The Changing Constants of Creep: A Letter on Region Splitting in Creep Lifing

V. Gray & M. Whittaker

Institute of Structural Materials, College of Engineering, Swansea University,

Swansea SA2 8PP, UK.

Correspondence Author: v.a.gray@swansea.ac.uk

Keywords: Region Splitting, Activation Energy, Steel, Creep

Abstract

This letter explores issues surrounding region splitting, a current technique used to improve creep life predictions. The history of the technique is discussed briefly and its current implementation by major research groups described in more detail. An example of novel or non-traditional region splitting is also explored with its first known application to nano-creep. The issues surrounding region splitting when considered as an industry practice are also briefly discussed. The purpose of this letter is to explicitly discuss region splitting as a creep lifing technique and identify the current and future issues researchers and industry may face when implementing this powerful technique.

1. Introduction

Over the past 20 years understanding the phenomenon known as creep has been fuelled by the demand for higher performing materials across all industries. The scope of such a challenge can be understood when considering the conditions in which creep is a major design consideration. On a large scale, one example is power generation where large components experience generally static loads in extreme environments with lifetimes of over 250,000h and failure, when it occurs, is mainly due to creep [1]. Contrastingly, any understanding of creep also needs to accommodate the other end of the scale too. In the gas turbine industry failure is usually a result of fatigue, however, input stresses for finite element fatigue models depend on detailed understanding of processes such as stress relaxation, which requires the modelling of creep strain on a localised scale [2]. It is arguably because of

the broad nature of creep that many models and methods have been developed in order to predict this phenomenon.

Although creep presents a complex and difficult problem for engineers and material scientists, significant achievements have been made. This is evident in the literature of the field with many published models and methods available such as those found in [3, 4]. These articles show that creep lifing is a complex field populated by many approaches that have differing levels of success often defined by the situation specific application [3]. One issue facing all these methods has been the use of 'stress partitioning' or 'region/regime splitting'. This is where a change in creep behaviour has been observed at certain stresses and is thought to be linked to a change in dominant creep mechanism. Referred to throughout this article simply as region splitting, it is being more widely used to predict long term creep behaviour and as a practice is coming under more scrutiny.

So far region splitting has only been discussed in terms of application to individual materials, but with its wider usage this technique needs to be more explicitly addressed. In this article the historical and physical background of region splitting is discussed, as well as how it is being implemented by current research groups. A novel application of region splitting to nano-creep is also discussed as a means of highlighting the potential this technique has in future research. Lastly, the limitations and potential issues of region splitting as an industry practice are discussed. The purpose of this article is to highlight and discuss the historical and current applications of region splitting with regards to its future use, whilst addressing concerns raised by reviewers when presented with region splitting in research papers. This article seeks to draw together the ideas and examples expressed in a number of publications in order to describe the current baseline understanding of region splitting and its role in creep lifing.

2. Background

Creep lifing methods rely on the determination of constants and parameters obtained empirically from representational datasets. One of the constants used in almost all creep lifing methods is the activation energy denoted by Q or Q_c. First popularised by Arrhenius, activation energy refers to the energy a chemical system needs to enact a certain process. In physical terms it can be thought of as a value that represents the atomic level behaviour of the

material. For creep, the behaviour of a material on an atomic scale is described as Lattice/Bulk Diffusion (Nabarro-Herring), Grain Boundary Diffusion (Coble), Dislocation Climb/Glide and Thermally Activated Glide. From mechanical testing under very precise conditions, the activation energy of these mechanisms is determined for a material and is visualised through a creep deformation mechanism map like that shown in Figure 1. Recent developments in simulation techniques such as Molecular Dynamics, means these activation energies can be more precisely determined for a very small range of temperature and stress conditions [5, 6].

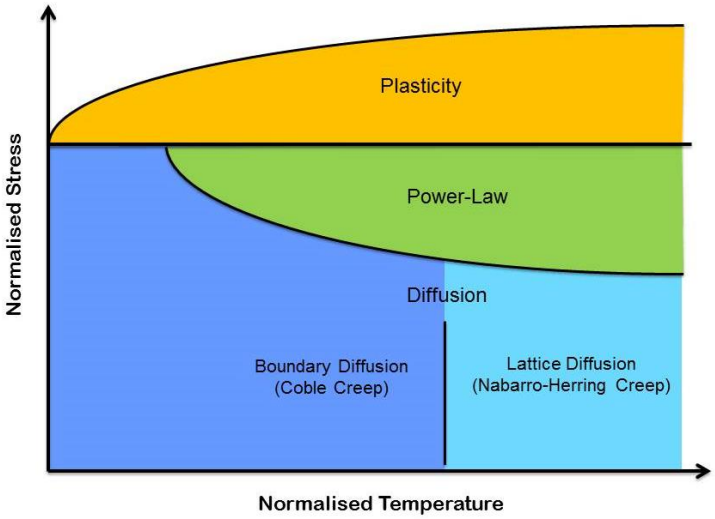

Figure 1. Example of a Simplified Creep Deformation Mechanism Map [1]

From the deformation map shown in Figure 1, it can be reasonably concluded that when measuring creep across a range of temperature and stress conditions, the life of the material will change according to the mechanism it experiences. *"According to the concept of the deformation and fracture mechanisms map we should accept the assumption that creep rupture data attained within the domain where creep or creep fracture is governed by one dominant mechanism cannot be used for prediction to another domain, where creep and fracture are controlled by different dominant mechanisms. As soon as the condition is changed and the boundary is crossed into another domain, the prediction becomes unreliable."*[7]

The earliest available example of region splitting found by these authors was by Bernstein in 1967 [8]. Whilst studying creep in Zirconium and Zircaloy-2, Bernstein observed that the

minimum creep rate could not be well modelled by a single activation energy, Q or Q_c. He then went on to develop an equation to describe his results:

$$\dot{\varepsilon} = D_1\sigma^n exp\left(-\frac{Q_1}{RT}\right) + D_2\sigma \exp\left(\frac{-Q_2}{RT}\right)$$

where D_1, D_2, Q_1 and Q_2 are constants. From the form of this equation it is evident that the first term, and hence first activation energy, is dominant at high stresses whilst the second is dominant at low stresses. Subsequently, fitted values for the activation energy for the high stress region matched those found elsewhere [9], further supporting the concept that each stress region was dominated by a different creep mechanism. Two years later, a study by Gilbert *et al.*[10] examined the same material over a larger range of temperatures and stresses. This study into the secondary creep rate observed five different regions with activation energies of 30-75, 70, 105, 66 and 100kcal/mole.

Later, in the 1980s after observing distinct changes in creep behaviour for high ferrite chromium steels [11, 12], Foldyna *et al.* used a two region split when implementing the Larson-Miller creep lifing model [13]. The breakpoint between the high and low stress regimes was determined to be approximately consistent with the critical or Orowan stress for the materials. It was proposed that the high stress dislocations overcame the secondary particles by the Orowan mechanism whilst the low stress region experienced dislocation climb.

In looking at these early cases we can identify two of the most fundamental issues surrounding region splitting as a technique. The first issue surrounds the use of region splitting to improve model predictions and whether it is being implemented to model creep mechanism change, or, whether it is being used simple to improve model predictions. The second issue is the attributing of the region splitting point to mechanisms without further microstructural evidence.

In the first case, work by Gilbert *et al.*[10] proposes that the numerous regions are linked to interaction of dislocations with oxygen impurities, dislocation intersection, dislocation interaction with precipitates, combined impurity atoms/clusters, grain boundary diffusional creep, and non-conservative jog motion in screw dislocations [10]. Although having some physical basis, Gilbert *et al.* acknowledge that these are not the only possible explanations [10]. Looking more closely at the activation energies of the regions, it raises the question as

to whether a change in mechanism has been observed or it is a result of data scatter/model failure. In this case it is easy to see that region splitting could be implemented as a means to improve the results of a creep model rather than as a means to accommodate and reflect a change in creep mechanism. This is the most fundamental issue surrounding region splitting as this technique is supposed to represent the underlying physical process of creep rather than being a model improvement technique.

In creep life modelling, the underlying physical process is often concluded from fitting relationships to data where certain values of constants or parameters are interpreted as signs that a specific physical process or creep mechanism is occurring. In the second case of Foldyna *et al.*, the breakpoint in activation energy roughly coincides with the Orowan stress [13]. This is hypothesised by the authors to mean that the physical mechanism change is linked to the Orowan mechanism. The fact that authors of the paper acknowledge this as a hypothesis due to insufficient evidence, highlights the need for region splitting to be implemented carefully and the conclusions drawn from implementation supported by further evidence as the breakpoint may be coincidental rather than conclusive in indicating the underlying mechanism of creep.

3. Current use of Region Splitting

In more recent times region splitting has been used more routinely in creep lifing research. This section explores the work of three leading research groups. How region splitting is conducted by these three groups will highlight further issues with region splitting as a technique whilst also identifying how a single technique can be implemented in many different ways to produce different outcomes.

Arguably, the most famous users of region splitting are Kimura, Kushima, Sawada *et al.* who have a number of works that implement high-low stress region splitting for a range of steels [14-20]. Kimura *et al.* implement the Larson-Miller approach to modelling creep life:

$$P_{LM} = f(\sigma) = T\left(C_{LM} + log\left(t_f\right)\right)$$

where P_{LM} is the Larson-Miller parameter which is a function of stress, σ. T is temperature, and t_f the time to failure. C_{LM} is the Larson-Miller constant whose value is often linked to certain creep mechanisms. To conduct region splitting Kimura *et al.* initially consider the constant temperature data on a double log plot i.e. log(σ) vs. log(t_f) at constant T. If region

splitting is observed, then this data will have multiple linear regions as seen in Ref. [19]. Kimura *et al.* observed for steels two distinct regions separated at the 'half yield' point. This is at half 0.2% temperature dependant proof stress which is proposed to coincide with the elastic limit of the material. In each of these regions P_{LM} and C_{LM} are defined, meaning above and below 'half yield' effectively have different creep models. This approach has evolved from application of a number of creep lifing models to experimental data covering a range of steels [14-21]. Although this approach has been indisputably effective at better predicting creep life, it is similar to Foldyna *et al.* [13] in that region splitting is implemented for model improvement and attributed to a known material property without rigorous microstructural investigation into whether the underlying creep mechanism has changed.

Another group implementing region splitting is Tohoku University in collaboration with industry partners, referred to here simply as Tohoku *et al.* [22-29]. Working with steels Tohoku *et al.* predict creep life using the Orr-Sherby-Dorn based relationship [27]:

$$t_f = t_o \sigma^{-n} exp\left(\frac{Q_c}{RT}\right)$$

where t_0 is a material property, n is the stress exponent, and R is the universal gas constant. To determine if region splitting is occurring, Tohoku *et al.* also consider the plot $\log(\sigma)$ vs. $\log(t_f)$ at constant T for multiple linear trends. If this is observed then they implement a region splitting model [27]:

$$t_{fH} = t_{0H}(\sigma) exp\left(\frac{Q_H}{RT}\right)$$

$$and \quad t_{fL} = t_{0L}(\sigma) exp\left(\frac{Q_L}{RT}\right)$$

where H and L are used to indicate the high and low stress regimes. The function $t_0(\sigma)$ is defined within these regions. The break between regimes is defined by the need to change the activation energy and is found by regression analysis of defined creep lifing curves. This means that the breakpoint is not standardised but in fact reactionary to each case. Although it makes this approach harder to apply across multiple conditions, Tohoku *et al.* often conduct substantial microstructural investigations to substantiate that the region splitting they observed is linked to a change in creep mechanism [22-29].

The third major research group using region splitting is Swansea University whom implement the creep model known as the Wilshire Equations [30]. The Wilshire Equation for failure time is given by:

$$ln\left(\frac{\sigma}{\sigma_N}\right) = -k_u\left[t_f exp\left(\frac{Q_c^*}{RT}\right)\right]^u$$

where k_u and u are fitted constants, and σ_N is the temperature dependant yield strength, proof stress, or ultimate tensile stress. This requires more testing as material properties such as those listed in sources like NIMS [31] are no longer used, but are instead obtained as close to the actual sample tested as possible preferably from the same batch of material. Q_c^* is the normalised activation energy obtained from a linear fit of ln(t_f) vs 1/T for a constant normalised stress, σ/σ_N. For a simple two region split, the gradient or Q_c^* will be constant over a range of σ/σ_N then suddenly jump to a different value. This method like Kimura *et al.*, provides a standardised breakpoint for region splitting but does so from data trends rather than from material properties [32].

Looking at how these three major research groups implement region splitting, we can see the already highlighted issues at play. The first issue highlighted in this paper is the use of region splitting as means to model a change in creep mechanism. The method of Kimura *et al.* is to impose a breakpoint using known material properties, Wilshire *et al.* impose a breakpoint according to data trends. Tohoku *et al.* on the other hand rigorously supplies microstructural evidence for the existence of multiple regions. The second issue of attributing creep mechanism from modelling rather than from microstructure is also evident. This is done by Kimura *et al.* through the knowledge of material properties and values of C_{LM}. For Wilshire *et al.*, and to a far lesser extent Tohoku *et al.*, mechanism is inferred through the values of Q_c^* or Q_c. Although Kimura *et al.* and Wilshire *et al.* are particularly vulnerable to these two issues they have one distinct advantage over Tohoku *et al*.

When implementing a creep model for a number of materials over a range of conditions, the ability to define where region splitting will occur is highly desirable. The need to predict and extrapolate creep properties over a range of temperatures and conditions confidently stems from the time and resource intensive nature of experimentally measuring creep. The standardised breakpoint therefore is highly desirable and can produce substantially better results like that of Kimura *et al.* in Ref. [19]. This definition of the breakpoint gives Kimura *et al.* and Wilshire *et al.* a strong advantage when large scale region splitting is considered. It should be noted, the choice of approach impacts how effective a standardised breakpoint will be, for example half yield is arguably suitable for steel yet would not be applicable to materials with lower rates of strain hardening, e.g. titanium alloys.

Already having introduced three distinct approaches to region splitting, closer examination of work done by Tohoku *et al.* and Wilshire *et al.* add another issue. For both Tohoku *et al.* and Wilshire *et al.*, there are two types of splitting, one with change of activation energy and constants, and another with just a change in constants. In the work done by Tohoku *et al.* the general approach to region splitting is linked to a change in activation energy Q_c. In some of their work [24] these regimes were split further, but not using the same method. Tohoku *et al.* [24] used the Orr-Sherby-Dorn method splitting their data into high and low stress regimes as already described. Within the high stress regime it was then modelled using two Orr-Sherby-Dorn functions with the same activation energy but different constants. This is similar to Wilshire *et al.* where in one case region splitting produced two activation energies and sets of constants [32], and in another case a single activation energy is used but the constants change at a specific value of σ/σ_N [30]. The definition of region splitting is understood to be the adjustment of a model as reflection of a change in creep mechanism, and as such the approaches of Tohoku *et al.* and Wilshire *et al.* reflect changing mechanism through a change in activation energy. The approach of changing just the model constants therefore does not fit the definition of region splitting and in this case is termed sub-region splitting. Sub-region splitting by Tohoku *et al.* [24] and Wilshire *et al.* [30] has not been evidentially substantiated [24, 30], thus the possible ramification is that sub-region splitting improves model prediction by reducing the models domain rather than by more accurately representing the underlying physical process.

Having described a number of issues surrounding the use of region splitting, and a range of approaches to implementing region splitting, we now present three case studies for further illustration. Much of the following is based on data obtained from the National Institute of Materials (NIMS) [31] and as such their contribution is recognised and appreciated.

3.1 Grade 91 & 122 Steel: Kimura et al. [18] vs Tohoku et al. [28]

Both Kimura *et al.* and Tohoku *et al.* have conducted a large amount of research into creep lifing of steels. Two materials both Kimura *et al.* and Tohoku *et al.* have analysed are Grade 91 and Grade 122 Steel. By conducting region splitting both Kimura *et al.* and Tohoku *et al.* were able to achieve more accurate creep life predictions. Looking firstly at Kimura *et al.s* work [18], the use of half yield as a standardised approach to region splitting is shown in Figure 2. The fits obtained by Kimura *et al.* are reasonably good for the data with the

exception of Grade 91 600 & 650°C below half yield strength, and for Grade 122 below half yield strength for 600°C. The change from a high-stress to a low-stress regime is stated to be linked with the half yield strength being the macroscopic elastic limit where deformation shifts to the plastic regime for the polycrystalline material [18].

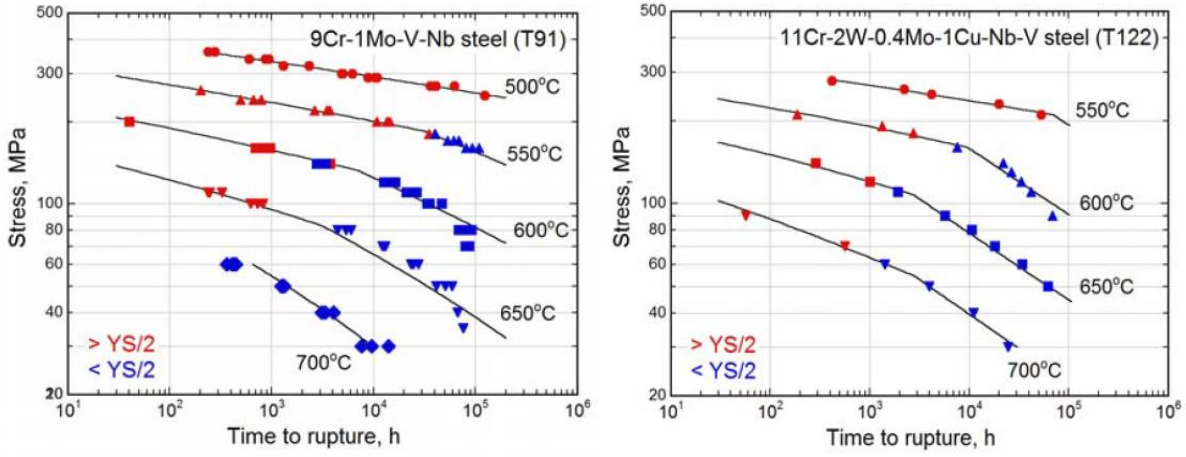

Figure 2. Region Splitting at Half Yield Strength by Kimura *et al.* for Grade 91 and Grade 122 Steel. Reproduced from [18]

Unlike Kimura *et al.*, Tohoku *et al.* [28] provide no standardised means of region splitting but rather use regression analysis to fit a model of different constants and activation energies. This is a substantially less uniform means of conducting region splitting as evidenced in Figure 3. Tohoku *et al.* examined the microstructure to determine the mechanism change and from transmission electron microscopy, the onset of static recovery of the lath martensitic structure was attributed to the change from high-stress to low-stress creep regimes [28]. Having two approaches to the same data shows how they can produce similar curves with similar breakpoints from different models. The more standardised approach of Kimura *et al.* is easier to implement across many datasets, yet the approach by Tohoku *et al.* is more rigorously supported by microstructural evidence.

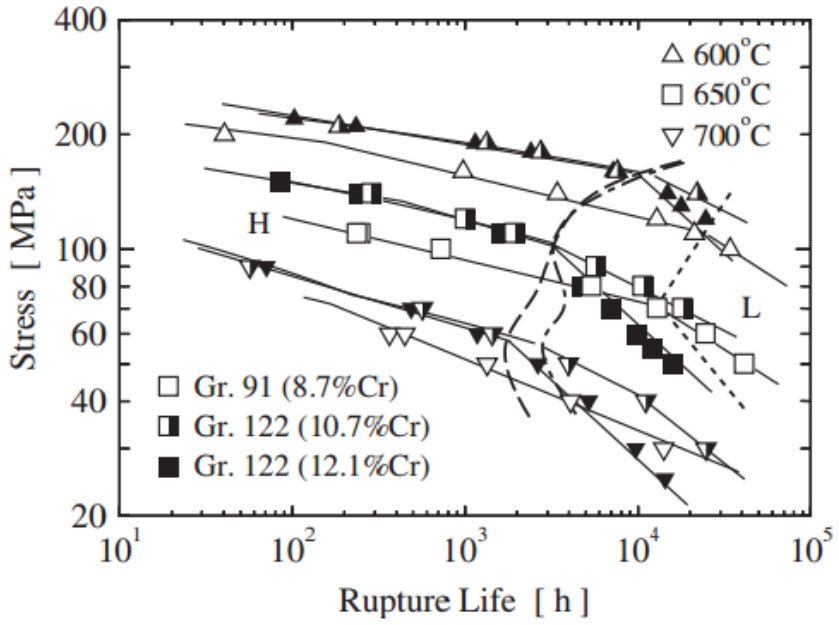

Figure 3. Region Splitting by Tohoku *et al.* for Grade 91 and Grade 122 Steel. Reproduced from [28]

3.2 316 & 316H Stainless Steel: Tohoku et al. [23, 34] vs Wilshire et al. [32]

Having the same proof stress, 316 and 316H stainless steel are very similar materials with similar creep life as shown in Figure 4. In looking at these two materials, Tohoku *et al.* split the creep data into four regions denoted by H, M, L, and L' [22, 34]. Having sufficient sampling for H, M, and L, the activation energies were found to be 465kJ/mol, 400kJ/mol and 299kJ/mol with the high stress exponents suggesting transgranular and/or intergranular fracture caused by deformation controlled growth of grain boundary cavities [34]. Taking a different approach using normalised activation energy, Wilshire *et al.* considered only a two region shown in Figure 4. For $\sigma>\sigma_{PS}$ denoted by H, activation energy was found to be 250kJ/mol, and, for $\sigma<\sigma_{PS}$ denoted by L, activation energy was found to be 150kJ/mol. These values align with lattice self diffusion, dislocations and plastic deformation for $\sigma>\sigma_{PS}$, and for $\sigma<\sigma_{PS}$ the activation energy is proposed to be linked to localised dislocation activity in the grain boundary zone. This demonstrates the issue with deducting creep mechanism from model constants as the proposed underlying creep process may be a result of the model rather than reality. Without microstructural evidence, the creep mechanism is unconfirmed and thus which model is more accurate cannot be determined.

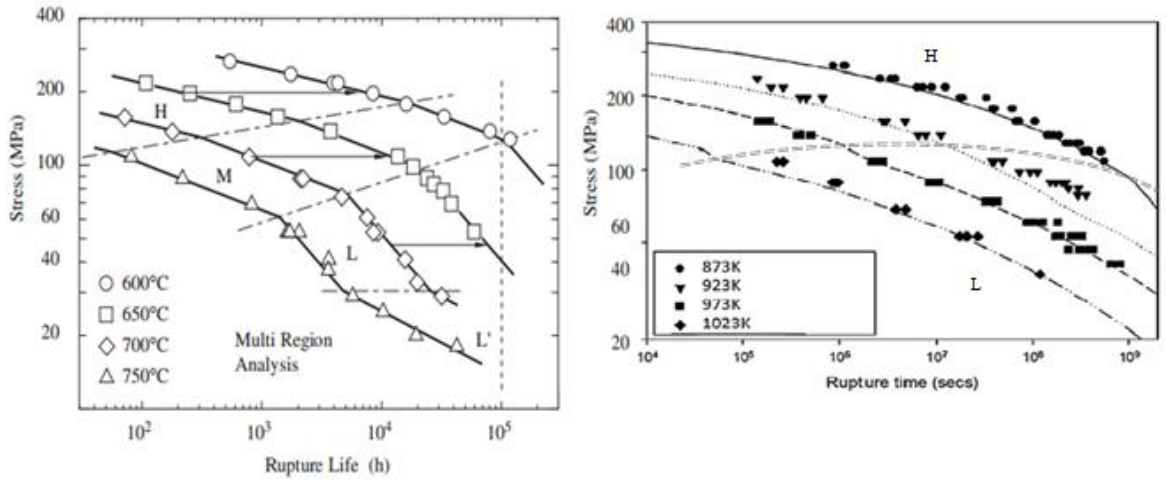

Figure 4. Region splitting by Tohoku *et al.* for 316 Stainless Steel (left), and, Wilshire *et al.* for 316H Stainless Steel (right). Reproduced from [23] and [32].

3.3 1Cr-1Mo-0.25V Rotor Steel: Wilshire et al. [33] vs. Kimura et al. [15]

Analysis conducted by Evans [33] (Wilshire *et al.*) of NIMS data for 1Cr-1Mo-0.25V Rotor Steel was based done so using sub-region splitting. In [33], having constant an activation energy of 284kJ/mol, an inflection point at $0.8\sigma_{PS}$ was observed where the constants used to model creep life and minimum strain rate changed. Kimura *et al.* [15], on the other hand, implement a half yield region split which is also shown in Figure 5. Kimura *et al.* justify their use of region splitting at half yield through observed recovery of the martensite microstructure at low stress contrasting the homogenous structure observed in high stress specimens. Wilshire *et al.* provide no microstructural evidence of a change in creep mechanism. The important aspect of this case study is the complexity of comparing region splitting approaches. Sub-region splitting vs conventional region splitting adds a further complication in a field where as evidenced by the first two case studies, the models and how they are implemented can define where region splitting occurs and what mechanism is understood to drive it.

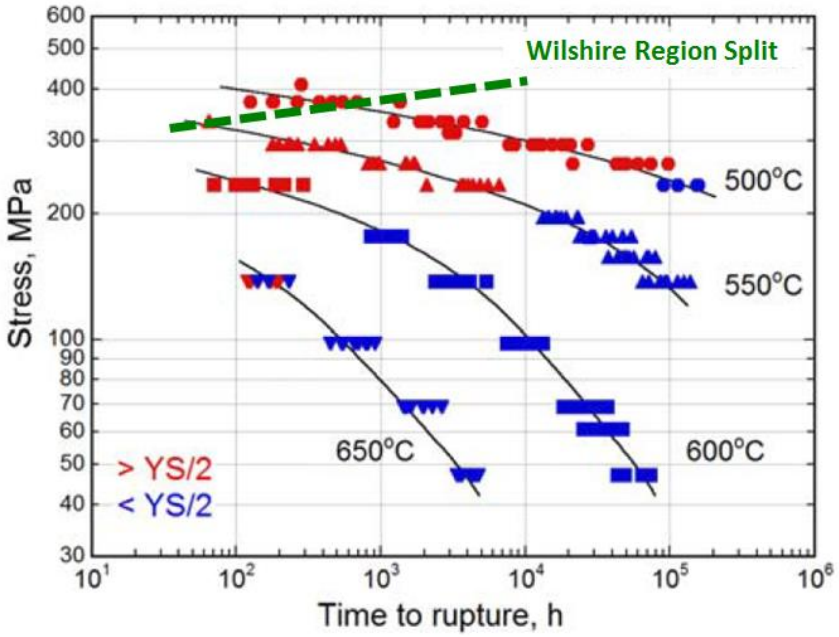

Figure 5. Region splitting by Kimura *et al.* [15] and, Wilshire *et al.* [33] for 1Cr-1Mo-0.25V Rotor Steel. Reproduced from [15].

Considering the case studies presented, the issues surrounding region splitting can be seen clearly through the contrast in analysis of similar or the same datasets conducted by different research groups using different methods. Common to all three case studies is the need for microstructural evidence to support region splitting as a practice. The first case study provides an insight into the usefulness of a standardised approach to region splitting as adopted by Kimura *et al*. It also highlights the possible inaccuracies of taking such an approach through the work by Tohoku *et al*. The second case study raises questions as to the number and nature of regions. The ability for Wilshire *et al*. and Tohoku *et al*. to split similar creep data into either 2 or 4 regions highlights the subjective and model dependant nature of region splitting as a practice in its current implementation. Also, this case study highlights how examining the activation energies for creep mechanism can result in differing answers dependant on the approach taken to data analysis. The third case study once again raises the inherent issue of where and how to region split but also demonstrates the use and ambiguity of sub-region splitting (model failure or mechanism change).

4. Region Splitting and Nano-Creep

Region splitting, even with its complex nature provides, a new avenue for analysing creep data. In the initial investigation by Kvapilova *et al.* [35] ultrafine nanocrystalline nickel was

analysed using the power law and Coble creep exponent, where the traditional activation energy and hence creep mechanism was indeterminate due to power law breakdown. Applying traditional region splitting did not provide any further solution, so in collaboration with Swansea University the data was reanalysed using the Wilshire Equations.

From analysis using normalised activation energy, the possibility of two creep mechanisms became apparent. In Figure 6 region splitting is used to model the minimum strain rate. Looking at the data obtained at 473K, it can be seen that the high stress model suitable for 273 and 373K no longer fits well. The low stress model on the other hand fits both the 473 and 523K data well. In proposing region splitting the activation energies were found to be 99kK/mol indicative of grain boundary self-diffusion for the high stress regime [36]. For the low stress regime the activation energy was found to be 59kJ/mol which is close to that for grain growth [37]. Grain growth was observed by TEM for 473K but not 373K supporting the concept two different creep mechanisms may be enacted over this dataset [36].

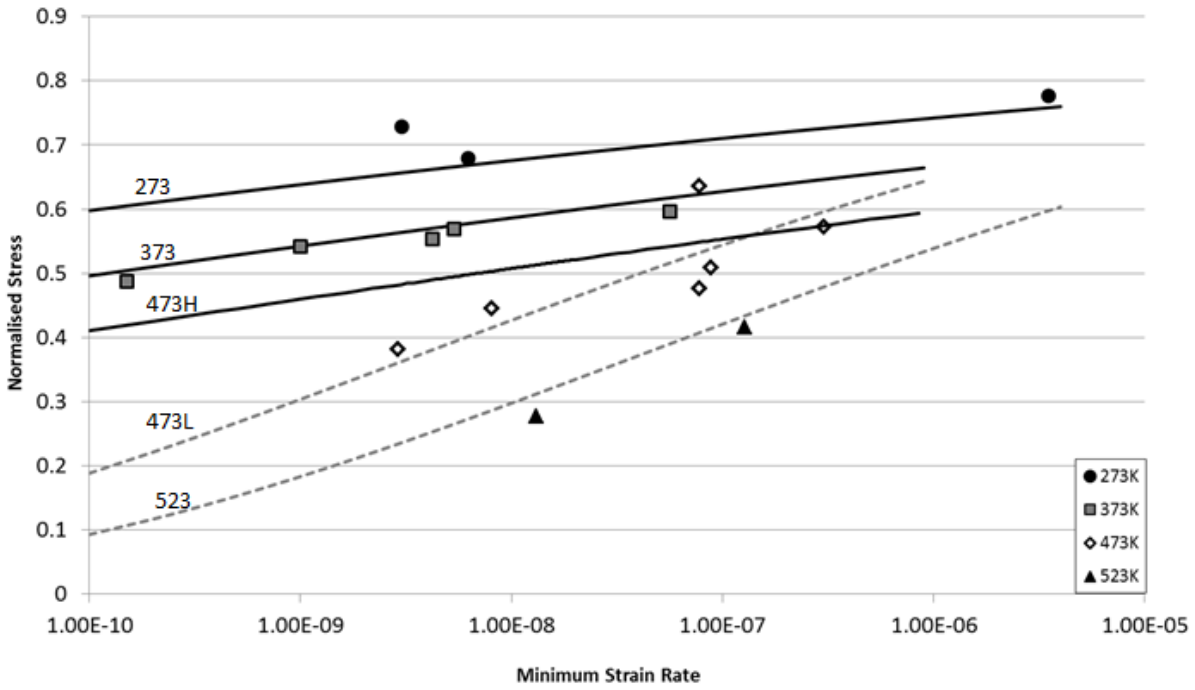

Figure 6. Wilshire modelling of nano-creep of Nickel using region splitting.

The purpose of this example is to demonstrate the potential of region splitting as a technique. By applying region splitting to nano-creep we demonstrate its application beyond traditional stress/temperature regimes, traditional materials and even traditional testing methods. The analysis conducted in this example is only indicative, yet provides insight into where region

splitting may be applied in the future and as such why it is important to consider the issues surrounding it as a technique.

5. Automation and Application

Any advancement in creep lifing needs to be considered on an industrial scale. In identifying a number of issues with implementing region and sub-region splitting, these need to be considered beyond the immediate research ramifications.

The first issue highlighted in this article is the use of region splitting without sufficient microstructural evidence of a change in dominant creep mechanism. When considering the implementation of region splitting for industrial purposes the need to define a minimum 'burden of proof' needs to be established i.e. what is the minimum threshold level of evidence required to justify implementing region splitting. This is essential if we wish to avoid using region splitting as another refined variable in creep life models.

A similar approach needs to be taken for the second issue of deducing creep mechanism. In justifying the use of a change in activation energy, the activation energies used and the consequences of the active mechanism need to be understood for design purposes. This also applies to sub-region splitting via changes in model constants as the use of this, coupled with activation energy region splitting, may provide more detailed results but their meaning has significant ramifications for design.

On an industrial scale the third issue of predicting the breakpoint is crucial. Without long term data characterising the breakpoint for a specific material, nor sufficient knowledge of generic breakpoint behaviour, prediction of the breakpoint is unreliable. Work needs to be done to define the breakpoint in the specific material but also generally across all materials. The transition from one activation energy to another also needs to be considered in finer detail as mechanism transition is dependant on the material and the 'zone of stability' of the activation energy need to be established. It can also be noted that since breakpoints in longer life creep tests are generally a product of microstructural aging and/or oxidation behaviour, higher temperature testing to accelerate these effects can often be beneficial in determining a breakpoint.

The final issue of sub-region splitting for industrial application raises the most influential issue with creep lifing. Creep is difficult to predict because of the need to run tests for model and property verification over very long periods of time. The difficulty with region and sub-region splitting is that once a set of data is divided, then the number of tests to verify results increases as a minimum sample size needs to be acheived. By having a single region or minimal number of regions, fewer data points are needed to satisfy the statistical threshold. This trade-off between accuracy and cost of tests in both time and money highlights the most likely limiting factor for region splitting becoming an industrywide practice.

6. Conclusion

When looking at the future of creep life modelling, it is clear that sophisticated approaches are being developed in order to more accurately predict behaviour of materials over a variety of conditions. Region splitting is becoming more widely used by researchers when modelling creep as it is a way of representing the physical reality of changing dominant creep mechanism at certain conditions. Reviewing the history of region splitting, it has been implemented in a number of different ways tracing back to the 1960s. Over the last 20 years the use of region splitting has become more commonplace but is often tied to a specific material and not discussed as technique in itself.

Examining region splitting as a creep life modelling technique, this paper identifies a number of issues surrounding the use of region splitting. As with all models, the smaller the domain modelled, the more accurately it can be described, and as such region splitting has the ability to produce better results by simply reducing the domain of data. This raises the most significant issue of region splitting which is the need for microstructural observation to support the use of this analysis technique. This can be seen in practical terms through the case studies presented where similar or the same data is analysed using region splitting to produce a range of results. From the first case study the use of a standardised approach to region splitting adopted by Kimura *et al.* shows significant advantages as an approach, but also possible disadvantages and inaccuracies as highlighted by Tohoku *et al*. The second case study raises the issue of identifying creep mechanisms and the resultant number of regions that should be used in analysis, as well as, the difference in approach to region splitting resulting and the different values of activation energy being obtained. The third case study highlights the use of sub-region splitting identifying it as separate technique that currently lacks microstructural evidence to support its use.

When considering the future of region splitting, it has the ability to be a significantly powerful technique in both research and industry. In this paper region splitting was used for the first time to analyse nano-creep. As such, it provided a different perspective on the underlying creep mechanisms which was not obtained from traditional analysis. As this technique becomes more broadly used it is likely to yield new insights into the behaviour of materials and also our methods of modelling material behaviour. Considering region splitting beyond the research arena, its application by industry also raises issues that need further consideration. The need for microstructural evidence to implement region splitting is essential, and therefore a threshold of evidence needs to be considered if region splitting is to be widely and commercially employed. The prediction of break points or region splits also needs to be standardised as well as the technique used i.e. region splitting or sub-region splitting. In looking at this technique, its power to predict creep life more accurately needs to weighed carefully against the risks of employing a not yet consistent or standardized approach, but the possibilities it offers to better predict the complex process of creep should not be underrated.

References

[1] “Power Plant Life Management and Performance Improvement”, Edited by J. E. Oakley, *Woodhead Publishing*, 2011.

[2] T. A. Cruse, S. Mahadevan and R. G. Tryon, “Fatigue Reliability of Gas Turbine Engine Structures”, *NASA/CR-97-206215*, 1997.

[3] Z. Abdallah, V. Gray, M. Whittaker and K. Perkins, “A Critical Analysis of the Conventionally Employed Creep Lifing Methods”, *Materials*, 2014, **7**, pp. 3371-3398.

[4] S. R. Holdsworth, “Constitutive equations for creep curves and predicting service life”, “*Creep-resistant steels” Edited by F. Abe, T-U. Kern, R. Viswanathan*, Woodhead Publishing in Materials, 2008.

[5] T. Frolov, Y. Mishin, “Molecular dynamics modelling of self-diffusion along a triple junction”, *Physics Review B*, 2009, **79**, 174110.

[6] H. Zhang, M. I. Mendelev, D. J. Srolovitz, “Computer Simulation of the elastically driven migration of a flat grain boundary”, *Acta Materialia*, 2004, **52**, 2569-2576.

[7] V. Foldyna, Z. Kubon, A. Jakobova and V. Vodarek, “Development of Advanced High Chromium Ferritic Steels”, *Microstructural Development and Stability in High Chromium Ferritic Power Plant Steels*, The Institute of Materials, 1997, pp. 73-92.

[8] I. M. Bernstein, “Diffusion Creep in Zr and Certain Zr Alloys”, *Transactions, American Institute of Mining, Metallurgical, and Petroleum Engineers*, 1967, **239**, pp. 1518.

[9] J. J. Holmes, “Activation Energies for Creep of Zircaloy-2”, *Journal of Nuclear Materials*, 1964, **13**, pp. 137.

[10] E. R. Gilbert, S. A. Duran, A. L. Bement, “Creep of Zirconium from 50 to 850°C”, *ASTM International*, STP43829S, January 1969.

[11] V. Foldyna, “Creep of low alloy and modified chromium steels” (Czech), *Technicke actuality VITKOVIC*, No. 1, 1988.

[12] V. Foldyna, A. Jakobova, V. Kupka, *Proceedings VIIIth International Symposium on Creep Resistant Metallic Materials*, September 1991, Ziln, Czechoslovakia, 186.

[13] V. Foldyna, A. Jakobova, V. Kupka, *Proceedings for Conference: Creep Fracture of Engineering Materials and Structures*, Editors: B. Wilshire & M. Evans, The Institute of Metals, London, UK, April 1993.

[14] K. Kimura, H. Kushima, F. Abe, “Degradation and Assessment of Long-Term Creep Strength of High Cr Ferritic Creep Resistant Steels”, *International Conference on Advances in Life Assessment and Optimization of Fossil Power Plants*, 2002.

[15] K. Kimura, H. Kushima, K. Sawada, "Long-Term Creep Strength Prediction of High Cr Ferritic Creep resistant Steels Based on Degradation Mechanisms", *Proceedings of the 6th International Charles Parsons Turbine Conference,* 2003, pp. 443.

[16] K. Kimura, K. Sawada, H. Kushima, Y. Toda, "Stress dependence of degradation and creep rupture life of creep strength enhanced ferritic steels", *5th International Conference on Advances in Materials Technology for Fossil Power Plants,* 2007.

[17] K. Kimura, K. Sawada, H. Kushima, "Strain rate dependence of yield strength and long-term creep strength evaluation of ASME Grade 91 steel", *Proceedings PVP2009: 2009 ASME Pressure Vessels and Piping Division Conference,* 2009.

[18] K. Kimura, K. Sawada, H. Kushima, "Creep Rupture Ductility of Creep Strength Enhanced Ferritic Steels", *Journal of Pressure Vessel Technology,* 2012, **134.**

[19] K. Kimura, "Creep Rupture Strength Evaluation with Region Splitting by Half Yield", *Proceedings of the ASME 2013 Pressure Vessels & Piping Division Conference*, 2013.

[20] K. Kimura, K. Sawada, H. Kushima, K. Kubo, "Effect of stress on the creep deformation of ASME Grade P92/T92 steels", *International Journal of Materials Research,* 2008, **99** (4) pp. 395-401.

[21] K. Kimura, O. Kanemaru, K. Sawada, H. Kushima, "Creep deformation and rupture strength property of ASME T/P92 steels", *Proceedings 38th MPA Seminar*, 2012.

[22] J. S. Lee, H. Ghassemi Armaki, K. Maruyama, T. Muraki, H. Asahi, "Causes of breakdown if creep strength in 9Cr-1.8W-0.5Mo-VNb steel", *Materials Science and Engineering: A,* 2006, **428** (1-2), pp. 270-275.

[23] K. Maruyama, H. Ghassemi Armaki, K. Yoshimi, "Multiregion analysis of creep rupture data of 316 stainless steel", *International Journal of Pressure Vessels and Piping*, 2007, **84** (3), pp. 717-176.

[24] H. Ghassemi Armaki, K. Maruyama, M. Yoshizawa, M. Igarashi, "Prevention of the overestimation of long-term creep rupture life by multiregion analysis on strength enhanced high Cr ferritic steels", *Materials Science and Engieering: A,* 2008, **490** (1-2) pp. 66-71.

[25] M. Yoshizawa, M. Igarashi, K. Moriguchi, A. Iseda, H. Ghassemi Armaki, K. Maruyama, "Effect of precipitates on long-term creep deformation properties of P92 and P122 type advanced ferritic steels for USC power plants", *Materials Science and Engineering: A*; 11th International Conference of Creep and Fracture of Engineering Materials and Structures, CREEP2008, 2009, **510-511**, pp. 162-168.

[26] H. Ghassemi Armaki, R. P. Chen, K. Maruyama, M. Yoshizawa, M. Igarashi, “Static recovery of tempered lath martensite microstructures during long-term aging in 9-12% Cr heat resistant steels”, *Materials Letters*, 2009, **63** (28), pp. 2423-2425.

[27] H. Ghassemi Armaki, R. P. Chen, K. Maruyama, M. Igrashi, “Premature creep failure in strength enhanced high Cr ferritic steels caused by static recovery of tempered martensite lath structures”, *Materials Science and Engineering: A*, 2010, **527** (24-25), pp. 6581-6588.

[28] K. Maruyama, H. Ghassemi Armaki, R. P. Chen, K. Yoshimi, M. Yoshizawa, M. Igarashi, “Cr concentration dependence of overestimation of long term creep life in strength enhanced high Cr ferritic steels”, *International Journal of Pressure Vessels and Piping; ECCC Second International Creep Conference* , 2010, **87** (6), pp. 276-281

[29] R. P. Chen, H. Ghassemi Armaki, K. Maruyama, M. Igarashi, “Long-term microstructural degradation and creep strength in Gr.91 steel”, *Materials Science and Engineering: A*, 2011, **528** (13-14), pp. 4390-4394.

[30] B. Wilshire, A. J. Battenbough, “Creep and creep fracture of polycrystalline copper”, *Materials Science and Engineering A*, 2007, **443**, pp. 156-166.

[31] National Institute for Materials Science (NIMS), Tsukuba, Japan.

[32] M. T. Whittaker, M. Evans, B. Wilshire, “Long-term creep data prediction for type 316H stainless steel”, *Materials Science and Engineering A*, 2012, **552**, 145-150.

[33] M. Evans, “The importance of creep strain in linking together the Wilshire equations for minimum creep rates and times to various strains (including the rupture strain): an illustration using 1CrMoV rotor steel”, *Journal of Materials Science*, 2014, **49**, 329-339.

[34] F. Abe, T-U. Kern, R. Viswanathan, “Creep-resistant steels”, ISBN 978-1-84569-178-3, 2008.

[35] M. Kvapilova, V. Sklenicka, K. Kucharova, G. Vidrich, M. Svoboda, “Comparison of creep behaviour and microstructural changes in electrodeposited ultrafine-grained nickel and its particle-reinforced nanocomposite”, *NANOCON 2012*, 2012.

[36] N. Wang, Z. Wang, K. T. K. Aust, U. Erb, “Room temperature creep behaviour of nanocrystalline nickel produced by an electrodeposition technique”, *Materials Science and Engineering A.*, 1997, A**237**, 150-158.

[37] S. Bansal, “Characterization of Nanostructured Metals and Metal nanowires for Chip-to-Package Interconnections”, *Georgia Institute of Technology: PhD Thesis*, December 2006