Associated conference: 5th International Small Sample Test Techniques Conference

Conference location: Swansea University, Bay Campus

Conference date: 10th - 12 July 2018

How to cite: Bridges, A. & Purdy, D. 2018. Post-test impression creep evaluation methods and findings for improved code of practice. *Ubiquity Proceedings*, 1(S1): 8 DOI: https://doi.org/10.5334/uproc.8

Published on: 10 September 2018

Post-test impression creep evaluation methods and findings for improved code of practice

A. Bridges [1],*, D. Purdy [1]

[1] Electric Power Research Institute, 1300 W. W.T Harris Blvd, Charlotte, NC 28262 USA
***** Correspondence: abridges@epri.com; Tel.: +1-704-595-2950

Abstract: The impression creep test is a small sample testing technique that has been used mostly for qualitative assessments intended for risk ranking of in-service components. Electric Power Research Institute (EPRI) has conducted testing to determine the limitations of the test method. This involved extensive analytical and physical posttest assessments that have led to recommendations to improve the current code of practice. Analytical assessments for determination of minimum strain rates suggest that having a standard procedure would be very beneficial to the testing community. Physical assessments that involve indentation depth measurements, hardness mapping and grain structure evaluations have provided methods for determining the affected area of deformation under the indentation surface. These methods may help in validating and revising current FEA models. Additional FEA modeling may also help answer further questions regarding applicable indentation range and appropriate testing conditions (stresses and temperatures). EPRI will continue to conduct impression creep testing to further evaluate the limitations of the test method and address questions from the work discussed in this paper.

Keywords: Impression creep, small sample testing, code of practice, hardness, FEA

---

1. Introduction

Coal-fired steam generation plants are reaching ages over 50+ years and are still operating with original materials that are well beyond their initial design life. This has led to an increase in the use of small sample testing at elevated temperatures for evaluations of in-service material. The impression creep (IC) test method uses minimal material and is considered a 'non-invasive' technique. Traditional creep testing methods (uni-axial creep) use a much larger volume of material, about 100-200 times more than impression creep and is considered a 'destructive' technique that generally requires weld repair or replacement of the extracted volume of material. The main steam (MS) and hot reheat (HRH) steam piping segments are typically evaluated using both methods. Scoop sampling can be used to extract material from the MS and HRH piping segments and impression creep specimens can be cut from the corresponding scoop samples [1].

Impression creep tests typically run until a 'steady state' creep rate is obtained and held for 100 hours. This usually leads to a total testing time of 300-500 hours depending on the material and testing conditions used. The test is also used for performing both stepped loads (isothermal) and stepped temperature (isostress) tests. The current code of practice does not address how long a test should be ran or the requirements for isothermal and isostress testing. This paper will address some of these concerns through an assessment of recent impression creep tests and posttest evaluations.

Posttest evaluations can be performed on impression creep samples for alignment checks, indentation depth measurements and evaluation of changes in grain orientation under the indentation deformation zone. Specimens can be cut in half perpendicular to the indent to examine the microstructure beneath the indent. A review of posttest evaluation methods and analytical findings has provided valuable information that can be used to revise a more rigorous code of practice for impression creep testing.

2. Materials and Methods

2.1. Standard Method Sample Preperation and Testing

The impression creep test uses a 1mm x 10mm rectangular indenter (a) to form an impression on a rectangular 10mm x 10mm x 2.5mm sample (b), as shown in Figure 1. The use of the rectangular indenter has lower localized deformation constraints than circular indenters [2] and has been adopted as the standard choice of indenter in the current code of practice. Finite element analysis work by Hyde et. al. [3] has led to the standard geometries currently adopted by the ECCC code of practice [4] which includes smaller specimens as well. A reference stress approach has been used to convert stress relationships from traditional uniaxial testing to testing stresses used in impression creep testing [2]. It is also important to note that this approach is based solely upon sample geometry and has shown to be material independent based on published research of CrMoV, stainless steels, 9Cr steels, 2.25Cr1Mo steels and a variety of filler weld metals [5-9].

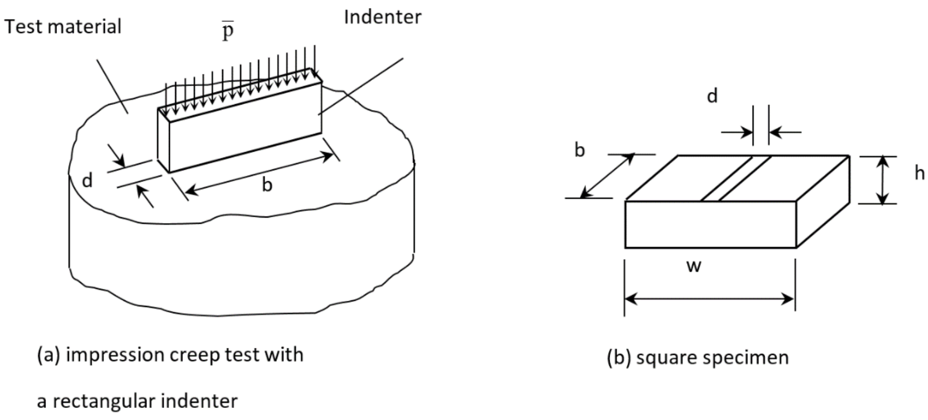

Figure 1. Standard Impression Creep Indenter and Test Specimen.

Samples are typically cut to ~2.55-2.60 mm thickness using electric discharge machining (EDM) before being grounded to a final thickness of 2.50 ± 0.02 mm, finishing 600 grit sandpaper. Electric Power Research Institute (EPRI) is currently using a Tinius Olsen twin-screw servo-mechanical (H25KS) loading frame with a high temperature ceramic shell furnace using kanthal windings. A software program has been specifically designed for controlling a static load with a signal input for linear variable differential transformers (LVDTs) to measure strain accumulation during the entire duration of the test. The independent three zone furnace uses type N thermocouples for control of temperature, but the sample temperature is measured with an external data acquisition system using three type K thermocouples. A high strength nickel based superalloy (Waspaloy) was chosen as the material indenter, as it has a much higher creep strength than that of the materials being tested and negligibly contributes to measured strain. These specifications are outlined in the current code of practice [4].

2.2. Metallographic Preperation for Posttest Evaluations

EPRI has conducted posttest evaluations of impression creep specimens for further examination of each test. This, along with more rigorous data analysis, has led to further questioning to the limitations of impression creep testing and recommended revisions to the current code of practice. Posttest evaluations include measuring the indentation profile in three dimensions using a confocal laser microscope (Keyence VK-X105), hardness testing of cross sections perpendicular to indent surface using a Vickers automated hardness tester (LECO AMH43), and evaluations of microstructure.

After testing, specimens are cut in half perpendicularly to the indentation surface. These are mounted and polished using standard metallographic techniques. Figure 2 shows the how the cross section cut is taken and mounted in a clear epoxy hot mount in preparation for physical posttest evaluation methods.

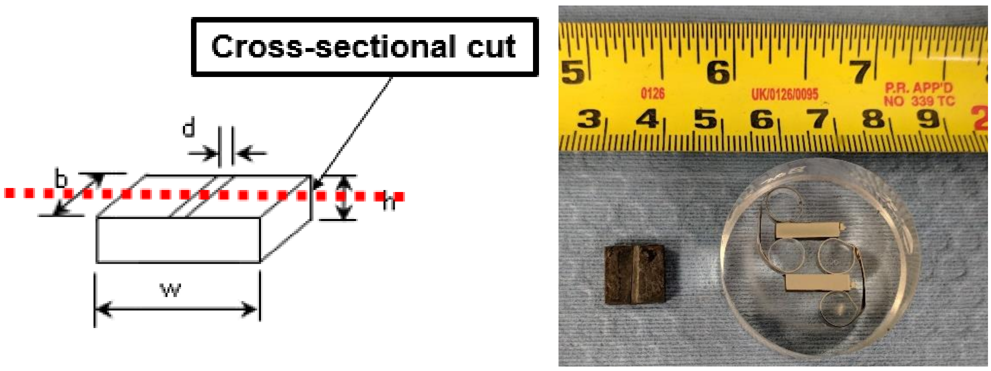

Figure 2. Preparation of Impression Creep Sample for Posttest Metallurgical Evaluation.

2.2. Standard Stress Conversions and Typical Impression Creep Curves

In the EPRI setup, the accumulated strain in an impression creep test is continuously captured by two water cooled LVDTs. The extensometry consists of upper and lower legs that are held between ridges on the upper and bottom half of the indenter. The legs move with the indenter during the test and translate movement to the LVDTs. Initial strain rates are high that quickly diminish to a somewhat constant rate. There is typically no acceleration regime after constant rates have been established, as the test is loaded with a compressive force and does not experience a change in the cross-sectional load-bearing area. The reference stress used to convert the mean pressure under the indenter (p) to a corresponding uniaxial stress (σ) is represented by:

$$\sigma = \eta p \quad (1)$$

The impression indentation displacement (Δ^c) is also converted to a uniaxial creep strain (ε^c) using:

$$\varepsilon^c = \frac{\Delta^c}{\beta d} \quad (2)$$

The reference parameters can then be represented by η and β, which are conversion factors, and d is the width of the rectangular indenter. To determine reference parameters using finite element analysis, Norton's creep power law is used [6]:

$$\dot{\varepsilon}^c = A\sigma^n \quad (3)$$

The reference stress approach allows impression creep testing to be used as an alternative to uniaxial creep testing when only a limited amount of material may be available for testing. Typical impression creep strain and strain-rate curves are shown in Figure 3.

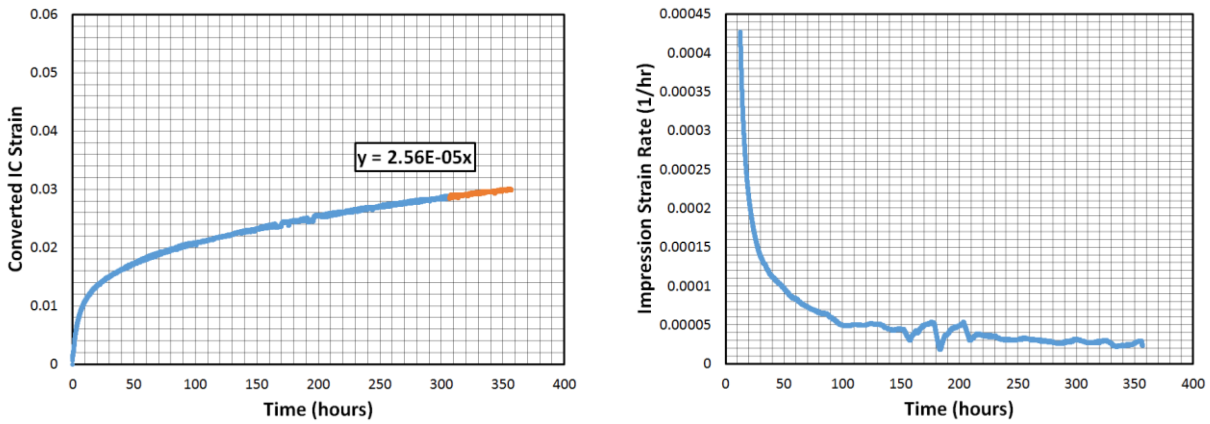

Figure 3. Typical Impression Creep Strain and Strain Rate Curves (Service Exposed Grade 22 Tested at 570°C and 80 MPa.

3. Results

3.1. Impression Creep Results

A Grade 91 sample was tested at 100 MPa and 625°C for about 475 hours. These strain and strain rate curves are shown in Figure 4. The strain rates were calculated using ±12.5-hours, ±25-hours, and ±50-hour increments, respectively. A ±50-hour increment that occurs 50 hours before the test terminates would be equivalent to the average rate in the last 100 hours of testing.

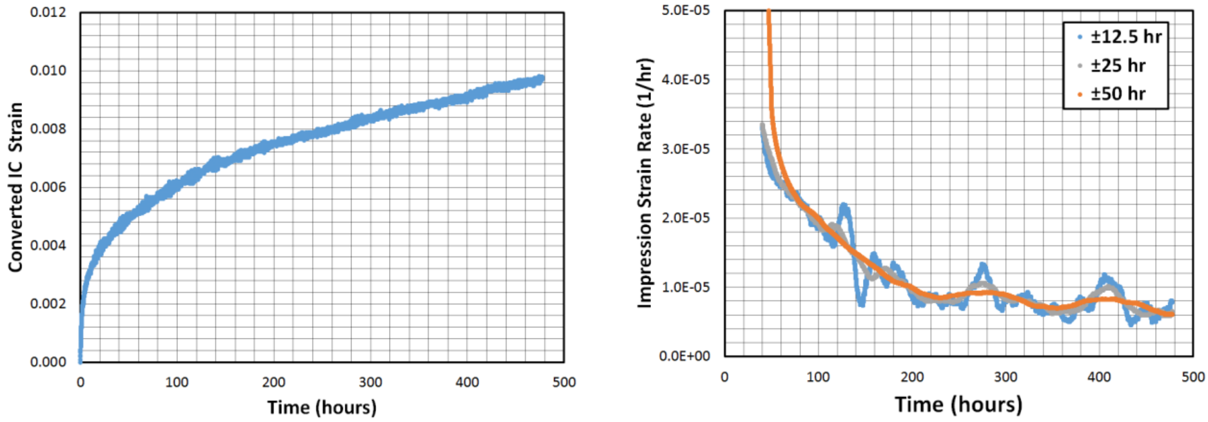

Figure 4. Impression Strain Curve and Strain-Rate Curves (using different averaging increments) for a Tempered Martensitic Grade 91 Steel Tested at 100 MPa and 625°C.

Another set of tests for tempered martensitic Grade 91 steel were tested at 625°C for tests of 80 and 100 MPa. Duplicate tests were conducted for each stress with strain and strain rate plots shown in Figure 5. The strain rates were calculated using ±50-hour increments.

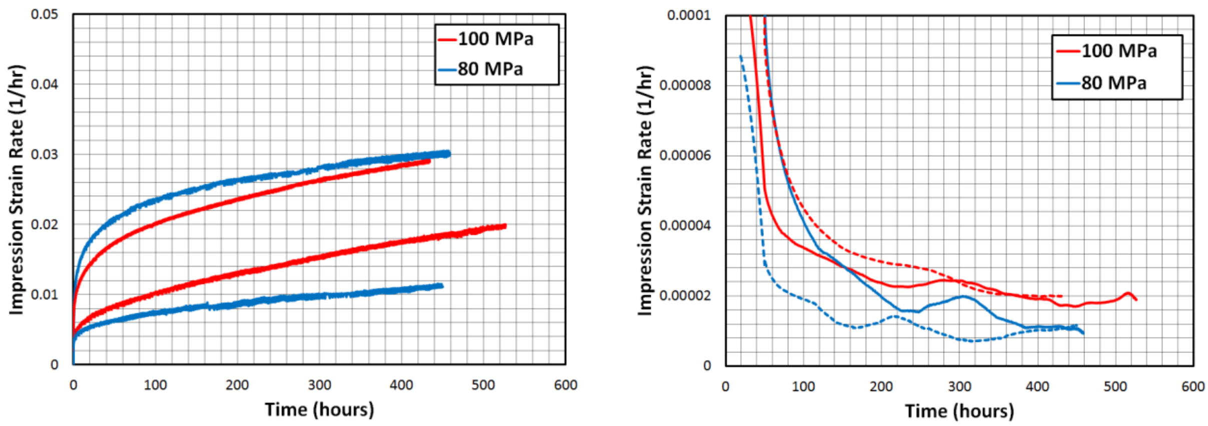

Figure 5. Comparison of Impression Strain Curve and Strain-Rate Curves for Grade 91 Samples at 625°C and both 80 and 100 MPa.

The final set of impression creep tests were conducted on a low alloy service exposed Grade 22 material. The testing was conducted at the base metal, weld metal and heat-affected zone from an extracted plug sample in the hot reheat piping section of a fossil power plant. Impression creep tests were ran for 300 to 350 hours at sample testing conditions of 80 MPa and 570°C. Accumulated strain and strain rate plots for all three tests are shown in Figure 6. The strain rates were calculated using ±50-hour increments.

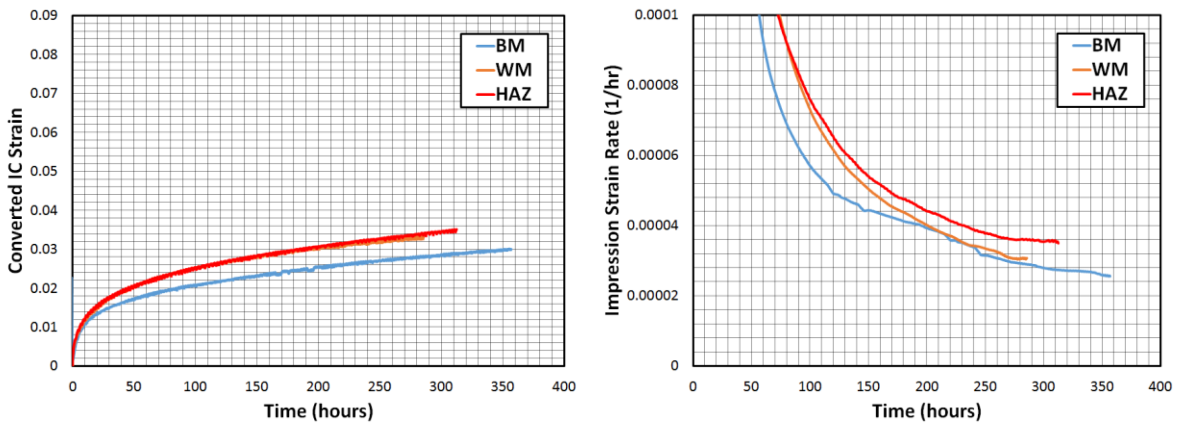

Figure 6. Comparison of Impression Strain Curve and Strain-Rate Curves for Ex-service Grade 22 Weld using ±50 hour increments (80 MPa and 570°C for each test).

3.2. Posttest Evaluation Results

After each impression creep test, measurements of the indent are made using the confocal laser microscope. Results can be compared to measurements from data files produced by the universal testing machine. Figure 7 shows the laser image with typical measurements and a depth measurement calculation using built in analysis software

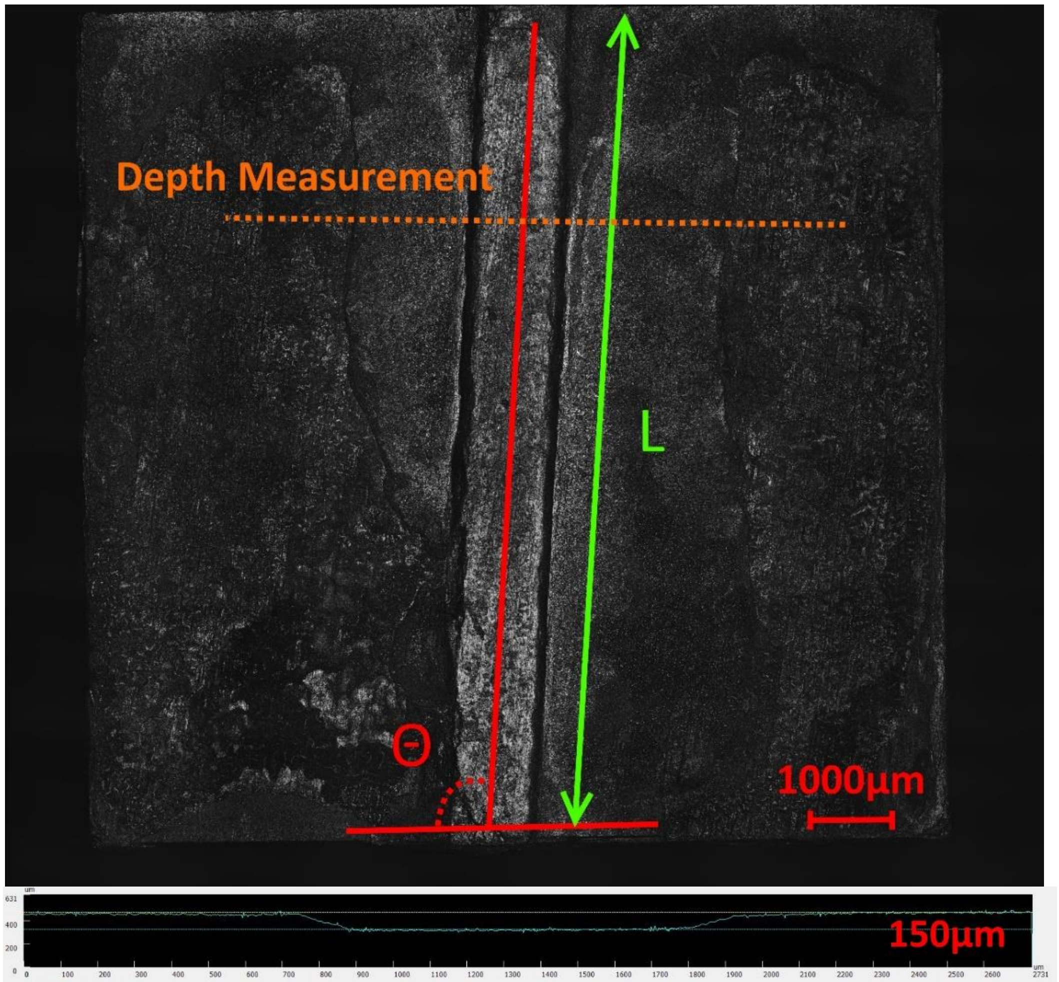

Figure 7. Impression Creep Laser Scan with 150µm Depth Measurement.

Indent measurements can also be measured after the sample has been cut in half perpendicular to the indent, mounted and polished. Results have shown to be the same as measurements taken using the first method shown in Figure 7. Though, it is interesting to note that the measured indentation from the data file was 174µm. This measurement was taken at the end of the test, which was still at testing load and temperature. It seems reasonable that there was some elastic recovery (26µm) after unloading. Polished samples can also be used for hardness testing and etching for evaluation of microstructure and elongation of grains along the stress field. Figure 8 shows a hardness plot of a tempered martensitic grade 91 material that was tested to a 31µm indentation depth. It clearly shows a strain softening effect beneath the indentation (center of the sample), which is a known effect in uni-axial testing of the same material. The hardness plot was created using a 0.2 kg load with 100 µm spacing.

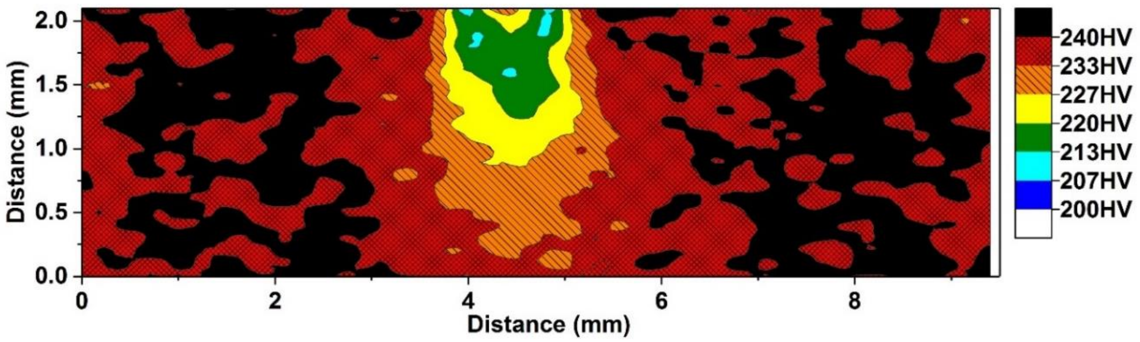

Figure 8. Hardness Plot of a Cross Section through an Impression Creep Sample of Tempered Martensitic Grade 91 Tested at a Temperature of 625°C and Stress of 100MPa; Overall Indentation Depth is 31 µm.

An example for an ex-service grade 22 seam weld is shown in Figure 9. The change in elongation of grains beneath the indent can been seen in the micrograph predominantly around the edges of the indentation. These results help visualize the effected stress field that is developed underneath the indent. The implications of these results are discussed in the next section.

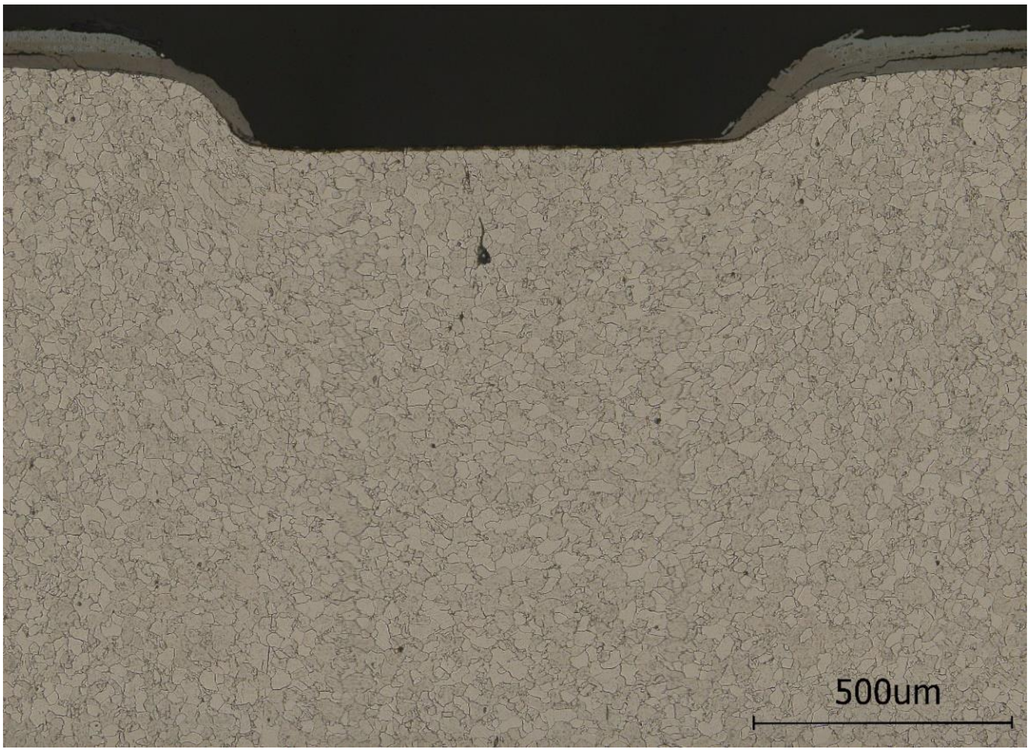

Figure 9. Microstructure of Ex-service Grade 22 Posttest Impression Creep Specimen showing Elongation of Grain Structure beneath the Indenter.

4. Discussion

4.1. Proposal to add Calculation of Minimum Creep Rates in Code of Practice

The current code of practice does not address how long impression creep tests should be ran, as failure does not occur in this testing method and defining a minimum strain rate may seem arbitrary. There are many different analytical methods that can be used to determine the 'minimum creep rate'. Proposing set guidelines may help alleviate any discrepancy between different labs. Currently, without any standard, it is possible that large variations in reported creep rates between different testing labs may be due to the length of testing time and analytical method used for calculation of minimum rates. Above, in Figure 4, strain-rates were reported using ±12.5-hours, ±25-hours, and ±50-hour averaging increments. It has been clearly shown that a smooth strain rate vs. time plot can be accomplished using longer averaging increments, such as ±50-hour increments. This also allows for more data to be used in the calculating the minimum creep rate. It essentially states that a 100-hour increment of strain values is used for calculating the minimum creep rate. In addition to this, the percent variation during the test is calculated to ensure adequate testing time to reach steady state creep. This is further explained in the proposed guidelines, below. It is also evident that the time needed to reach a steady state rate can be dependent on the material (Grade 22 > Grade 91), and that some materials have shown more fluctuations than others (Grade 91 > Grade 22), as shown in Figure 5. The potential material effects on strain rate due to loading and temperature changes are not discussed in this paper, but another in these conference proceedings [7].

The following guidelines are proposed for addendum to the current code of practice:

1. Impression Creep tests should be tested to a minimum of 300 hours, regardless of testing conditions and material
2. Strain-rates should be calculated using ±50-hour time increments
    a. It is acceptable to use only the last 50 hours for the final time stamp – if percent variation requirements are also met
    b. Strain-rates should be analyzed before termination of any test to determine if recommended criteria have been met, ex. >300 hours, within 10% variation
3. The very lowest value from the strain-rate vs. time curve (using ±50-hour time increments) should be used when reported 'minimum creep rate'
    a. This may not always be at the very end of a test, ex. Grade 91 in Figure 10
    b. The time-point where MCR is determined should ***always*** be reported
4. Percent variation should be calculated using ±10-hour time increments from the already calculated strain-rate vs. time curve, using the following equation:

$$\% \, Variation = \frac{(V_1 - V_2)}{\frac{(V_1 + V_2)}{2}} \, x \, 100 \qquad (1)$$

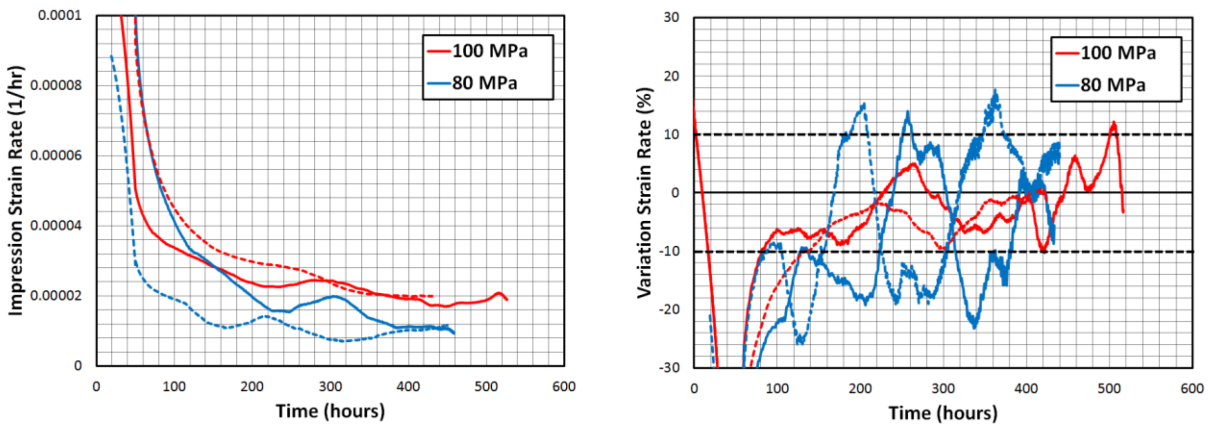

Figure 10. Example for Measurement of Minimum Strain-Rate and Percent Variation for Grade 91

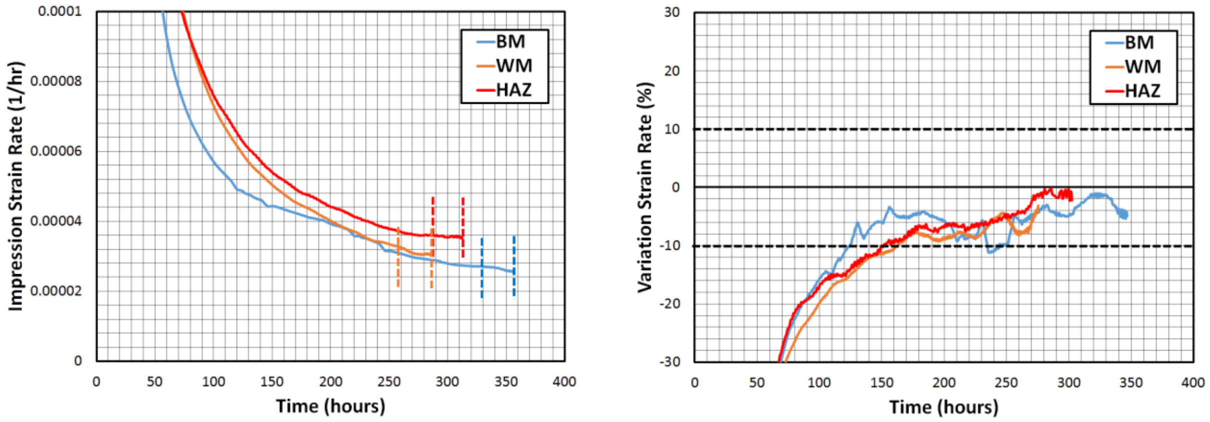

Figure 11. Example for Measurement of Minimum Strain-Rate and Percent Variation for Grade 22

The following comments are justification for recommended parameters in guidelines above:

1. It has been observed in some tests that significant fluctuations in strain-rates can occur up until and even after 300 hours of testing, even when using ±50-hour time increments for calculation of strain rate. Fluctuations appear to be less severe beyond 300 hours. The percent variations in Figure 9 and 10 were calculated using ±10-hour increments from the strain-rate vs time curve. It shows that the percent variations fluctuate more in the Grade 91 tests compared to the Grade 22 test. This question further explored in reference [7].
2. A minimum variation of 10% between ±10-hour increments from the strain-rate vs. time curve is a proposed guideline to provide ***consistency between labs***. 10% variation in strain-rates appears to be a reasonable target with limited test results. This number ***may change*** with additional results over time. In uni-axial testing there is usually a clear minimum before tertiary creep is reached, but there is no agreed upon standard that explains how to properly measure the creep rate. An exact number can be difficult to calculate due to the lack of knowledge of material effects during compressive loading and limited data to evaluate. This number should be re-considered as additional data is gathered and analyzed.
3. It is important to reiterate that the main purpose of these guidelines is to provide ***consistency*** between the different labs. Different individuals are currently using a variety of approaches to measure the minimum creep rate and open collaboration to set agreed upon guidelines is vital for further development of the testing technique.
4. Good engineering judgement should always be practiced when conducting impression creep tests. Any irregular findings and observations should be reported accordingly.

4.2. Considerations if Impression Creep is used as Quantative Assessment (IC-rates in lieu of uni-axial rates)

Uni-axial creep tests were also performed at 80 and 100MPa using a 625°C testing temperature for the same temper of Grade 91 shown in Figure 5. A comparison of results is shown in Table 2. [8]

Table 2. Comparison of Uniaxial Impression Creep Minimum Creep Rates for a Temper of Grade 91

Test Method	Testing Stress (MPa)	Measured Minimum Creep Rate (1/hr)	Time at Measured Minimum Creep Rate (hours)
Uniaxial	80	3.15×10^{-6}	-
Impression Creep	80	9.29×10^{-6}	456
Impression Creep	80	7.16×10^{-6}	320
Uniaxial	100	5.41×10^{-5}	-
Impression Creep	100	1.71×10^{-5}	445
Impression Creep	100	1.98×10^{-5}	434

The test results show that the duplicate impression creep rates were consistent (within 15-20%), but a factor of 2.5 to 3.5 greater than the corresponding uniaxial creep rates. In the uniaxial test, the creep rate at 100MPa was approximately 17 times greater than at 80 MPa. Comparison of impression creep tests from 100MPa to 80 MPa only show a factor of 1.5 to 2.5 times greater. If the impression creep test is to be used in as a direct relationship, these questions should be addressed and answered. The current conversion factors determined from FEA analysis [2] used to determine the converted IC strain rates may need to be revisited. There has also been work on an alternative approach to relating impression minimum creep rates to uniaxial rupture lives. Where it has been common to use traditional Monkman-Grant (MG) relationships in impression creep evaluations, Brett has proposed an Impression Monkman-Grant (Imp-MG) relationship [9]. A comparison of the relationships with actual data (from Table 2) is shown in Figure 12.

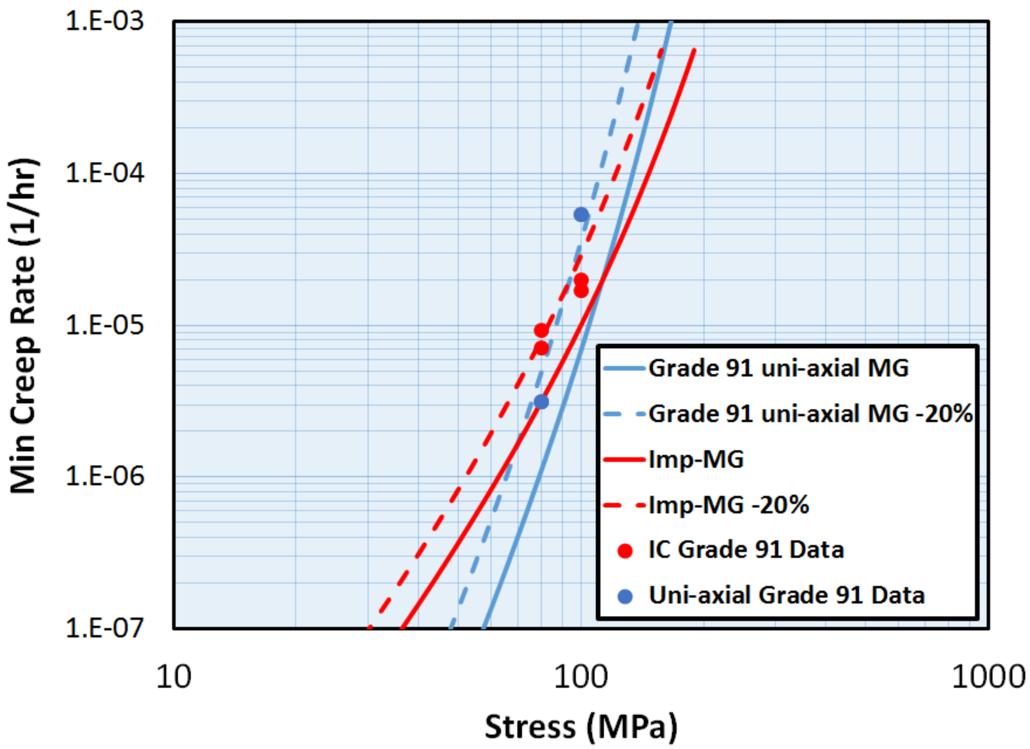

Figure 12. Comparison of Grade 91 uni-axial MG to Imp-MG relationship to actual data.

The Imp-MG relationship directly compares uniaxial rupture times to impression creep rates of the same testing condition. It is important to note that this relationship assumes that the impression creep minimum creep rates ***are not the same*** as expected uni-axial minimum creep rates, as shown in Figure 11. Improved and revised FEA models ***may*** also help further the use of impression creep rates in situ of uni-axial creep rates at the same 'testing conditions'. The findings discussed in this paper show that careful considerations must be made before directly comparing impression creep strain rates to uni-axial rates. Further testing for a variety of materials, rigorous analysis and additional FEA work will help further understand the implications of this.

4.3. Physical Methods for Determining Effected Deformation Area

Posttest evaluations methods shown in section 3.2 of the results section have provided tools for physically measuring the affected interaction volume. Testing of normalized and tempered Grade 91 has shown strain softening behavior, as shown in Figure 8. Strain hardening is expected in some alloys, which would demonstrate a very different reaction in the interaction volume. Even though some alloys have been shown to retain the same hardness throughout testing (neither softening nor hardening), samples can be etched to reveal microstructure. Elongation of grains have been noticed at the edges beneath the indentation. It is also possible that TEM and SEM work could be explored to further characterize these materials after testing to examine dislocation pileup formation, grain orientation effects, etc. Further FEA work may be needed to address some of the additional questions regarding applicable indentation range and testing conditions (appropriate stresses and temperatures) and the impact of an increasing softened zone as the test progresses in strain softening materials. Physical findings from hardness plots and evaluation of elongated grains may help validate and improve current FEA models.

5. Conclusion

These findings led by EPRI have shown additional testing parameters that should be considered for the current code of practice to improve consistency in test results across multiple labs. There should be a more consistent approach to determining the minimum creep rate and a proposed set of amendments to the current code of practice are discussed in this paper. A guideline that requires the test to reach a 'steady-state' for a given number of hours appears to be the most appropriate guideline for testing of all materials, and the term 'minimum creep rates' was defined for the impression creep test. It was determined that each test should be ran to a minimum of 300 hours and creep rates are to be calculated using ±50-hour time increments. A 10% variation in strain-rate was determined to be a reasonable target with limited test results. Observations showed that the time needed to reach a steady state rate can be dependent on the material (Grade 22 > Grade 91), and that some materials have shown more fluctuations in variation than others (Grade 91 > Grade 22). All testing was conducted using the exact same testing equipment.

EPRI has used additional assessment methods, such as analytical and physical posttest examinations, for determining the limits of the impression creep test. The test has currently been used in a qualitative manner, such as a risk ranking evaluation for main steam and hot reheat piping components [9-10]. The additional assessments and experiments conducted by EPRI have shown that there may be issues when using the impression creep test in certain quantitative assessments. Analytical posttest assessments have shown that a universal procedure for measurement of strain rate would be very beneficial to the testing community and likely lead to the having a more widely accepted test method. Physical posttest assessments, such as laser measurements, hardness testing and grain structure evaluations have shown that there are physical ways to measure the effected zone of deformation (interaction volume) under the indentation surface. These methods may help improve current FEA models and provide a better understanding of how different materials react under a compressive loading state. EPRI will continue to conduct a variety of tests on different materials with a goal of providing a ***reliable test method*** for both qualitative and semi-quantitative assessments.

Acknowledgments: This work was supported by members of EPRI's Materials and Repair program.

References

1. Sun, W, et al. "Application of Impression Creep Data in Life Assessment of Power Plant Materials at High Temperatures." *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, vol. 222, no. 3, Dec. 2008, pp. 175–182.
2. Hyde, T.H.; Yehia, K.A.; Becker, A.A. Interpretation of impression creep data using a reference stress approach, International Journal of Mechanical Sciences, Volume 35, Issue 6, 1993, Pages 451-462.
3. Hyde T.H.; Sun W.; 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 1996;38:1089–102.
4. ECCC Guidelines for Impression Creep Testing; Discussion at 3th International ECCC Conference, 2014.
5. Recent Research Findings and Expanded Database for Impression Creep Testing: EPRI, Palo Alto, CA: 2017. 3002009056.
6. Hyde, T.H.; Sun, W.; Becker, A.A. Analysis of the impression creep test method using a rectangular indenter for determining the creep properties in welds, International Journal of Mechanical Sciences, Volume 38, Issue 10, 1996, Pages 1089-1102.
7. Bridges, A.; Purdy, D. Potential Implications of Step Loading in Impression Creep Testing; 5th International Conference SSTT, Swansea UK, 2018.
8. Life Management of Creep-Strength-Enchanced Grade 91 Steels – Atlas of Microstructures: Base Metal. EPRI, Palo Alto, CA: 2013. 3002000080.
9. A Guide to In-Service High Temperature Headers and Piping Materials Evaluation by Impression Creep Testing. EPRI, Palo Alto, CA: 2016. 3002009055.
10. Brennan, K.; Brett, S.J.; Eaton-Mckay, J. Impression Creep Testing of Aberrant Grade 91 Material Removed from Piping in Service; 4th International ECCC Conference, 2017.