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Auerkari, Pertti; Rantala, Juhani; Pohja, Rami; Yli-Olli, Sanni; Pohjanne, Pekka

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Residual life assessment supported by testing of ex-service material

Auerkari P, Rantala J H, Pohja R, Yli-Olli S, Pohjanne P

VTT Technical Research Centre of Finland Ltd
Espoo, Finland

Abstract

Creep testing of engineering materials can provide the experimental basis for both design and later ex-service residual life assessment (RLA) of structures limited by creep for their mechanical performance and life. As the assessment will necessarily involve time-consuming testing, it is of interest to make most of it by reasonably justified methods and criteria. This paper aims to discuss these in terms of the somewhat conflicting needs of predictive accuracy (uncertainty) and available time to decisions. With examples, the opportunities and limitations are considered through the experience on accelerated testing and from larger scale creep data assessments to describe the material-specific creep and rupture behaviour to support design. In the course of recent decades, the effort in Europe and elsewhere in the world set a solid foundation for such descriptions that can equally deal with new and established material grades, as well as with materials that need to be assessed after having suffered in-service degradation.

1. Introduction

At high temperatures well below melting point, common solids such as rocks and metals will flow to the direction of imposed stress, i.e. behave like viscous liquids. This flow, or creep, happens at a rate that depends on material, stress and temperature, and must be accounted for when it limits the life of the metallic containment of process fluids such as hot steam of hydrocarbons. However, creeping structural materials differ from common everyday liquids by what happens in the end: normal liquids can continue flowing but creeping solids can fail by fracture or rupture after reaching their maximum strain, or creep ductility.

To establish the creep performance for design has required testing programs and use the results to describe the acceptable levels of design stress for given operating conditions. For example for common steels of pressure equipment, the acceptable levels appear in appropriate codes or standards.

In addition, exposure to the thermal and chemical in-service environment can degrade materials, with corresponding reduction in the creep life (Figure 1). To indicate the performance for residual life assessment or RLA [1] may require retesting, but doing it as for design purposes would take too long time. Some faster methods such as accelerated testing must then suffice to support the subsequent planning and actions.

2. Principles of accelerated creep testing for life prediction

To minimise the potential errors associated with accelerated creep testing, it is useful to follow a few principles. First, to quantify the essential features of the material-specific stress and temperature dependence of creep life, comparisons of fitted parametric and algebraic model expressions [2,3] may help in selecting one for describing the test data. Most of the expressions originate from models for the minimum creep strain rate, with temperature dependence including at least an Arrhenius-type activation energy term. Stress dependence is theoretically more challenging, and often numerically tackled by polynomial fitting [2,3].

A flexible parametric expression for uniaxial creep rupture at stress σ, temperature T and time to rupture t_r is the Mendelson-Roberts-Manson model [2-6]:

$$P(\sigma) = [\log(t_r) + C]/(T-T_o)^r \tag{1}$$

Here P(σ) is a fitted polynomial of log(σ), and C, T_o and r fitting constants. Common simplifications include the Larson-Miller (LM: $T_o = 0$, $r = -1$) and Manson-Haferd expressions (MH: $T_o = 0$, $r = 1$):

$$\text{LM : } P(\sigma) = T\cdot[\log(t_r) + C] \tag{2}$$

$$\text{MH: } P(\sigma) = [\log(t_r) + C] / T \tag{3}$$

For accelerated testing of ex-service material, one could conduct a test series at a constant (service) temperature and a range of elevated stresses, aiming then to extrapolate the rupture time to the service stress level. For such isothermal fitting, simple LM and MH models are similar, and tend to predict overly long extrapolated time to failure. The reasons for this are similar as for the historically persistent decrease of acceptable design stress values in the materials standards. Towards longer term and increasingly sparse creep rupture data, the isothermal log(stress)-log(time) curves tend to show bending that is non-conservatively predicted even when the materials are no longer very new [4,6–8].

Alternatively, testing can take place at or close to the service stress, with acceleration by elevated temperature. This combination with MH model, i.e. extrapolating temperature to the service level on linear scale against $\log(t_r)$, is known as the isostress approach and appears to provide reasonably conservative values for the time to rupture [6].

Another indication of the generally satisfactory performance of the MH models appears in [2], showing that also for large creep data sets of many alloys, the MH models have provided optimal fits.

Figures 2 and 3 present examples of ex-service isostress test results of a cross-weld P91 pipe, and of alloy 800H tube, respectively. Both plots show faithful (log)linearity and low scatter. The expected scatter can be larger for example inside boilers and furnaces with uneven thermal loads. For all cases, it is important to try sampling the most heavily affected material, to assess the minimum life. To evaluate the performance of isostress testing results and fitting-based life assessment, for example the goodness of fit can be assessed by conventional measures such as correlation coefficient. Evaluation of the scatter in the predicted life is also possible by culling data points starting from the longest creep test.

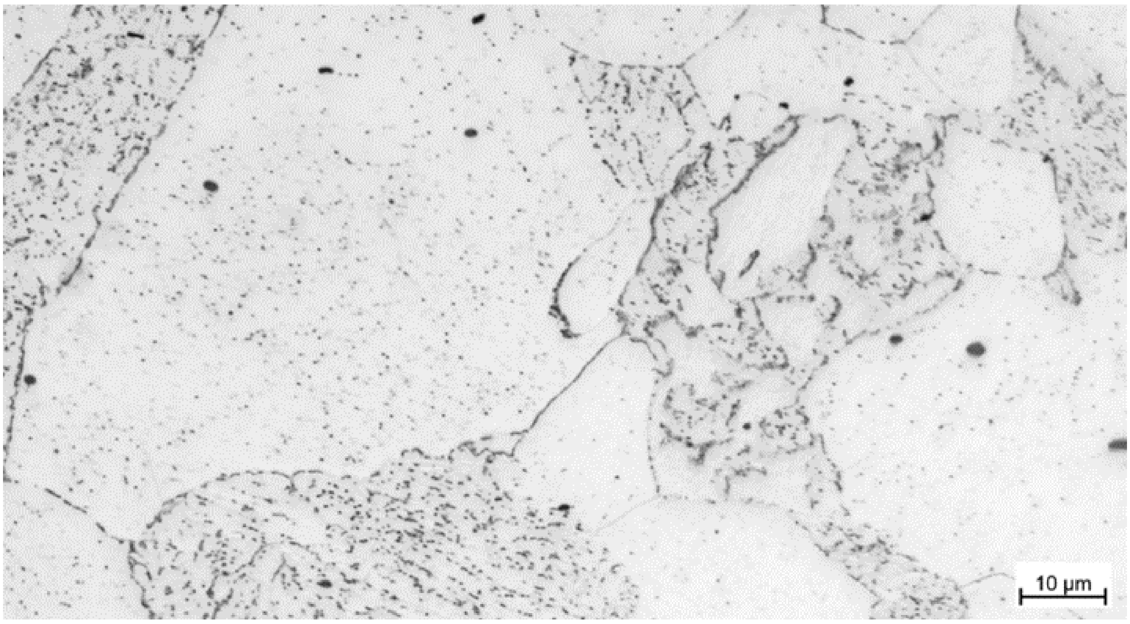

Figure 1. Appearance of ex-service tube (10CrMo9-10) with thermal changes in microstructure.

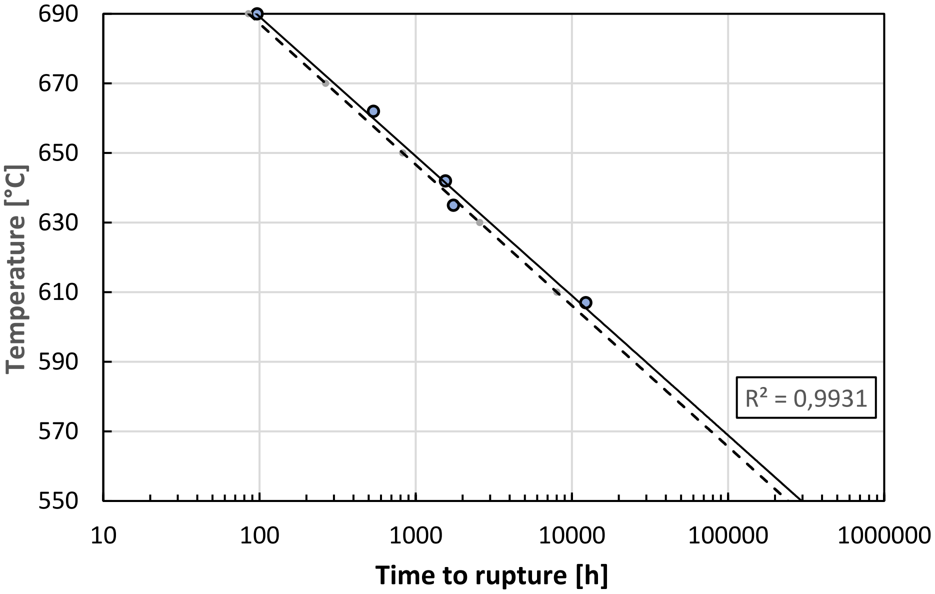

Figure 2. Isostress (69 MPa) cross-weld rupture test results of an ex-service P91 pipe (points with MH fit, solid line) in comparison to the upper range of P22 parent material scatter band (ISO data, dashed line)

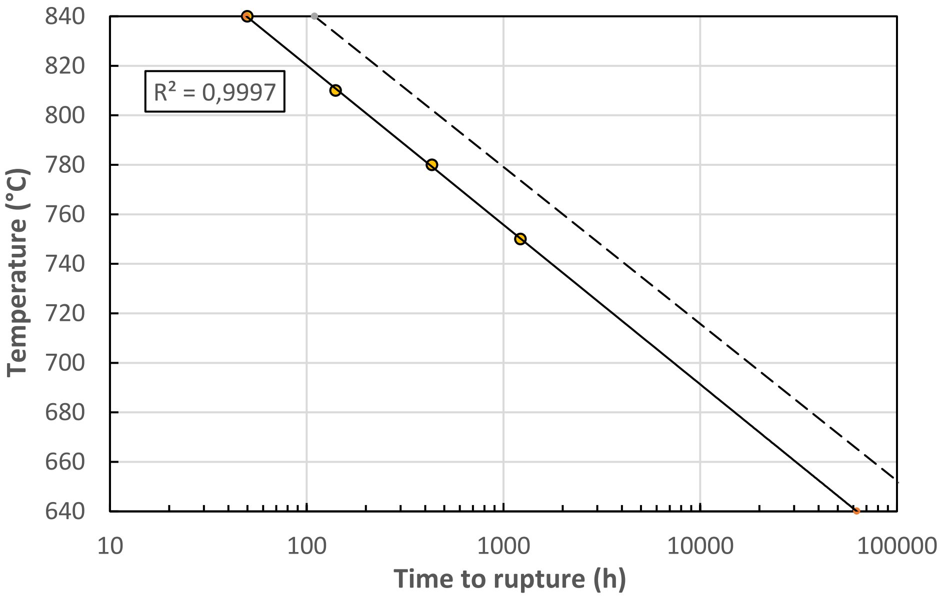

Figure 3. Isostress (65 MPa) rupture test results of ex-service Alloy 800H (points with MH fit, solid line), with comparison to as-new material mean (ECCC, dashed line)

3. Advantages and limitations of the approach

The experimental isostress approach, as described above, carries distinct advantages for creep life assessment. The approach is simple, provides quantitative values of predicted life that are in principle conservative, without being overly conservative according to the experience accumulated over many years [4,6,8].

However, as good as the general experience with isotress creep testing results may have been, there are some caveats to consider, such as the potential sources of bias, and ways to manage uncertainty. Particularly when testing the samples only at one stress level, it is important to select the test stress properly to represent the application. Also to avoid undue uncertainty, the following aspects will need some attention:

- representative sampling, for example when only a part of the sampled ex-service component has been subjected to the most severe service conditions and the effort aims to assess minimum life;
- possible defects or very inhomogeneous, brittle or otherwise problematic test material, including the impact of specimen fabrication, to avoid undue changes, gradients in properties or other obstacles to apply the approach;
- testing design, features and condition of the testing facility, calibration and other quality assurance issues affecting the results; in general, the level of care and attention should be balanced with the required predictive accuracy that the accelerated testing aims to provide.

In practice, the approach may work best in applications where the service conditions would impose thermal damage on the material, without showing much other damage indicated as discontinuities (cavities, cracks) by NDT. The benefits could be most apparent e.g. in assessing the effects of overheating or using a component well beyond the design life, or other cases where there appears to be no immediate threat to integrity but longer term life is of interest. Furthermore, the approach could be useful to establish an optimal degree of derating towards the end of life.

4. Summary

Creep testing of engineering materials can provide the experimental basis for both design and later ex-service residual life assessment (RLA) of structures limited by creep for mechanical performance and life. As the assessment will require time-consuming testing, it is of interest to make most of it by reasonably justified methods and criteria. In this paper, the approach is discussed in terms of the somewhat conflicting needs of predictive accuracy (or uncertainty) and time to decisions. The opportunities and limitations are considered with examples through the experience extending to larger scale creep data assessments for setting the material-specific standard values for design. In the course of recent decades, the practices of creep life assessment have become de facto standard descriptions to deal with both design related and ex-service assessments of the material performance. The best practices are relatively insensitive to common sources of uncertainty, and to the devaluations in the accepted creep strength values of emerging new material grades.

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