhibiting high ductility at fracture are shown in Figs 3 and 4. Fig.3 shows uniaxial and impression data on ex-service 2Cr weld metal tested at a range of stresses at 570°C (a typical operating temperature for this material in the UK). The ex-service weld metal was found to be significantly weaker than weld metal of this type entering service. While impression creep strain rates and uniaxial minimum creep rates appear to be converging as stress approaches the relevant hoop stress typical of service (40MPa), they increasingly diverge as stress rises.

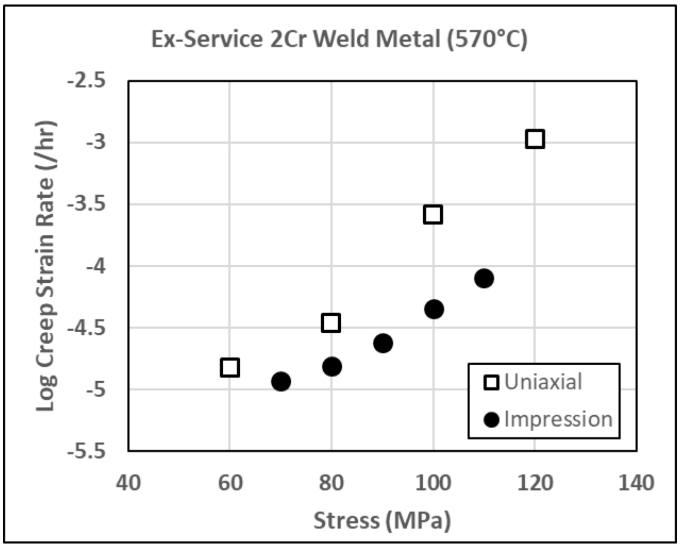

Figure 3. Uniaxial and impression strain rates for a ductile ex-service 2Cr weld metal.

Fig.4 shows uniaxial and impression data on a mis-heat treated grade 91 material in a 100% Ferrite metallurgical condition at a range of temperatures at 76MPa, a stress level typical of the hoop stress for grade 91 material in service in the UK. It can again be seen that, while impression creep strain rates and uniaxial minimum creep rates converge at the lowest strain rates, they increasingly diverge as the strain rates increase, in this case with increasing test temperature.

It should be explained that, while 100% Ferrite is clearly an aberrant material condition for grade 91, it is unfortunately of interest to plant operators because the widespread presence of such material in service has been established in the UK and elsewhere [2][3]. This type of microstructure can be created either where tempering of parent material or post weld heat treatment of a weld overshoots sufficiently into the austenitic range to remove

Martensite before falling back to the correct heat treatment temperature range. Under these conditions the Martensite is not reformed on cooling to ambient.

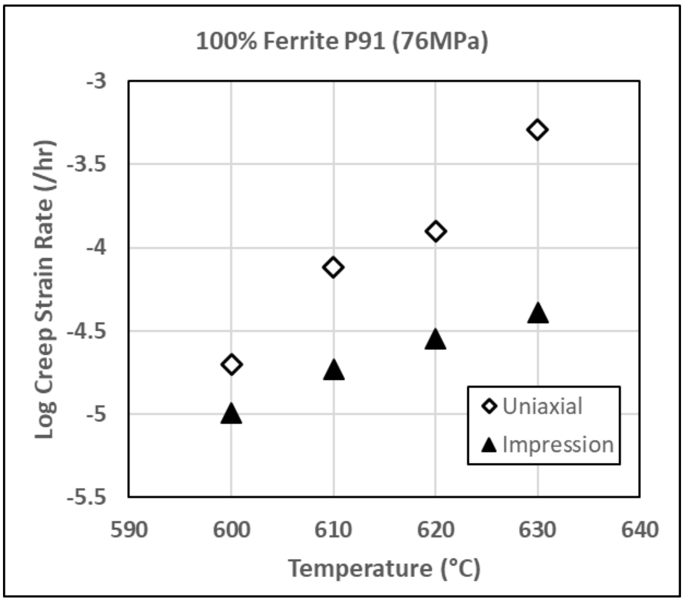

Figure 4. Uniaxial and impression strain rates for a mis-heat treated ductile 100% Ferrite grade 91material.

An explanation of the behavior shown in Fig.3 and Fig.4 lies in the fact that the conventional uniaxial creep test is a constant load test in which the axial stress increases during the test as the specimen elongates and the cross section reduces. The impression test in contrast is a constant stress test. The uniaxial minimum creep strain rate and the impression creep strain rate are therefore being measured at different effective stress levels. As illustrated schematically in Fig.5, where the uniaxial ductility is low or moderate (e.g. where the strain at the point of measurement is less than 1%), the reduction of cross section at the point of measurement may be small enough to be ignored. In high ductility materials the reduction of cross section at the point of measurement may be more substantial.

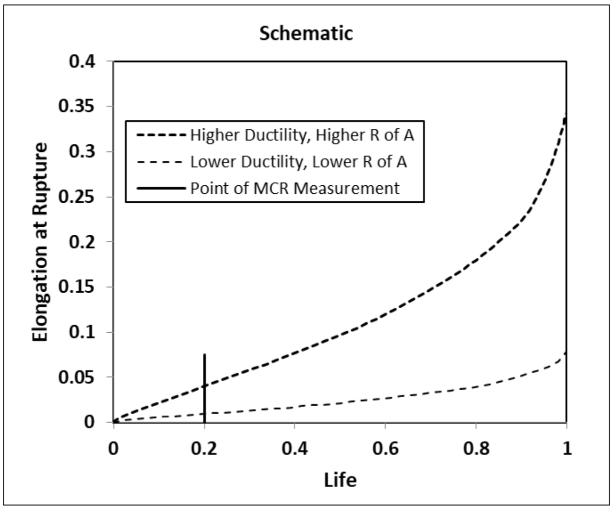

Figure 5. Measurement of minimum creep strain rate in uniaxial specimens of differing ductility.

The issue has particular relevance in the case of mis-heat treated grade 91 in a 100% Ferrite metallurgical condition. The high ductility of this type of material (generally >90% reduction of area at failure) means that the measured uniaxial minimum creep strain rates will always be significantly higher than the measured impression creep strain rates.

A further complication arising with 100% Ferrite grade 91 is that conventional uniaxial creep tests on material in this condition do not obey the conventional Monkman Grant relationship (equation 1 above). This is illustrated in Fig.6 below.

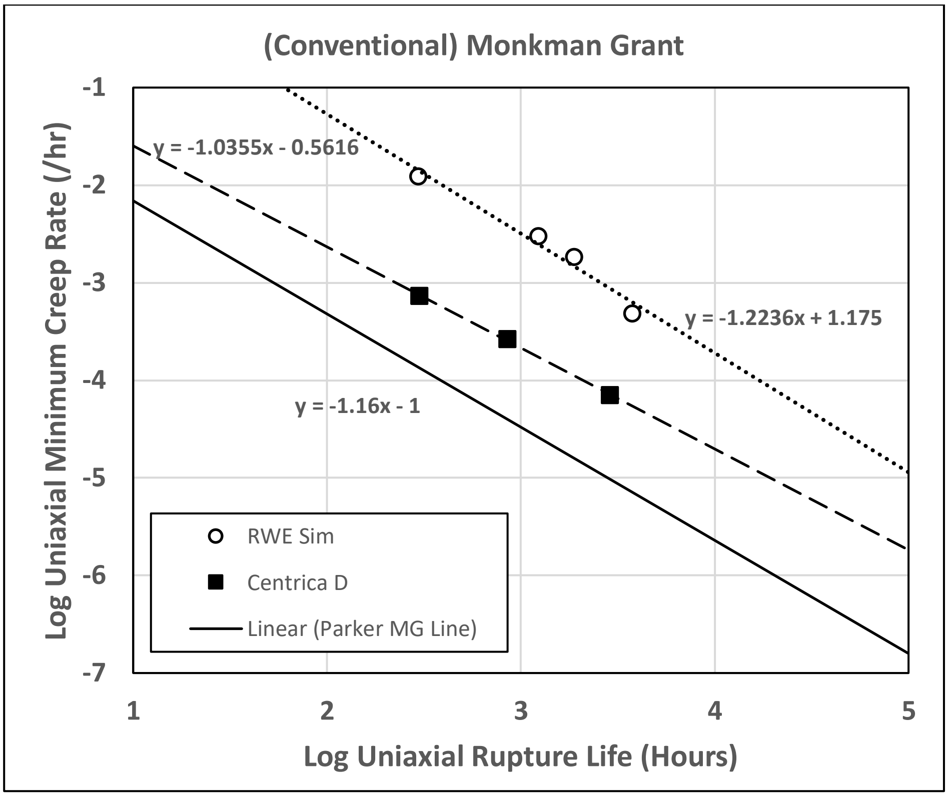

Figure 6. Conventional Monkman Grant data for two 100% Ferrite P91 materials compared to the Parker relationship for normal martensitic P91 (equation 1).

4. Rupture Life Prediction using Impression Data and the Impression Monkman Grant Relationship.

Given these anomalies, it was clear that the use of impression creep strain data in lieu of uniaxial minimum creep strain rate and a conventional Monkman Grant relationship would not be a viable approach for 100% Ferrite grade 91. The widespread presence of this form of mis-heat treated material on plant however necessitated that an equivalent approach be developed. This led to the concept of an Impression Monkman Grant relationship, in which the measured impression creep strain rate could be correlated directly with uniaxial rupture life obtained at the same test conditions. It was argued that, provided a consistent relationship of this type could be demonstrated, it would no longer be necessary either for impression and uniaxial strain rates to be interchangeable or for the material to obey the conventional Monkman Grant relationship.

4.1. Impression Monkman Grant Utilising Martensitic Grade 91 Data

To generate an Impression Monkman Grant relationship ideally requires “paired values” of impression creep strain rate and uniaxial rupture life at each of the test conditions. In the absence of such data, provisional use was made of the Bar 257 data shown in Fig.2.

As a first step, the uniaxial rupture lives of the Bar 257 uniaxial tests were compared to those predicted for grade 91 material with mean properties. Although in principle any suitable assessment for mean rupture life could have been used, for the purposes of this exercise the Cipolla 2005 assessment was adopted (using the full version of the equation, as shown in [3]). The stress of each of the Bar 257 uniaxial tests was compared to the stress which would have produced failure in the same time for material of mean properties. The average strength level was found to be Mean-21%. The Cipolla equation, with this correction factor on stress, was then used to estimate a rupture life at each of the available impression creep strain rates for Bar 257 to produce Fig.7 below. This represents the

Impression Monkman Grant relationship for Bar 257, linking the impression creep strain rate directly to the corresponding uniaxial rupture life.

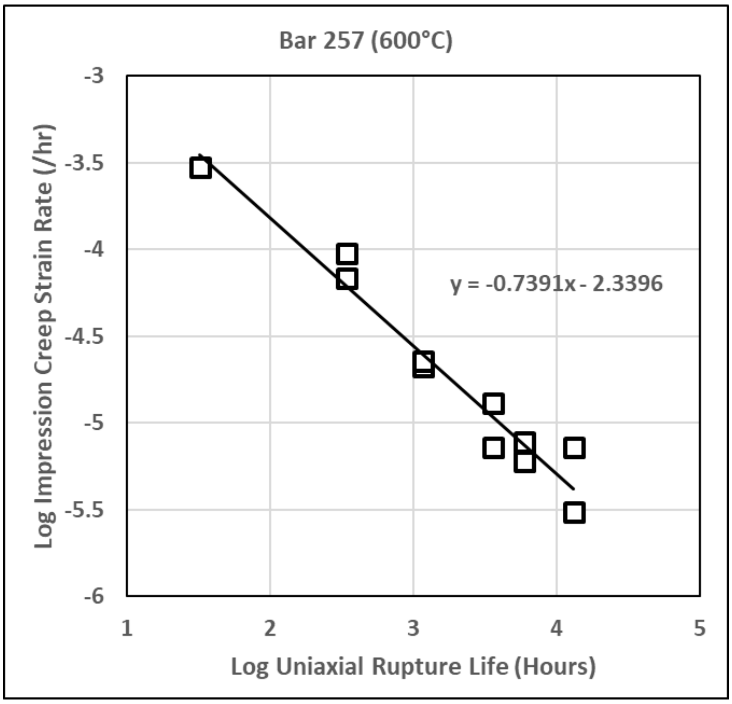

Figure 7. The Impression Monkman Grant relationship for Bar 257, comparing measured impression creep data to interpolated values of uniaxial rupture life at the same stress and temperature.

The equation derived for Bar 257 is:

$$\mathbf{ICR = 0.004575\ t_f^{\,-0.7391}} \quad (2)$$

where ICR is the impression creep strain rate (per hour) and t_f is the rupture life (in hours) in conventional uniaxial creep testing at the same stress and temperature.

This equation has been applied successfully to grade 91 materials sampled from plant and impression creep tested [2][3]. Additional data obtained for aberrant 100% Ferrite grade 91 materials has however allowed an alternative relationship to be produced using “paired” values, i.e. impression creep strain rates and uniaxial rupture lives for the same materials at the same test conditions. This is shown in the next section.

4.2. Impression Monkman Grant Utilising 100% Ferrite Grade 91 “Paired” Data

The currently available data for for 100% Ferrite materials using paired values are shown in Fig.8. The equation derived is:

$$\mathbf{ICR = 0.0057597\ t_f^{\,-0.7265}} \quad (3)$$

where ICR is the impression creep strain rate (per hour) and tf is the rupture life (in hours) in conventional uniaxial creep testing at the same stress and temperature.

This is very similar to equation 2, which is represented by the broken line in Fig.8. In fact, the lines are so close that it is possible that the underlying relationship is the same for both martensitic and 100% Ferrite materials, although further data will be required to demonstrate this. A key point to note is that the wide spread of data seen in Fig.6 for conventional Monkman Grant is not shown in Fig.8 for Impression Monkman Grant. The Impression Monkman Grant relationship appears to be far less sensitive to microstructural condition.

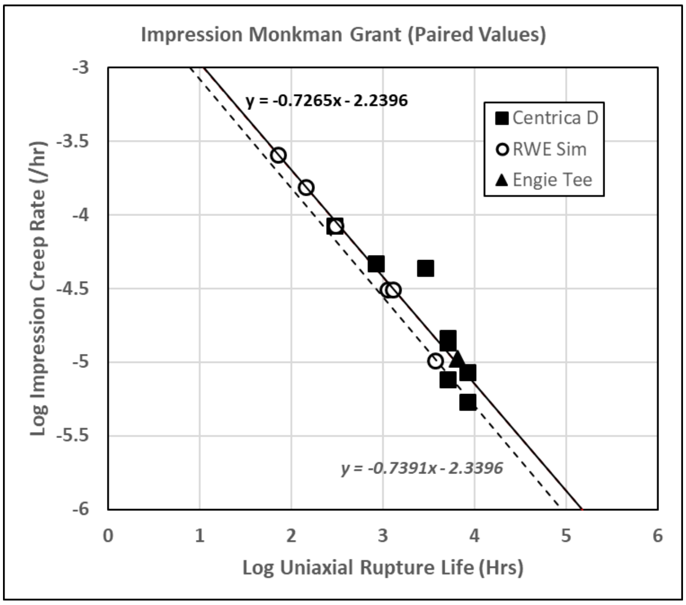

Figure 8. The Impression Monkman Grant relationship for 100% Ferrite grade 91 materials, using paired values of measured impression creep strain rate and measured uniaxial rupture life obtained at the same the same test conditions.

Equation 3 can be used as an alternative to Equation 2 to convert available impression data into predicted uniaxial rupture life to be compared to measured rupture life. This is shown in Fig.9 for two examples of aberrant 100% Ferrite grade 91 material and two examples of martensitic grade 91 material: Bar 257 and an as-received pipe material identified as 2328. The lines drawn for each material are the average strength levels relative to the mean derived from the uniaxial data. It can be seen that the uniaxial data points and those estimated from the impression data are scattered more or less uniformly around the lines and in good agreement.

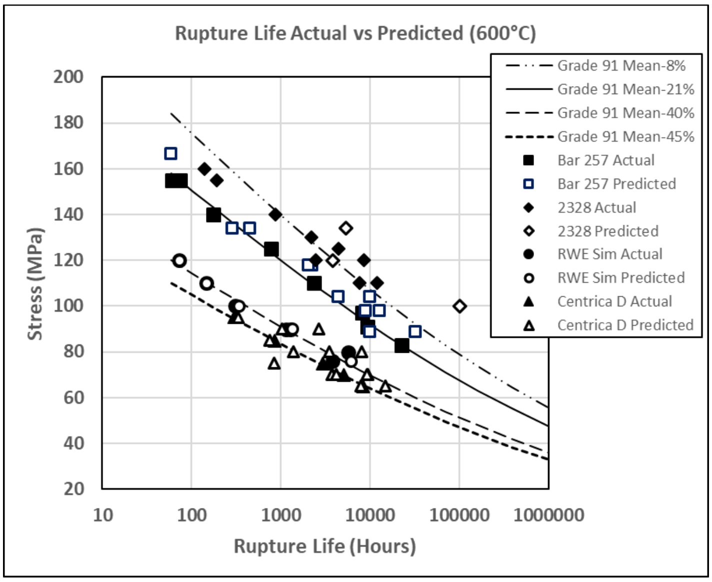

Figure 9. Uniaxial rupture life predicted from impression creep data and the Impression Monkman Grant relationship (equation 3) compared to measured values of uniaxial rupture life for two 100% Ferrite grade 91 materials, the martensitic material Bar 257, and a martensitic pipe material 2328.

An alternative comparison is shown in Fig.10, where the average strength values and standard deviations of the two sets of data are compared for each of the materials.

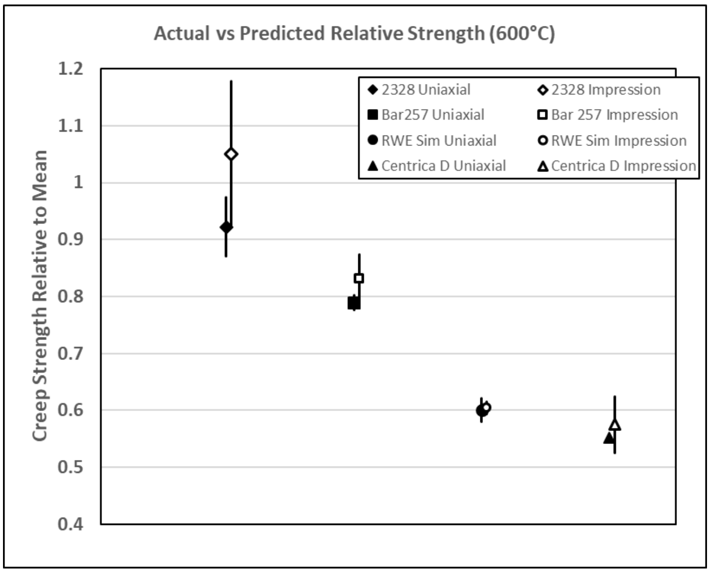

Figure 10. Creep strength relative to the (Cipolla 2005) Mean predicted from impression creep data and the Impression Monkman Grant relationship (equation 3) compared to measured values of uniaxial rupture life for two 100% Ferrite grade 91 materials, the martensitic material Bar 257, and a martensitic pipe material 2328.

Using the equation for mean grade 91 rupture life, either Equation 2 or Equation 3 can be used to predict corresponding lines of impression creep strain rate at different strength levels with reasonable accuracy. This is illustrated in Fig.11, which shows all the impression data currently available for 100% Ferrite grade 91 compared to predicted rates. The strength of this microstructural condition falls broadly within the range Mean-35% to Mean-50%, regardless of which Impression Monkman Grant equation is used.

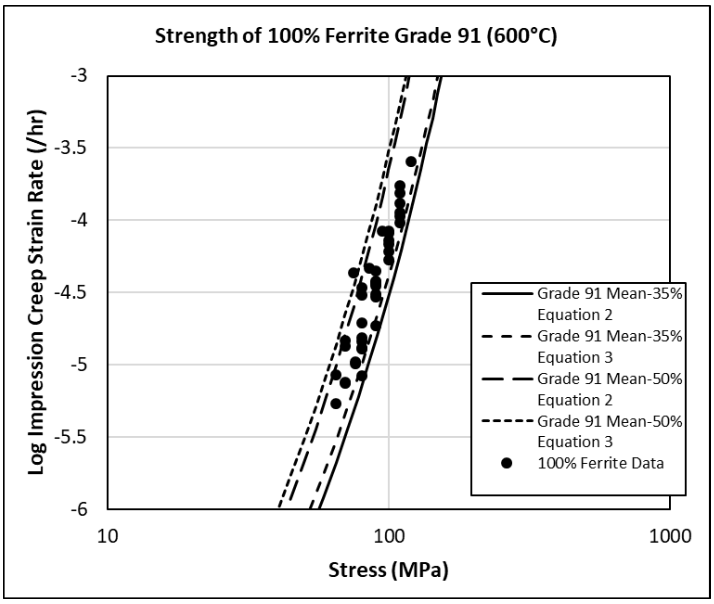

Figure 11. Impression creep data for 100% Ferrite grade 91 compared to impression creep strain rate predicted using Equations 2 and 3.

5. Discussion

The use of an Impression Monkman Grant relationship is a practical means of converting impression creep strain data into estimated uniaxial rupture life.

Under test conditions at which impression creep strain rate and uniaxial minimum creep strain rate can be regarded as interchangeable, the Impression Monkman Grant relationship and the conventional uniaxial Monkman Grant relationship will predict the same uniaxial rupture life from the same measured creep strain rate. This has been found to be the case for example both for ex-service CrMoV and grade 91 in the normal martensitic condition in the lower stress and/or lower temperature test range. It is not however the case for these two materials in the higher stress and/or higher temperature test range, where impression strain rate is found to be lower than the minimum uniaxial minimum creep strain rate. These test conditions correspond to the shortest life uniaxial tests and to uniaxial specimens failing with high ductility.

This divergence between the strain rates is a greater problem for materials which fail generally with high ductility over the normal test range. This has been found to be the case for example both for ex-service 2Cr weld metal and grade 91 in the aberrant 100% Ferrite condition. The latter material is particularly important for plant operators because of the widespread presence of such material currently in service.

Focusing on grade 91, for the weaker end of the normal martensitic range, and the weak aberrant condition, both Equation 2 and Equation 3 will give reasonably accurate estimates of rupture life for both types of material using measured impression creep strain rates at 600°C. Where the material under investigation is martensitic, the previously published Equation 2, based on a weak martensitic material, may be more appropriate. This equation will give slightly conservative estimates of uniaxial rupture life for the 100% Ferrite condition. Where the material under investigation is 100% Ferrite, Equation 3, based on this type of microstructure, may provide a more accurate estimate of uniaxial rupture life.

Acknowledgments: The impression creep testing referred to in this paper was commissioned by the UK generating companies Centrica, SSE, Engie and RWE Generation, and the release of unpublished data is gratefully acknowledged. Impression testing was carried out either at Nottingham University or at Wood plc, Warrington.

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