Materials Research Proceedings **5** (2018) 177-182 doi: http://dx.doi.org/10.21741/9781945291814-31

Calculation of Residual Life for P91 Material Based on Creep Rate and Time to Rupture

Przemysław OSOCHA

Cracow University of Technology, Faculty of Mechanical Engineering, al. Jana Pawła II 37, PL-31-864 Kraków, Poland

osocha@mech.pk.edu.pl

Keywords: Creep Rupture, Creep Test, Monkman-Grant, Residual Life

Abstract. The presented paper shows methods of residual life prediction based on creep test data. Real test data for P91 material will be used. Different methods will be shown. Calculations are based on the steady creep rate connection with the time to rupture.

Introduction

Creep is the non-linearity of a material at which the material continuously deforms under a constant load. Also, if a material is subjected to constant deformation, the phenomenon of relaxation will decrease with time as a result of creeping reaction forces and stresses.

Creep is a term that describes the tendency of a material to permanently move or deform to reduce existing stresses. The deformation of a material appears as a result of prolonged stresses close to the yield point or material strength point. Creep is particularly dangerous in materials subjected to high temperatures, especially those close to the material melting point temperature. The creep rate is a function of material properties, time, temperature and applied loads (forces or stresses) and deformations. Long-term operation in creep conditions may lead to deformations that result in device failure. For example, turbine blades may be lengthened so that they come into contact with the casing, causing damage.

Usually, there is no sudden crack in the creep process, but a material subjected to loads in the long term eventually fails. Creep does not occur during a sudden load, but is the effect of cumulative long-term creep distortion. Creep deformation is a time-dependent strain.

Creep dependence on temperature and stress

Increase of temperature values and/or stress values results in an increase of the creep strain and change of the shape of creep strain curves (Fig. 1). Fig. 1 shows the dependence of the change in the creep strain at a constant temperature of 600°C for different loads: 100, 120 and 140 MPa, for P91 steel.

There is a number of empirical formulas of non-linear dependence of creep strain on time. Eq. 1equation presents one of them:

$$\varepsilon = \varepsilon_0 + D\sigma^a\left(1-\exp\left(bt\right)\right)+B\sigma^n t \quad . \tag{1}$$

where B, n, D, a, b are empirical constants, while ε is the creep strain, ε_0 is the initial strain, σ is the stress and t is time.

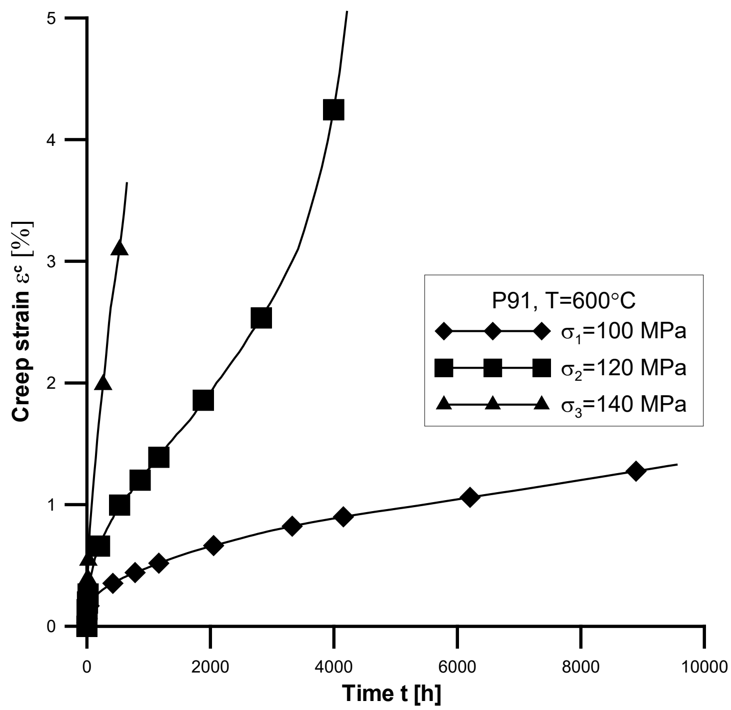

Fig. 1. Influence of temperature change on the shape of creep strain curves as a function of time for P91 steel.

If $t>t_{II}$ then Eq.1 formula takes the form of Eq. 2, where t_{II} is the time of transition from primary to secondary creep stage:

$$\varepsilon = \varepsilon_0 + D\sigma^a + B\sigma^n t \tag{2}$$

And in that case the creep rate is the minimal one, i.e. creep rate in Eq. 3 secondary creep stage:

$$\frac{d\varepsilon}{dt} = B\sigma^n = \dot{\varepsilon}_{II}^c = \dot{\varepsilon}_{\min}^c, \tag{3}$$

where $\dot{\varepsilon}_{II}^c$ is the creep rate in secondary creep stage, and it is minimal creep rate $\dot{\varepsilon}_{\min}^c$.

To take into account the influence of temperature in Eq. 3 equation, the Arrhenius model is used for Eq. 4 creep rate:

$$\dot{\varepsilon}_{\min}^c = A\sigma^n \exp\left(-\frac{Q}{RT}\right). \tag{4}$$

where n is the stress exponent, Q is the creep process activation energy, R is the universal gas constant and T is the absolute thermodynamic temperature.

In order to determine the values of constants present in Eq. 4 equation, it is necessary to perform a series of creep tests at constant temperature as well as a series of tests at constant tension.

Materials Research Proceedings **5** (2018) 177-182 doi: http://dx.doi.org/10.21741/9781945291814-31

For isothermal tests, the exponential factor assumes a constant value and Eq. 4 formula takes the form of the Norton-Bailey formula [1] Eq. 5:

$$\dot{\varepsilon}^{c}_{\min} = B\sigma^{n} \tag{5}$$

Eq. 5 equation can be linearized by logarithmising both sides of Eq. 6:

$$\log \dot{\varepsilon}^{c}_{\min} = \log B + n \log \sigma \tag{6}$$

Log-log charts of minimal creep rate $\dot{\varepsilon}^{c}_{\min}$ in dependence on stress σ are often in the form of two straight lines whose directional coefficient *n* for small stresses is of smaller value, while for higher stresses *n* is higher, which indicates the existence of different creep mechanisms for smaller and larger values of applied stress. Data for P91 steel [2] for creep tests at 600°C, 620°C and 640°C is shown in Fig. 2.

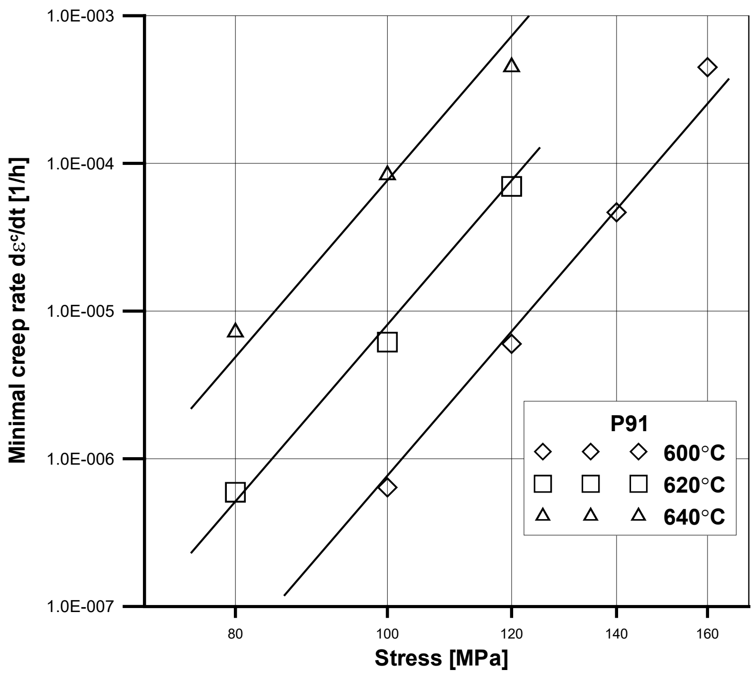

Fig. 2. The minimal creep rate as a function of stress log($\dot{\varepsilon}^{c}_{\min}$)-log(σ) for different temperatures for P91 steel.

Using the linearized Eq. 6 formula, the coefficients of Eq. 5 formula for P91 steel were chosen. The average value of exponent *n* for the analyzed range of temperatures and stresses equals 12.34. The data from creep tests describing the dependence of minimum creep rate on stress for P91 steel is shown in Fig. 2.

Methods of creep wear assessment

When designing engineering projects with creeping processes involved, the very essential task is to determine the behavior of the material over a long time period. There are three basic methods to solve the problem:

Materials Research Proceedings **5** (2018) 177-182 doi: http://dx.doi.org/10.21741/9781945291814-31

1) destructive tensile tests – charts of strain change in time,

2) dependence of the minimum creep rate on time to rupture – Monkman-Grant formula [3],

3) time compensated by temperature – time-temperature parameters.

Regardless of the method chosen, the following conditions must be met:

a) the duration of the test must equal at least 10% of the planned operating time,

b) creep and/or destruction mechanisms must not change in the analyzed ranges of time, temperatures and stresses.

There is a relationship between the minimum creep rate and time to rupture [4] (i.e. Monkman-Grant formula). This dependence is based on the observation that deformation is a macroscopic symptom of total creep failure. The destruction will occur when the material damage, in the form of creep cavities and cracks formed by the joining of creep cavities, reaches a critical level. This critical level of damage ε_r, leading to rupture, can be predicted on the base of the minimal creep rate and time to rupture Eq. 7.

$$\left(\dot{\varepsilon}^{c}_{\min}\right)^{m} \cdot t_r = K \approx \varepsilon_r \quad (7)$$

After calculating, on the base of experimental data, constants *m* and *K*, the Monkman-Grant Eq. 7 formula allow the minimum creep rate $\dot{\varepsilon}^{c}_{\min}$ or time to rupture t_r to be determined.

Predicting creep strain over a long time period using extrapolation is difficult due to a number of factors, such as dispersion among experimental data, especially in terms of sample temperatures and methods of heating; available temperature ranges and trial times; microstructure changes occurring during tests and affecting the strain; and environmental impact such as oxidation, reducing effective force transmitted by the sample.

One of the first attempts to extrapolate data from creep tests was conducted by F. H. Norton (1929), known for the introduction of Eq. 5 creep formula, commonly used in model creep processes.

The relationship between the minimal creep rate (in the secondary creep stage) and the applied stress can be used during the design phase. After establishing the maximum acceptable creep rate in the secondary stage, the corresponding maximum allowable stress can be determined.

The assumption of Larson-Miller that the creep rate in the secondary creep stage is inversely proportional to the time to rupture, has been refined and presented by Monkman-Grant in the form of the following Eq. 8 formula:

$$\left(\dot{\varepsilon}^{c}_{\min}\right)^{m} \cdot t_r = K \quad (8)$$

where *K* and *m* are constants.

Eq. 8 equation, known as the Monkman-Grant formula, on the log-log plot of the minimum creep rate as a function of time to rupture for a given material (Fig. 3) should have a directional coefficient of constant value regardless of temperature or applied stress. Eq. 8 equation can be linearized to form the following Eq. 9 equation:

$$\log \dot{\varepsilon}^{c}_{\min} = -\frac{1}{m} \log t_r + \log K \quad (9)$$

Materials Research Proceedings **5** (2018) 177-182 doi: http://dx.doi.org/10.21741/9781945291814-31

Creating a log-log plot of time to rupture, depending on the minimum creep rate, results in a straight line. It is possible to determine the constants *K* and *m* this way. The constant *m* is usually in the range from 0.8 to 1.2.

When the material constants in the Monkman-Grant Eq. 8 formula are determined on the base of experimental data, it is possible to determine the associated minimum creep rate assuming the operational life time of the element, get to know the minimum creep rate (eg. from measurements) and calculate the time to rupture.

Results

To estimate the time to rupture, knowing the creep rate in the secondary creep stage, the minimum creep rate for a given stress and temperature can be measured experimentally or calculated from Eq. 4 formula if constants *A* and *Q* are determined. After determining the minimum creep rate, time to rupture for the analyzed material can be determined from the Monkman-Grant Eq. 8 formula.

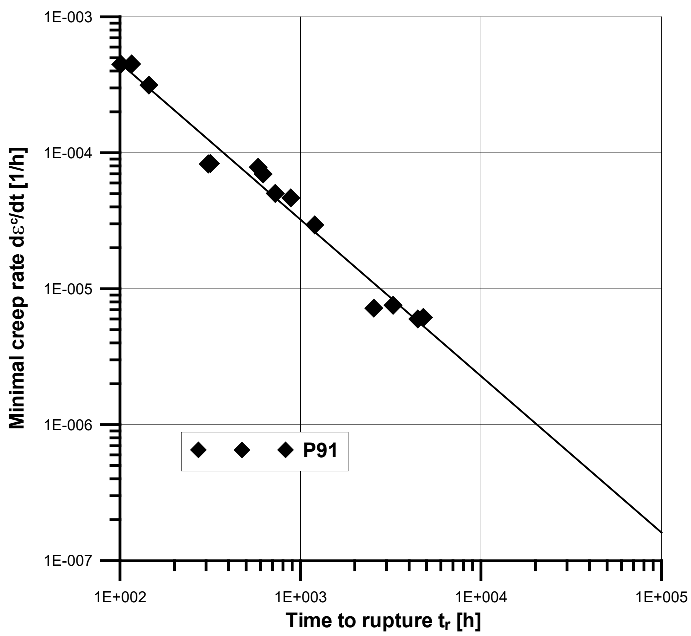

Fig. 3. Monkman-Grant dependence plot for P91 steel.

The Monkman-Grant formula along with the Norton formula can be used for extrapolation. The minimum creep rate associated with the assumed time to rupture can be read from the Monkman-Grant chart (Fig. 3), and then the stress that produces such a minimum creep rate can be determined from the Norton Eq. 5 formula. The Monkman-Grant dependence for P91 steel is shown in Fig. 3.

Using the Monkman-Grant formula and the Norton formula, the maximum allowable stress under the given operating conditions can be determined for the assumed element life time. From the Monkman-Grant Eq. 8 equation, for the P91 steel shown in Fig. 3, it can be stated that for the time to rupture of 100,000 hours, the minimum creep rate is $1.6 \cdot 10^{-7}$ [1 / hour]. In turn, from the Norton Eq. 5 equation shown in Fig. 2, it can be read that this creep speed [5] at 600°C is achieved at a stress level of 88 MPa.

Conclusion

The selected methods presented in this paper allow for the calculation of creep strain or time to rupture for engineering materials like P91 steel. But for the reliability of calculations, a rich set of creep test data is required. The paper presents used theory, all used equations, real material data are presented in the charts. All the calculations are explained step by step. The calculations shown could be used to assure safe operation of various structures operating in creep conditions, like power plants, jet engines, etc. It seems that the promising direction of the method development would be to include methods of the multivariate analysis [6-8], fuzzy description of uncertain knowledge [9-11] as well as specific methods of the materials science analysis [11, 12] and the image analysis [13, 14].

References

[1] A. Jakowluk, Procesy pełzania i zmęczenia w materiałach, WNT, Warszawa, 1993.

[2] ODIN Materials Database (Mat-DB). In: Online Data & Information Network for Energy. European Communities. Available via European. Commission Joint Research Centre (JRC). https://odin.jrc.ec.europa.eu/

[3] D. C. Dunand, B. Q. Han, A. M. Jansen, Monkman-grant analysis of creep fracture in dispersion-strengthened and particulate-reinforced aluminum. Metallurgical and Materials Transactions A, 30(3), (1999) 829-838. https://doi.org/10.1007/s11661-999-0076-y

[4] W.G. Kim, S.H. Kim, W.S. Ryu, Evaluation of Monkman-Grant parameters for type 316LN and modified 9Cr-Mo stainless steels, KSME international journal 16.11 (2002) 1420-1427. https://doi.org/10.1007/BF02985134

[5] P.J. Ennis, A. Czyrska-Filemonowicz, Recent advances in creep resistant steels for power plant applications, OMMI, Vol 1, No.1, April 2002.

[6] E. Skrzypczak-Pietraszek, J. Pietraszek, Phenolic acids in in vitro cultures of Exacum affine Balf. f., Acta Biol Cracov Bot 51 (2009) 62-62.

[7] A.J. Izenman, Modern Multivariate Statistical Techniques. Regression, Classification and Manifold Learning. Springer, New York, 2008.

[8] E. Skrzypczak-Pietraszek, I. Kwiecien, A. Goldyn, J. Pietraszek, HPLC-DAD analysis of arbutin produced from hydroquinone in a biotransformation process in Origanum majorana L. shoot culture, Phytochem. Lett. 20 (2017) 443-448. https://doi.org/10.1016/j.phytol.2017.01.009

[9] J. Pietraszek, Fuzzy Regression Compared to Classical Experimental Design in the Case of Flywheel Assembly, Lect. Notes Artif. Int. 7267 (2012) 310-317.

[10] J. Pietraszek, The Modified Sequential-Binary Approach for Fuzzy Operations on Correlated Assessments, Lect. Notes Artif. Int. 7894 (2013) 353-364. https://doi.org/10.1007/978-3-642-38658-9_32

[11] J. Pietraszek, M. Kolomycki, A. Szczotok, R. Dwornicka, The Fuzzy Approach to Assessment of ANOVA Results, Lect. Notes Artif. Int. 9875 (2016) 260-268.

[10] J. Korzekwa, A. Gadek-Moszczak, M. Bara, The Influence of Sample Preparation on SEM Measurements of Anodic Oxide Layers, Prakt. Metallogr.-Pr. M. 53 (2016) (1) 36-49.

[11] A. Szczotok, B. Chmiela, Effect of Heat Treatment on Chemical Segregation in CMSX-4 Nickel-Base Superalloy, J. Mater. Eng. Perform. 23 (2014) (8) 2739-2747. https://doi.org/10.1007/978-3-319-45243-2_24

[12] A. Szczotok, Metallographic Study of the Casting Made from CMSX-6 Sc Nickel-Based Superalloy, Arch. Metall. Mater. 62 (2017) (2) 581-586.

[13] A. Gadek-Moszczak, History of Stereology, Image Anal. Stereol. 36 (2017) (3) 151-152.

[14] A. Gadek-Moszczak, P. Matusiewicz, Polish Stereology - a Historical Review, Image Anal Stereol 36 (2017) (3) 207-221.