Standard text for cover page and foreword of a CWA

Impression Creep Testing
Draft for Comment (2022-04-19)

Foreword

This CEN Workshop Agreement has been developed in accordance with the CEN-CENELEC Guide 29 “CEN/CENELEC Workshop Agreements – A rapid prototyping to standardization” and with the relevant provisions of CEN/CENELEC Internal Regulations - Part 2. It was approved by a Workshop of representatives of interested parties on YYYY-MM-DD, the constitution of which was supported by CEN following the public call for participation made on YYYY-MM-DD. However, this CEN Workshop Agreement does not necessarily include all relevant stakeholders.

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The following organizations and individuals developed and approved this CEN Workshop Agreement:

- Wei Sun: Faculty of Engineering, University of Nottingham, Nottingham NG7 2RD UK
- Juhani Rantala: VTT Technical Research Centre of Finland, FI-02044, Espoo, Finland
- Dan Purdy, Alex Bridges: Electric Power Research Institute, Charlotte, NC, 28262. USA
- Andrew Wisbey, Jack Eaton-Mckay, Colin Austin, James Holden: Jacobs, Warrington, WA3 6GA UK

- Alison Clark: RWE Generation UK, Swindon, SN5 6PB UK
- Bernd Kuhn: Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany
- Daniel Omacht: UTMdev s.r.o. 703 00 Ostrava-Vitkovice, Czech Republic
- Rannou Benoit: Naval Group Research, F-44340 Bouguenais, France
- Antonello Alvino: INAIL, 00133 Rome, Italy
- Steve Brett: Steve Brett Consultancy Limited, Calne, SN11 0QH, UK

Contributions from Matthias Bruchhausen, Stefan Holmstrom and Tim Austin, JRC Petten, prior to the launch of the Workshp are also gratefully acknowledged.

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Contents

Introduction

Small sample testing in general, and impression creep in particular, offers the opportunity for owner/operators of power generation equipment to perform non-invasive testing of their high value equipment to determine risk or risk-ranking as they look to prioritize maintenance activities. Small sample concepts such as impression creep afford the opportunity to quantify high temperature creep behaviour relevant to high energy piping; high temperature valves; high pressure steam turbines; gas compressor, combustor, and turbine; and other critical components. However, in order to use this data in a consistent manner and have confidence in the determination of risk – either through comparative ranking or through component-specific life prediction, this test method needs to be internationally recognized and demonstrated to be consistent.

Assessment of in-service plant to determine remnant life is of obvious significant industrial interest, particularly to high temperature plant operators, where plant life extension or confirmation of existing plant life is needed. As more power plants operate beyond their design life, the requirement for these services increases.

In addition to application to plant, the technique has potential use in materials research in general. Specific examples include alloy development, where it provides a rapid method of performance ranking on small amounts of material, and investigation of strength variation within large section components.

There are significant commercial benefits in using impression creep testing over conventional uniaxial creep testing. These include:

- The ability to produce creep strain data relatively quickly.
- The small specimen size makes extraction from components feasible without significantly affecting the structural integrity of plant.
- The possibility to test a single specimen at several stresses or temperatures enables multiple assessments.
- Increasingly, the maturity of underlying technical understanding and quality of results increases confidence in the technique.

1 Scope

In order that operators of power plant can use impression creep testing as an integral part of the remanent life strategy they adopt for their high temperature components, impression creep needs to become a more generally accepted test method. There is an associated need for standardisation of both the test technique itself and the use that is made of the data generated. This should lead to acceptance of the approach by power plant operators and third parties such as plant insurers, boiler inspectors, etc.

The impression creep test method, using a rectangular indenter, has been used extensively in the last 10 years, for a number of UK and EU projects and for industrial applications (e.g. TWI, British Energy, RWE Generation UK, Structural Integrity Associates). Some industrial organizations have already built or are in the process of developing the test facilities for impression creep testing. EPRI has included impression creep testing into a collaborative (~ 25 partners) research programme in order to assess the practicality of the technique.

This document builds on, and updates, earlier recommendations/guidelines produced for impression creep testing [1][2][3].

2 Normative references

The following normative references are relevant to this document.

BS EN ISO 204: 2018 Metallic materials - Uniaxial creep testing in tension - Method of test

ASTM E139 – 11 (Reapproved 2018): Standard Test Methods for Conducting Creep, Creep-Rupture, and Stress-Rupture Tests of Metallic Materials

BS EN ISO 9513: 2012 Metallic materials - Calibration of extensometer systems used in uniaxial testing

BS EN ISO 7500 - 1: 2018 Metallic materials - Calibration and verification of static uniaxial testing machines

3 Terms and definitions

3.1

Impression Creep Test

The Impression creep test is a small-scale testing technique in which the indentation rate of a rectangular indenter into a parallel sided rectangular specimen can be converted into equivalent creep strain rate.

3.2

Impression Monkman Grant Relationship

The Impression Monkman Grant relationship is 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.

4 Impression Creep Testing Using a Rectangular Indenter

As shown in Figure 1, the impression creep testing technique involves the application of a steady load **F** to a flat-ended, rectangular indenter of width **d** placed on the surface of a rectangular specimen of surface area **b** x **w** and height **h** at elevated temperature. The displacement-time record from such a test is related to the creep properties of a relatively small volume of material in the immediate vicinity of the indenter **[4]**. Tests are most easily described in terms of specimen/indenter dimensions, eg 10x10x2.5mm specimen + 1.0mm indenter.

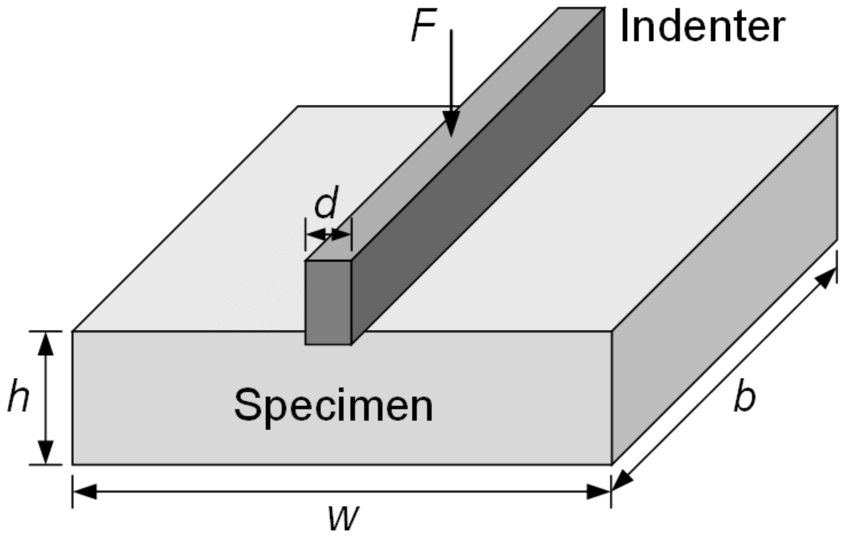

Fig. 1 Impression creep test with a rectangular indenter.

4.1 Conversion Relationships

For the rectangular type of indenter, it has been shown [**4**] that the reference stress approach can be used to convert the mean pressure under the indenter, $\bar{p}$, to the corresponding uniaxial stress, σ, i.e.

$$\sigma = \eta\bar{p} \tag{1}$$

and to convert the creep displacement, Δ^c, to the corresponding uniaxial creep strain, ε^c, i.e.

$$\varepsilon^c = \frac{\Delta^c}{\beta d} \tag{2}$$

where η and β are conversion parameters (reference parameters) and d is the width of the rectangular indenter, Fig. **1**(a). Therefore, the secondary creep properties can be obtained from impression creep test data using such conversion relationships. The technique can produce accurate results when the impression creep deformation occurring during the tests is small, compared with the indenter width or the specimen thickness. These conversion factors are material independent. They depend on dimension ratios of indenter and specimens and have been determined previously for a practical range of dimensions [**4,5**].

4.2 Typical Test Result

A typical indentation trace is shown in Figure 2. Once the indenter is fully embedded, the deformation rate (depth of indentation with time) becomes near linear. The measured indentation rate can then be converted into the equivalent creep strain rate.

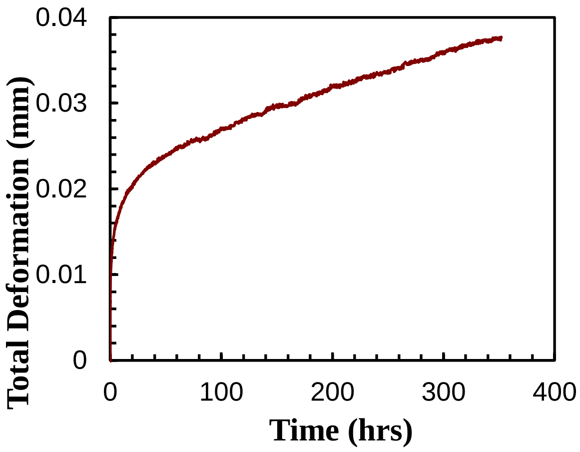

Fig. 2 Typical indentation trace

5 Apparatus

5.1 Requirements of Test Rigs

Both standard servo-electric machines or specially designed dead load rigs can be used for impression creep testing. The fundamental elements of the test machines should include the loading system, deformation measurement system, heating and temperature control system, inert gas environment (if necessary) and the data recording system etc.

In most practical cases, the load required for impression creep tests are within a range of 1 to 5kN, for the recommended specimen and indenter dimensions described in Section 5. Therefore, to ensure accurate load application, it is recommended that the full load capacity of the test rigs should not exceed

100kN. A 10kN load capacity would generally be satisfactory for a purpose-built impression creep test rig.

A typical test rig, in which the loading fixtures and extensometers etc, are similar to those used for a uniaxial creep test, can be seen in Figure 3. Because of the relatively simple testing geometry the impression creep test can be carried out on a variety of test rigs. The earliest tests were carried out on relatively complex rigs with a capacity well in excess of that required. Subsequently simpler rigs were adopted by several testing laboratories. These were fitted with a 10kN compression load cell able to operate at continuous stationary loads of up to 10kN. The machines have LVDTs with a range of ±1mm, and appropriate logging software. More recently Jacobs have demonstrated the use of a modified deadweight rig. To an extent, regardless of the basic rig design, the loading fixtures, extensometers, and furnace are interchangeable.

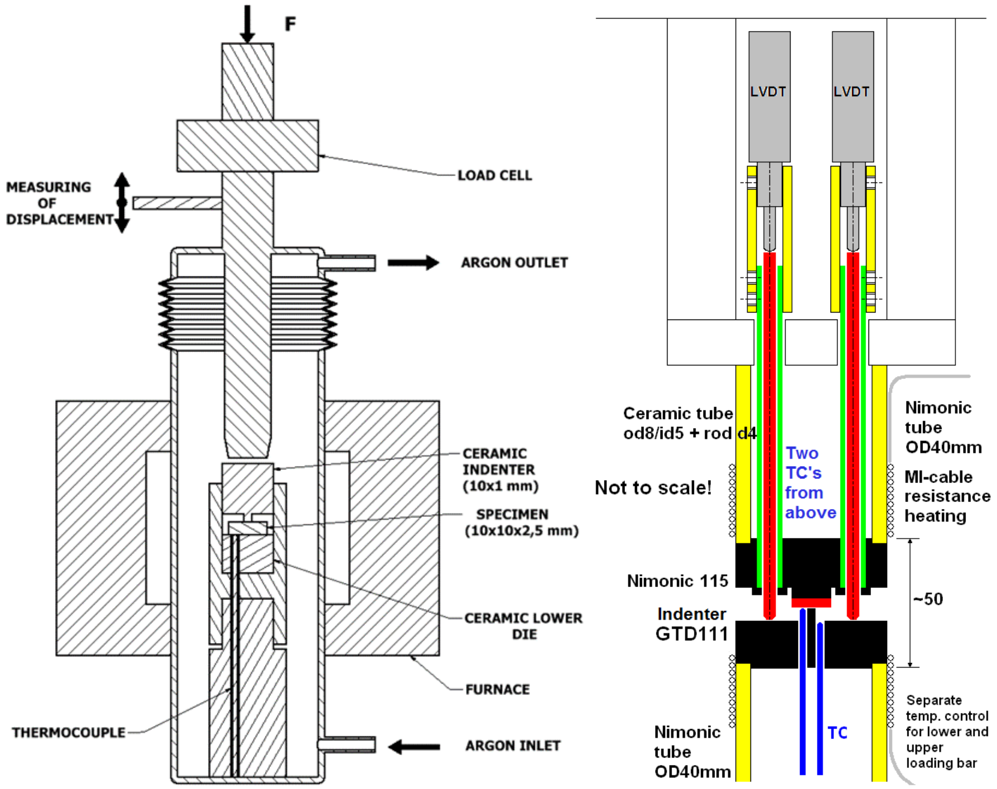

Fig. 3 Examples of different impression test rigs, one employing a ceramic indenter, and an inert atmosphere, the other using a nickel-based indenter and a normal atmosphere.

6 Test Pieces

6.1 Indenter and Specimen

The indenter and specimen geometries are fully defined by three ratios, i.e. w/d, w/b and h/d, where d is the width of the indenter and w, b and h are the width, breadth and height of the rectangular specimen (see Fig 1 in Section 4).

6.2 Indenter Requirements

The material of the indenter must be significantly stronger in creep than the test material. Nickel-based superalloys have been used for the indenters. The minimum creep strain rates for these materials, at the same stress and temperature levels, are orders of magnitude lower than those of typical power plant steels tested, e.g. low alloy steel or grade 91, in the applicable stress and temperature ranges. The widths of the indenters which have been used are 1.0mm or 0.8mm. The length of the indenter should be slightly longer than the length of the specimen, as illustrated in Fig.1. The indenter must be carefully machined and should be checked after each test. Grinding of the contact surface of the indenter may be needed after a number of tests. Care should be taken to ensure that the specimen surface is parallel to the flat surface of the indenter.

One of the laboratories has successfully demonstrated the use of a ceramic indenter, which opens up the possibility of testing stronger materials [6].

6.3 Recommended Specimen and Indenter Dimensions

The majority of early tests were carried out on specimen with dimensions of w x b x h = 10 x 10 x 2.5mm with indenter dimension d = 1mm. More recently specimens with w x b x h = 8 x 8 x 2mm with d = 0.8mm have been adopted. Such specimen sizes and dimension ratios ensure that full contact is maintained between the specimen and the supporting bar, and they prevent significant bending deformation from occurring. In addition, specimens of this size can be produced, in most cases, from scoop samples, and from the HAZs from, for example, main steam pipe welds in power plants. In some cases, where insufficient material was available, these standard specimen dimensions have had to be reduced. In these cases, modified conversion factors should be applied [7].

In terms of surface preparation, the requirements for the indenter are the same as those for the specimen, as shown in Section 6.4 below.

6.4 Specimen Preparation

The important requirements in specimen preparation are the quality of the two contact surfaces and the accuracy of the thickness. A small excess for each contact surface should be left during the initial machining, and the two surfaces should then be carefully ground to the final thickness to remove any machining marks and to eliminate the residual stresses and surface damage which might have been caused by the initial machining.

Any final polishing of the specimen is typically carried out using FEPA P120 (ANSI #120 grit) followed by FEPA P500 (ANSI #320 grit) sandpaper. It is considered that the surface finish of the specimen is less critical than that the top and bottom surfaces of the specimen are parallel. During polishing, therefore, the specimen thickness should be checked at multiple points on the surface to ensure that the surfaces are parallel within +/- 0.01mm. The specimen should have an arithmetic mean roughness Ra value of maximum 0.30µm or 12 micro-inch.

7 Testing, Measurement and Control

7.1 Indenter and Specimen Alignment and Load Application

Accurate alignment between the indenter, lower loading bar and the specimen must be achieved before starting a test. The indenter should be located in the middle of the specimen and the accuracy of the location should be checked after the test. The method of load application should be such that the load can be controlled to +/-1% agreeing with recommendations for creep testing by ECCC. The load system should be accurately and regularly calibrated. A key factor is that the indenting surface of the indenter and the specimen surface to be indented, are parallel.

To demonstrate reproducibility of the test, a rig hysteresis check is recommended (see 6.4.1).

7.2 Displacement Measurement

Extensometry and strain gauging which measure the deformation of the indentation in a continuous way may be used if they are suitably calibrated and applied in accordance with good testing practice and the manufacturer's instructions. The displacement of the indentation deformation should be continuously recorded and monitored.

The recorded maximum total indentation deformation (occurring at the end of the test) can be checked by measuring the depth of indentation after the test. The opportunity can also be used to identify any wear on the indenter. The use of a laser microscope can improve the accuracy of this process.

Using an example from one of the laboratories, the deformation measurement system adopts a loading arrangement similar to that used for a uniaxial creep test. The specimen fits between the indenter and an anvil that replicate a uniaxial specimen. The extensometer is located on the reproduced knife ridges. Two water cooled LVDTs measure the movement of the extensometer and hence indentation depth, outside the furnace. The signal from the LVDTs is averaged by the signal conditioning system on the Mayes machine and recorded on a data logger. The measuring range of the extensometers is +/-0.2mm with an accuracy of +/-0.5%.

7.3 Temperature Control and Test Environment

The impression creep tests can be performed in air if the test temperatures are within the normal range of operating temperature for the material.

Using Nottingham University as an example, three 0.5mm dia. K type thermocouples are used to control the temperature. The middle one is close to the specimen and the upper and lower thermocouples are about 25mm away from the specimen, near to the extensometer ridges. These positions may not always be held at the specified temperature due to the heat balance in the furnace. However, experience of many tests, with the temperatures checked by calibrated thermocouples and visual output, has produced a high degree of confidence in using such methods. Platinum resistance probes could be used in order to obtain a higher level of accuracy of temperature control or measurement.

A more direct procedure is to spot weld a thermocouple to the specimen itself. In this case it should be attached on a side of the specimen away from the indented surface to ensure that it does not interfere with the indentation process. Additionally, the spot weld itself should not extend beyond the specimen thickness and the thermocouple wire should be arranged so as to avoid putting any stray loading on the specimen.

7.3.1 Types of Thermocouple

Thermocouples should meet the requirements of BS EN ISO 204 (see Section 2).

7.4 Test Procedure

The test procedure can be carried out as either a single step test at one stress and one temperature, or as a stepped stress test in which the stress is changed during the test at a single temperature. Stepped temperature tests, in which the temperature is changed during the test at a single stress can also be carried out, but this variation is not discussed here.

7.4.1 Hysteresis Check

The purpose of the hysteresis check is to ensure the proper operation of the displacement measurement system. The hysteresis check immediately before heating up will also help achieve a good contact between the specimen and the indenter by smoothing out surface roughness and reducing microscopic misalignment.

After positioning and aligning, the specimen is pre-loaded with a small, controlled force (typically 10-100 N). The whole testing set-up is then subjected to several (3-5) loading cycles at room temperature up to the intended testing load or below the elastic limit of the tested material, whichever is lower, until the hysteresis between the cyclic loading and unloading curves becomes minimized. The loading can be done either at a constant loading rate (typically 2 MPa/s) or in a stepwise manner having 5-10 load steps between the minimum and maximum load. The displacement response is recorded and plotted as hysteresis loops of displacement versus load. In case of constant rate load ramp the operator has to make sure that the data logging system is fast enough to record the load and displacement in real time, otherwise the loading rate has to be lowered. In case of stepwise loading the operator has to make sure that all the signals have fully stabilised before taking the readings.

After the hysteresis check the test set-up is heated at a small pre-load (max 25% of the test load) to the test temperature without removing the specimen. Care must be taken that the compressive load is on all the time during heating up in order to maintain the contact between the indenter and the specimen.

After gaining confidence in the displacement measurement system the hysteresis check can be regarded as voluntary, but periodical checks are recommended in order to spot any malfunctioning of the extensometer system. The hysteresis check procedure is mandatory if such changes are made to the rig which could influence the displacement measurement.

7.4.2 Single Step Test

The test should aim to have a duration of 400+/-50hrs at the required stress, with the impression indentation rate measured by linear regression over the last 100hrs.

A +/-50hr margin has been chosen to enable test laboratories to continue testing over a weekend, if necessary. The indentation rate should be measured by linear regression over the last 100hrs of the test.

7.4.3 Stepped Stress Test

The test will start with the lowest stress and increase stress.

An initial step of 400+/-50hrs will be carried out at the minimum stress, with the impression indentation rate measured by linear regression over the last 100hrs.

Subsequent steps will be carried out at gradually increasing stress levels, each step lasting 150+/-50hrs, with the indentation rate again measured over the last 100hrs of each step. The contact between the indenter and the specimen must be maintained at all times.

7.4.4 Specimen/Indenter Dimensions

The impression specimen/indenter dimensions will be 10mm x 10mm x 2.5mm with a 1.0mm wide indenter or 8mm x 8mm x 2mm with a 0.8mm wide indenter. All the test laboratories are believed to be able to test the larger configuration and some can test the smaller. See Sections 6.3 and 6.4.

7.4.5 Limitation to Indentation

Historically indentation has been limited to 10% of specimen thickness (ie dimension **h** in Fig 1, Section 4). Analysis to support this has been published [8].

7.4.6 Post-Test Procedure

Once the test is completed the load should be reduced to a level of preload before turning the furnace off. This preserves the indentation surface, avoiding further oxidation. The load can be removed completely once the furnace has reached room temperature.

7.4.7 Test Validity

The test can be considered valid once the trace has become acceptably linear. The linearity of the indentation trace can be assessed against the following validity criteria:

7.4.7.1 Basic Validity

The trace can be regarded as sufficiently linear if the difference between the rate measured over the last 100 hours and the rate measured over the last 75 hours is less than 10%.

7.4.7.2 Complex Validity

Percent variation should be calculated using ±10-hour time increments from the already calculated strain-rate vs. time curve, using the following equation:

$$\%\ Variation = (V_1 - V_2)/((V_1 + V_2)/2)\ x\ 100$$

....where V_1, V_2 are the rates at the start and end of the time interval.

Again, the variation should be less than 10%.

7.4.8 Interrupted Tests

Because the impression creep test does not destroy the specimen, it is possible in principle to return to a specimen and continue testing at a later date, In this case, care is required in realigning the indenter to the groove created by the first period of testing, but several laboratories have accomplished this successfully.

Where a test is interrupted unintentionally, perhaps for example by a power cut, the specimen should remain under load until the power is returned and the test conditions are restored. If necessary, the test or the relevant step in a stepped stress test should be extended to meet the requirement of measuring the indentation rate over 100hrs (see 7.4.2 and 7.4.3).

8 Reporting Requirements

The report of an impression creep test should include the following details:

Material

Specimen identity

Specimen dimensions

Specimen/indenter orientation (see Annex A4)

Indenter dimension

Indenter material

Test temperature

Load(s)

Converted stress(es)

Total test duration

Individual step duration

Range of time over which the rate is measured

Validity

Confirmation of room temperature stability

Named individual carrying out the test (optional)

9 References

1. T H HYDE, W SUN & S J BRETT Some Recommendations on the Standardization of Impression Creep Testing. 2nd International ECCC Conference: Creep & Fracture in High Temperature Components – Design & Life Assessment, EMPA, Switzerland, April 21 – 23, 2009.
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4. Hyde, T.H., Sun, W. and Becker, A.A. (1996) Analysis of the impression creep test method using a rectangular indenter for determining the creep properties in welds, Int. J. Mech. Sci., 38, 1089-1102.
5. Hyde, T.H. and Sun, W. Evaluation of the conversion relationship for impression creep testing (submitted to Int. J. of Pres. Ves. & Piping).
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7. Sun, W., Hyde, T.H. and Brett, S.J. (2008) Application of impression creep data in life assessment of power plant materials at high temperatures. Proc. Instn Mech. Engrs. Part L, J. of Materials: Design and Applications 222, 175-182.
8. S. Li, D. Purdy, S.J. Brett, D. Deng, A. Shibli, W. Sun: Effect of Indentation Depth in Impression Creep Test: Conversion Relationships and Correction Functions. Submitted to Special Issue of Materials at High Temperatures 2021.

Annex A
(informative)

A.1 Relationship to uniaxial creep test properties

A.1.1 The Impression Monkman Grant Relationship

While the impression creep test does not produce a specimen failure, 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. It must be recognised however that, because the impression creep test is a constant stress test and the uniaxial rupture test is a constant load test, the strain rates in the two types of creep test are not interchangeable. Necking down of the specimen during the uniaxial creep test results in an increase in stress during the test which is absent in the impression test. As a consequence, the resulting strain rate in the uniaxial case will rise, with this effect increasing with the ductility of the material.

To compensate for this effect, use can be made of an empirical relationship between the creep strain rate measured in the impression creep test and the rupture life in a uniaxial test carried out at the same nominal conditions. This relationship, termed the "Impression Monkman Grant" relationship has been found to be reproducible and can, in principle, be established for any given material.

Where possible, impression creep testing should be carried out at the same temperature and stress conditions used for the uniaxial testing, to produce "paired values" of impression creep strain rate and uniaxial rupture life. Where this is not possible, an Impression Monkman Grant relationship can nevertheless be produced by using interpolated values of rupture life at the impression test conditions, where sufficient uniaxial data are available in the range of interest.

While the precise relationship may vary with material, an example is shown in Figure A1. In this case the material of interest was aberrant (mis heat-treated) grade 91 and paired values obtained from five different materials from a variety of sources **[A1]**.

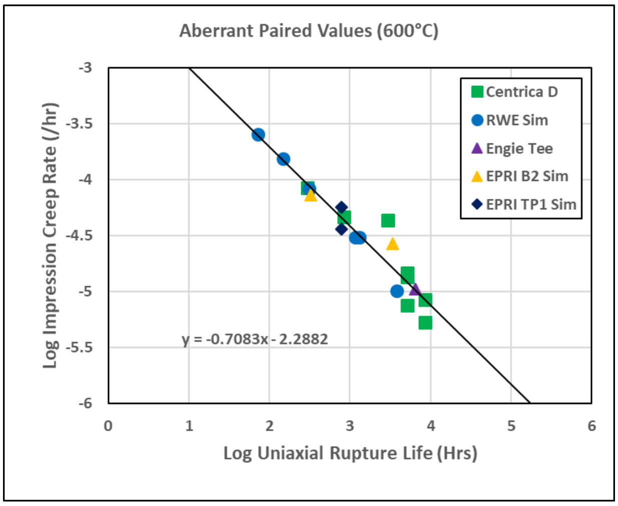


Figure A1: Impression Monkman Grant relationship for aberrant grade 91, using paired values of impression creep rate and uniaxial rupture life at the same test conditions for five aberrant (100% ferrite) grade 91 materials.

The equation derived is:

$$\mathbf{ICR = 0.0051499\ t_f^{-0.7083}}$$

…. 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.

It should be noted that the relationship derived allows either impression creep strain rate data to be converted into equivalent rupture life or rupture data to be converted into impression creep strain rate data. In this case this enabled the strength relative to mean grade 91 material to be determined by either method.

Reference

A1. S J BRETT, A BRIDGES & D PURDY. The creep strength of aberrant grade 91 steel. Materials at High Temperatures. Published online: 10 May 2021. DOI: 10.1080/09603409.2021.1912581

A.2 Guidance on specimen sampling from components

The information provided here is drawn from scoop sampling carried out in the UK on low alloy steam pipework, but is considered to be generally applicable to on-site sampling.

A2.1 The impression creep specimens from main steam and hot reheat steam pipe were taken from on-site scoop samples obtained with an on-site sampler. A number of portable sampling devices are currently available, including mechanical cutting electro-discharge cutting and tube drilling options.

A2.3 The scoop samples were obtained in the form of shallow discs, typically 24-28mm across at their widest circumference and up to 3.5-4.5mm thick (in the through-wall direction), with a mass of 6-10gm.

A2.4 The sampler used had a 50mm diameter hemispherical mechanical cutter which defined the curvature of the sample at its deepest part. The sample surface corresponding to the original pipe surface is flatter, reflecting the much larger diameter of the pipes sampled (typically 350mm for main steam and 450mm for hot reheat).

A2.5 The depression left in the pipe surface also reflects the diameter of the hemispherical cutter. For the pipe sampled it was no greater than 5mm deep at its deepest point and up to about 30mm across. Care was taken to de-burr and polish the shallow excavation.

A2.6 Cutting time was found to be variable, depending primarily on the size of the scoop sample and the individual cutter. A typical cutting time was 1.5-1.75 hours, although this could lengthen considerably in the event of power loss or mechanical breakdown. More modern versions of mechanical samplers have successfully obtained scoop samples of the required size in under an hour.

A2.7 In order to track scoop samples during subsequent processing, each one was individually labelled with a unique identification number as soon as it became available. The sampling location of each scoop sample was also recorded.

A2.8 Specimen Manufacture in Relation to Testing

A2.8.1 For these specimens a standard test at the same stress and temperature was adopted as an initial ranking exercise. Because the specimens are not destroyed in an impression test, they were able to be retained for more elaborate testing (e.g. stepped stress or stepped temperature) at a later date.

A2.8.2 A standard test specimen size of 10mm×10mm×2.5mm thick was adopted. This was sufficiently thick to allow the ranking test to be followed by further testing, if required.

A2.8.3 For typical main steam and hot reheat pipework geometries sampled, scoop samples needed to be a minimum of 3.2mm thickness (excluding any oxide scale present), to yield a specimen of this size.

A2.8.4 Where this could not be achieved the options were to use an alternative standard size (e.g. 8mm×8mm×2mm) or a 10mm×10mm×2.5mm specimen with partially reduced dimensions. In either case the loads were adjusted to test the specimen at the common stress condition.

A2.8.5 During machining of the specimen the surface corresponding to the greatest depth in the pipe was identified as the test surface. The intention was that the point of impression should correspond to material as deep into the pipe as possible. In practice this was found to be 2.5-3mm. The first step in the specimen preparation was to trim the scoop sample to approximately 13mm square using a fine hacksaw. The spherical surface was then surface ground until a flat approximately 12mm diameter was generated: the sample was then turned over and the outer side ground to a specimen thickness of 2.7mm. The edges were then machined to give a specimen 10mm×10mm ±0.05mm. Both faces were then finish ground to 2.5mm ±0.02mm. The proportion removed from either face of the specimen was adjusted such that the spherical profile of the scoop sample was still visible on the corners of the specimen. This ensured that the impression test was made at the deepest point in the sample and gave visible proof of the direction of loading.

A2.8.6 The small off cuts obtained from the specimen preparation exercise were retained and returned with the tested specimen. These were then available to provide metallographic information, hardness and (possibly) limited chemical analysis.

A.3 Conversion Between Indentation Rate and Creep Rate

The impression creep testing technique involves the application of a steady load to a flat-ended indenter, placed on the surface of a material at elevated temperature. The displacement-time record from such a test is related to the secondary creep properties of a relatively small volume of material in the immediate vicinity of the indenter. As shown in Section 4, for a rectangular indenter, the reference stress approach can be used to convert the mean pressure under the indenter, **p**, to the corresponding uniaxial stress, **σ**, i.e.

$$\sigma = \eta \overline{p}$$

and to convert the creep displacement to the corresponding uniaxial creep strain i.e.

$$\varepsilon^c = \frac{\Delta^c}{\beta d}$$

where **η** and **β** are the reference parameters (conversion factors) and **d** is the width of the rectangular indenter (see Fig.1, Section 4).

The load required to produce a given stress is **σ/η** and the measured indentation rate is divided by **βd** to produce the equivalent uniaxial creep strain rate.

For a specimen with w = b = 10mm, h = 2.5mm and indenter width d = 1.0mm, the conversion factors obtained from a 3D Finite Analysis [A3] analyses are:

η = 0.430

β = 2.180

The indentation rate measured in the test is therefore divided by 2.18 to produce the creep strain rate.

For a specimen with w = b = 8mm, h = 2mm and indenter width d = 0.8mm, while **η** and **β** remain unchanged, the factor between indentation rate and creep strain rate changes to 2.180 x 0.8 = 1.744.

Similarly, for a given stress, the load will be reduced a factor of 0.8 x 0.8 = 0.64.

Where the standard dimensions (h = 2.5mm, d = 1.0mm, or h = 2.0mm, d + 0.8mm) are not precisely met, the following corrections can be made to the conversion factors. These are applicable within, or close to, the size range for which most data are available.

Polynomial Fitting of Impression Test Conversion Factors ($R^2 = 1$)

(h/d = 2.0 – 2.5)

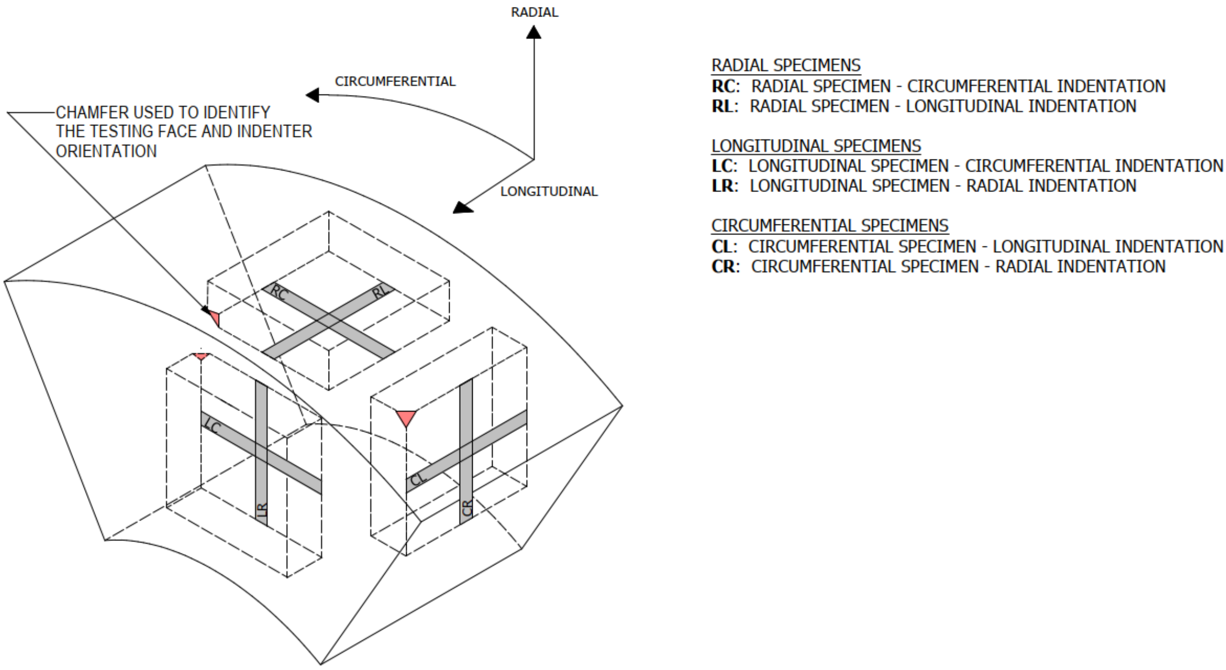
$$\eta = 0.056 \left(\frac{h}{d}\right)^2 - 0.338 \frac{h}{d} + 0.926$$

$$\beta = -0.0992 \left(\frac{h}{d}\right)^2 + 0.9036 \frac{h}{d} + 0.5407$$

Reference

A3. T.H. Hyde, W. Sun, "Evaluation of conversion relationships for impression creep test at elevated temperatures," *International Journal of Pressure Vessels and Piping* 86 757-763, 2009.

A.4 Specimen/Indenter Orientation



1. The circumferential, longitudinal, and radial directions correspond to the original sampled component, in this case assumed to be a pipe. The circumferential direction is clockwise when looking in the longitudinal direction.

2. Specimen orientation is defined by whichever of these directions is normal to the indented surface, with the arrow representing the direction of indentation.

3. Each specimen orientation has two possible indenter orientations, defined by the direction corresponding to the line of intersection with the specimen.

4. Chamfered corners, sometimes called “witness marks”, in each case placed in the positive quadrant, are used to distinguish the indented surface. For R type specimens this mark is on the side furthest away from the component surface (consistent with the convention previously used for specimens machined from scoop samples).

A.5 Round Robin Testing

Interim for Draft for Comment – this Section to be to be updated when the tests are complete.

To provide confidence in the use of impression creep testing, this CWA has included a Round Robin exercise on a common material using a common test procedure.

The common material chosen is referred to as Bar 257, a grade 91 forging with lower bound creep strength. This material was originally obtained from a header manufacturer in the UK as a section of cylindrical forged bar with an outside diameter of 257mm. Records showed that it had been normalised for 5.5 hours at 1040°C in the austenite range, air cooled to produce transformation to martensite, tempered for 12 hours at 760°C, and then air cooled. Its microstructural condition was tempered martensite with a Vickers hardness of 204. Material held by EPRI was distributed to the other participating laboratories.

The chemical composition was provided by the manufacturer on the original material test certificates (Cameron Serial No. 28584 – Cast No. P9661-1-2 and Clyde Shaw Cast No. G5535) but more detailed analyses were carried out subsequently as part of several collaborations. The most recent, carried out by EPRI, is shown below.

Table A5.1 Bar 257 Chemical Composition

Composition (wt%)						
C	S	O	N	Al	B	Ca
0.122	0.0081	0.0015	0.0282	0.028	<0.0005	<0.0005
Co	Cr	Cu	Fe	La	Mn	Mo
0.015	9.097	0.14	88.25	<0.002	0.53	1.05
Nb	Ni	P	Si	Ta	Ti	V
0.063	0.16	0.015	0.25	0.002	0.002	0.209
W	Zr	As	Bi	Pb	Sb	Sn
<0.002	<0.002	0.013	<0.0001	0.000055	0.0019	0.008

The common test procedure adopted was a four-step stepped stress test at 100MPa, 110MPa, 120MPa and 130MPa, at 600°C. The specimen/indenter dimensions were 10x10x2.5mm/1.0mm (conversion factors: $\eta = 0.430$, $\beta = 2.180$), with the standard test configuration being LR (see A4). One laboratory chose to use an 8x8x2.0mm/0.8mm combination (see Section 6.3).

The Round Robin repeated an earlier exercise involving four of the participating laboratories which had tested the same material, but which had not used the newly agreed common testing procedure **[A5.1][A5.2]**. For the remainder of this section the earlier Round Robin will be referred to as "RR1" and the current CWA Round Robin as "RR2".

RR2 allows several comparisons to be made:

- Laboratory to laboratory variation in the impression creep strain rates.
- Comparison of the RR2 results with the earlier RR1 results.
    - Comparison of creep strength for this material.
    - Comparison of Impression Monkman Grant relationship for this material (see A1).

The interim results obtained to date, from three of the laboratories, are summarised below.

Table A5.2 The Results of the RR2 Impression Tests (by Laboratory)

Laboratory	Series	Material	Orientation	Specimen	Indenter	
Nottingham	RR2	Bar 257	LR	10x10x2.5mm	1.0mm	
Load (N)	Stress (MPa)	ICR (/hr)	Log ICR	Hours Range	R2 Value	Validity 100hrs/75hrs
2325	100	1.1827E-05	-4.9271	360-460	86.58%	0.8903
2557	110	16383E-05	-4.7856	530-630	87.15%	1.0364
2791	120	3.2553E-05	-4.4874	695-795	97.6%	1.0570
3023	130	6.5282E-05	-4.1852	845-945	99.14%	1.0373

Laboratory	Series	Material	Orientation	Specimen	Indenter	
VTT	RR2	Bar 257	LR	10x10x2.5mm	1.0mm	
Load (N)	Stress (MPa)	ICR (/hr)	Log ICR	Hours Range	R2 Value	Validity 100hrs/75hrs
2325	100	5.323E-06	-5.2738	444-545	97.31%	1.0006
2557	110	1.1693E-05	-4.9321	617-717	99.51%	1.0296
2791	120	2.1356E-05	-4.6705	780- 880	99.87%	1.0160
3023	130	3.8399E-05	-4.4157	1005-1040	99.75%	-----

Laboratory	Series	Material	Orientation	Specimen	Indenter	
Jacobs	RR2	Bar 257	LR	8x8x2.0mm	0.8mm	
Load (N)	Stress (MPa)	ICR (/hr)	Log ICR	Hours Range	R2 Value	Validity 100hrs/75hrs
1488	100	6.7702E-06	-5.1694	325-425	79.24%	0.8426
1637	110	1.3896E-05	-4.8571	486-586	92.29%	1.0579
1786	120	2.1805E-05	-4.6614	657.5-757.5	98.36%	1.145
1935	130	3.2857E-05	-4.4834	822.5-922.5	99.36%	1.06

NB: Loads are lower for Jacobs because of the choice of a smaller specimen/indenter size.

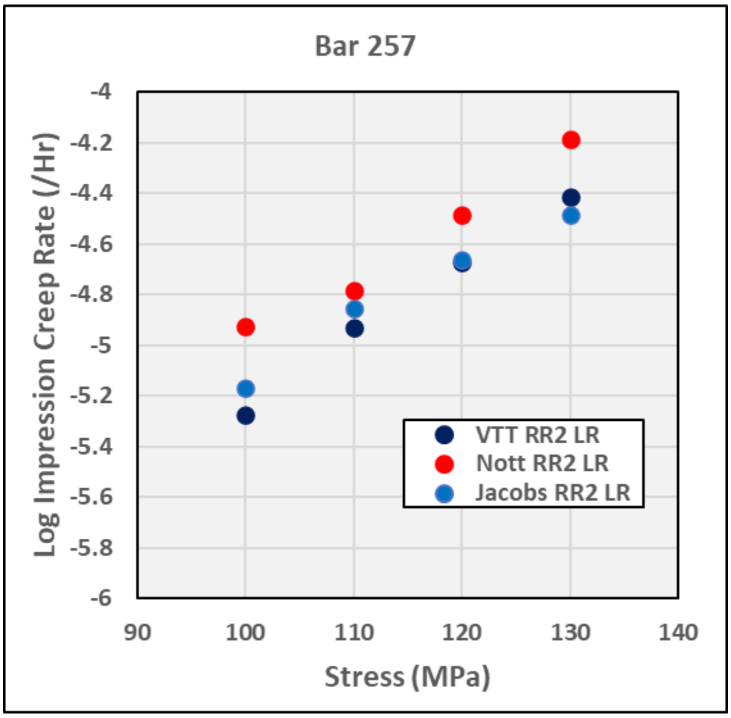


Figure A5.1. Interim Impression Creep Results at 600°C from RR2.

As shown in Fig.A5.1, the data are in good agreement.

To obtain equivalent rupture life from the impression creep strain rates use must be made of the Impression Monkman Grant relationship for this material (see A1). Although uniaxial rupture lives at 600°C are not available at the specific stresses used in RR2, interpolated values can be used.

Uniaxial rupture data for Bar 257 in the range 97-140MPa at 600°C is shown as a Log-Log plot in Figure A5.2. The data have a good linear relationship over this range (R2 = 99.3%), which covers the test range of 100-130MPa at 600°C used for the RR2 impression tests. This allows uniaxial rupture lives to be derived at the specific stresses used in the impression tests by interpolation.

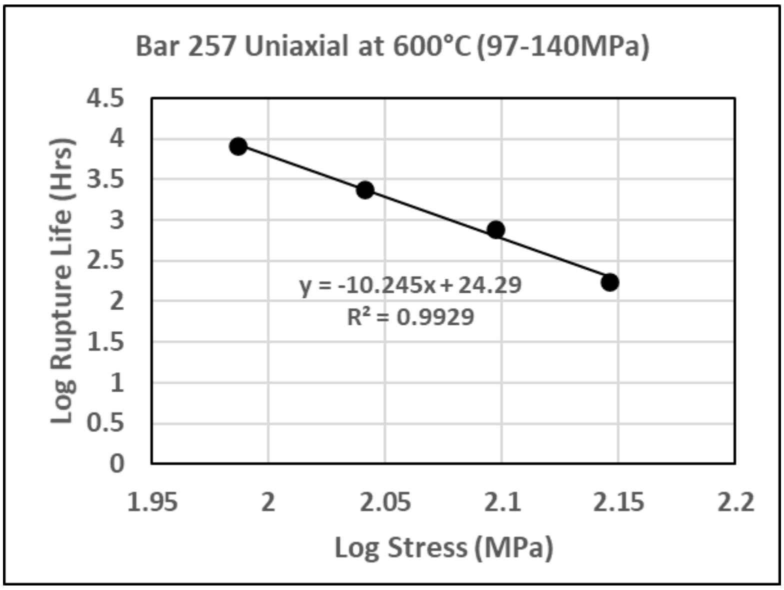


Figure A5.2. Log-Log Plot of Bar 257 Rupture Data at 600°C.

Using the resulting relationship (Log Life = -10.245 x Log Stress + 24.29) shown, the interpolated rupture lives at the impression creep stresses are shown in Table A5.3.

Table A5.3. Interpolated Values Derived from Fig. A5.1.

Stress (MPa)	Log Hrs
100	3.8
110	3.3759
120	2.9887
130	2.6327

The strength of Bar 257 relative to the ECCC2019 grade 91 assessment **[A5.3]** can be calculated by dividing the stress required to produce a given rupture life at 600°C by the stress required to produce the same rupture life in material with mean properties. Using the actual Bar 257 rupture lives in Figure A5.2 the strength is 0.7755 (Mean-22.45%), while using the interpolated values in Table A5.3 the strength is 0.7754 (Mean-22.46%). The close agreement provides confidence in the use of the interpolated values to derive the Impression Monkman Grant relationship for this material.

The Log ICR values from Table A5.2 are plotted against the corresponding Log Hrs values from Table A5.3 in Figure A5.3 below. This provides an interim Impression Monkman Grant relationship to be derived from the RR2 results to date.

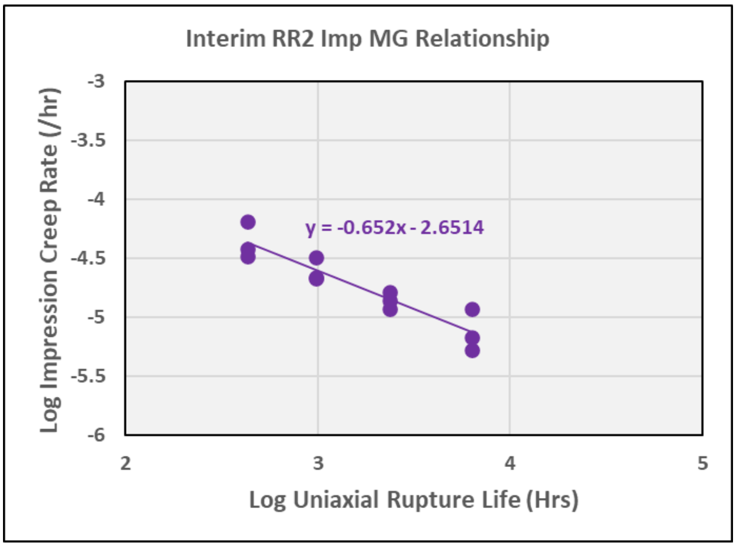


Figure A5.3. The Interim Impression Monkman Grant Relationship derived from RR2.

This gives the following Impression Monkman Grant relationship for Bar 257:

Log ICR = -0.625 x Log t_f -2.6514 or, alternatively, **ICR = 0.002232 t_f -0.625** - RR2

… where ICR is the impression creep strain rate (/hour) and t_f is the rupture life (hours).

An analysis of the RR1 results, following a similar procedure to that used for RR2 above, has been published **[A5.2]** and the RR1 results shown in Fig. A5.4 below.

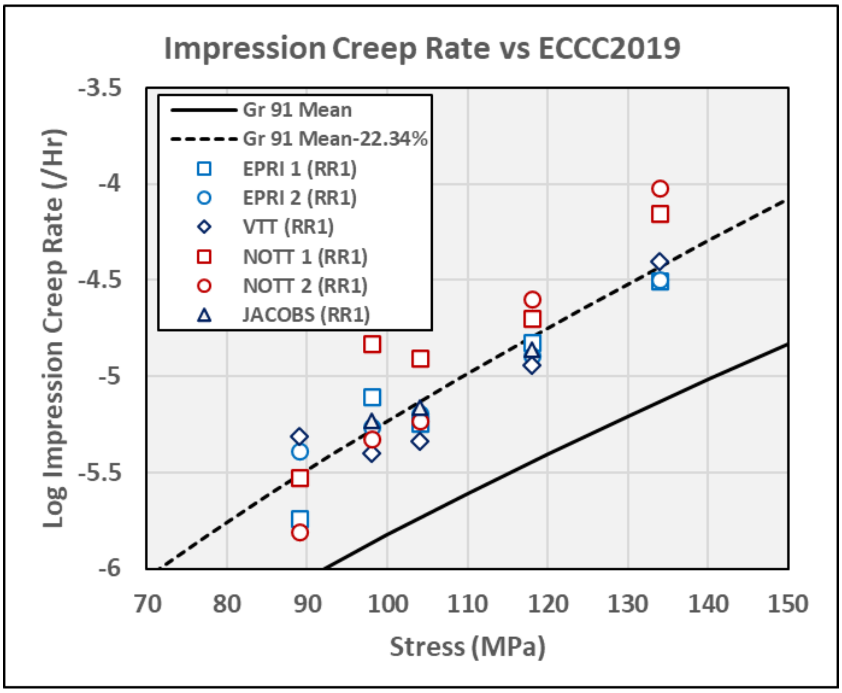


Figure A5.4. The Results from RR1.

The interim RR2 data and the RR1 data are summarised in Fig. A5.5.

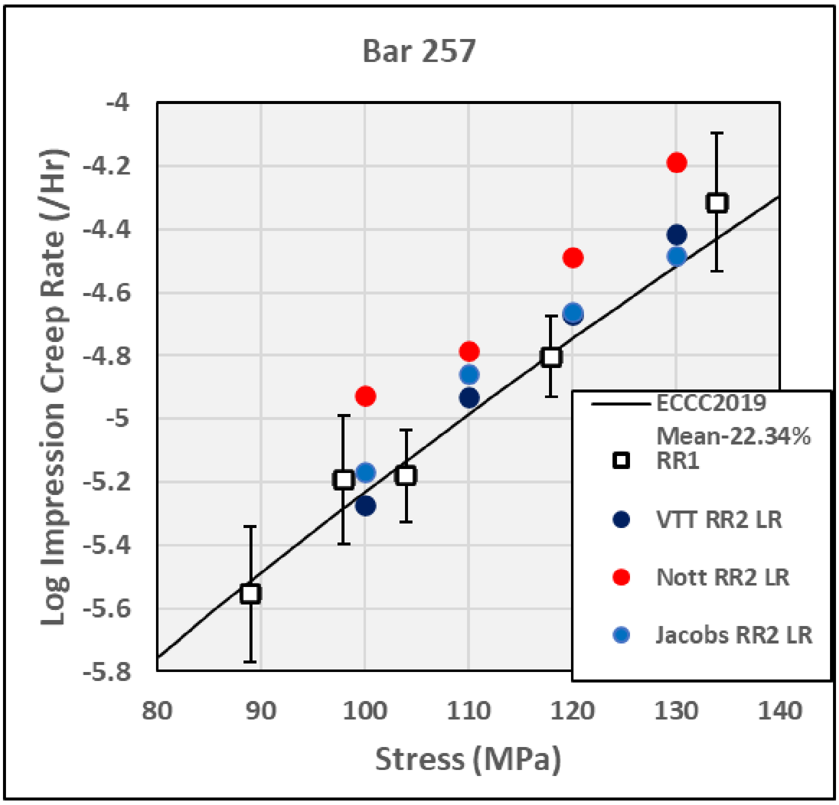


Figure A5.5. The Interim Results from RR1 compared to RR2.

Discussion

It is apparent from Fig.A5.5 that the interim RR2 data tend to lie above the RR1 average line, implying a somewhat lower creep strength. While additional RR2 data may alter this, if corroborated, further investigation may be required.

If a significant difference is confirmed, there are several factors to be taken into account:

- Although all laboratories taking participating in RR1 used a similar procedure, involving a stepped stress test with increasing stress, these were not as tightly defined as for RR2.
- The material in RR1 was obtained at depths of up to 60mm in the original forged bar, whereas material in RR2 came from closer to the surface (~10mm).
- The material tested in RR1 and RR2 came from two different discs cut from the original forged bar, potentially up to 0.5m apart.
- While the RR2 material was tested in the LR specimen/indenter orientation (see Section A.4), the RR1 specimens were C type (CR or CL not defined).

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