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SELECTING A DEPENDENCE FOR THE APPROXIMATION OF EXPERIMENTAL DATA ON SECONDARY CREEP AND CREEP RUPTURE STRENGTH

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As a rule, for the evaluation of the mechanical characteristics of a metallic material by secondary creep and creep rupture strength, tests are carried out for uniaxial tension of cylindrical specimens under the influence of a stationary axial force. These mechanical characteristics include the experimental dependence of constant strain rate on nominal stress and the experimental dependence of rupture time on nominal stress. In order not to conduct a large number of experiments, so that these mechanical characteristics can be determined at any nominal stress, one of the two empirical dependencies is used, allowing the corresponding experimental dependences to be approximated with the smallest total error. As such empirical dependences, a power dependence with two material parameters and a fractional power dependence with four material parameters are considered, two of which acquire the definite physical meaning of starting creep stress (the maximum stress at which the strain rate is zero) and break creep stress (the minimum stress at which instantaneous rupture occurs). When choosing an empirical dependence, the author used experimental data obtained by him from mechanical tests for uniaxial tension of cylindrical VT5 and VT6 titanium alloy specimens at 650 °C. The calculated total errors testify that both empirical dependences satisfactorily approximate the considered experimental data.

Keywords: secondary creep, creep rupture strength, approximation of experimental data, titanium alloy

1. Introduction

Creep is defined as the time dependence of deformation under the action of stationary forces (or stationary stresses). This dependence is termed the creep curve and characterized by three successive stages in time: decreasing strain rate (I), constant strain rate (II), and increasing strain rate (III). In this study, stage II is considered, which is termed secondary creep. Creep rupture strength is a phenomenon associated with the creep process, in which the rupture time from a given only stationary force (or stationary stress) is considered without taking into account the history of deformation. In what follows, the paper discusses the choice of an empirical approximation for the most accurate description of secondary creep and creep rupture strength. Mechanical creep characteristics for a given material at a given temperature are extracted from experimental creep curves. The nominal stress dependence of strain rate and the nominal stress dependence of rupture time are considered as mechanical characteristics. Two different approximations are considered in order to describe these two experimental dependencies, namely the one discussed in [1, 2] and that presented in [3]. The power dependence [1, 2] has two material parameters:

$$A_1 v_{sec}^{app} = \left(\frac{\sigma_{nom}}{\sigma_{dim}} \right)^{n_1}, \quad A_1 > 0, \quad n_1 > 0, \tag{1}$$

$$\frac{t_{rupt}^{app}}{B_1} = \left(\frac{\sigma_{nom}}{\sigma_{dim}} \right)^{-m_1}, \quad B_1 > 0, \quad m_1 > 0, \tag{2}$$

where v_{sec}^{app} is elongation rate at the secondary creep; t_{rupt}^{app} is rupture time; σ_{nom} is nominal stress; $\sigma_{dim} = 1\,\text{MPa}$ is arbitrary dimensionless stress; n_1 and m_1 are dimensionless parameters, A_1 and B_1 are dimension parameters, where $A_1 = [\frac{\text{h}}{\text{mm}}]$ and $B_1 = [\text{h}]$. The nominal stress $\sigma_{nom} = \frac{F}{S_0}$, where F is stationary axial force, S_0 is initial cross-sectional area. The nominal stress σ_{nom} in dependences (1) and (2) is not limited by anything. In fact, the secondary creep and the creep rupture strength under consideration are limited by ultimate creep stresses. These ultimate creep stresses are taken into account in the fractional power dependence [3], which has four material parameters:

$$A_2 v_{sec}^{app} = \left(\frac{\sigma_{nom} - \sigma_{start}}{\sigma_{break} - \sigma_{nom}} \right)^{n_2}, \quad \sigma_{start} < \sigma_{nom} < \sigma_{break}, \quad A_2 > 0, \quad n_2 > 0, \tag{3}$$

$$\frac{t_{rupt}^{app}}{B_2} = \left(\frac{\sigma_{nom} - \sigma_{start}}{\sigma_{break} - \sigma_{nom}} \right)^{-m_2}, \quad \sigma_{start} < \sigma_{nom} < \sigma_{break}, \quad B_2 > 0, \quad m_2 > 0, \tag{4}$$

where n_2 and m_2 are dimensionless parameters; A_2 and B_2 are dimension parameters, $A_2 = [\frac{\text{h}}{\text{mm}}]$ and $B_2 = [\text{h}]$. Dependencies (2) and (4) differ from each other in the graph (Fig. 1), where σ_{start} is starting creep stress (the maximum stress at which the creep process starts) and σ_{break} is breaking creep stress (the minimum stress at which instantaneous rupture occurs).

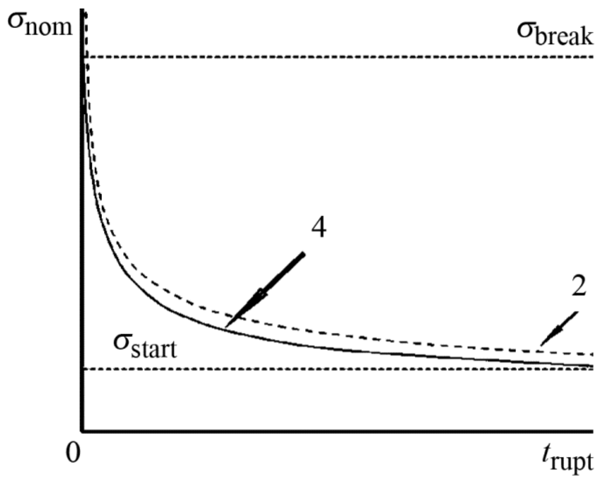


Fig. 1. The mechanical dependences (2) and (4) of nominal stress on rupture time

It is obvious that the approximation discussed in [3] can describe the experimental creep data more accurately than the approximation found in [1, 2]. The experimental study of creep for various metallic materials [4–13] shows that, to analyze mechanical characteristics, experimental scientists use the approximation discussed in [1, 2]. The practical application of the approximation presented in [3] has until recently implied the measurement of ultimate creep stresses in a special experiment. In the present study, instead of measuring starting creep stress and breaking creep stress (creep rupture stress) in an experiment, it is proposed to calculate them from the condition of the minimum total error of the difference between the experimental and approximating values of elongation rate at secondary creep and rupture time. It is proposed to ascertain the expediency and practical applicability of the approximation found in [3] by analyzing the comparison of the minimum total errors between dependences (1) and (3), as well as between dependences (2) and (4).

2. The procedure of calculating the material parameters

The total errors of the difference between the experimental and approximating values of elongation rate at secondary creep and rupture time are considered as a criterion for choosing an approximation,

$$\Delta_v = \min\left(\sum_1^N \left|\lg \frac{v_{\text{sec}}^{\text{app}}}{v_{\text{sec}}^{\text{exp}}}\right|\right) \tag{5}$$

$$\Delta_t = \min\left(\sum_1^N \left|\lg \frac{t_{\text{rupt}}^{\text{app}}}{t_{\text{rupt}}^{\text{exp}}}\right|\right), \tag{6}$$

where N is the number of experiments. The algorithm of nonlinear optimization [14] – the Generalized Reduced Gradient Method (GRG2) in the Solver Add-in of Microsoft Excel – allows the total errors (5) and (6) to be calculated, where the initial approximation $v_{\text{sec}}^{\text{app}} = v_{\text{sec}}^{\text{exp}}$ is used for the total error (5) and the initial approximation $t_{\text{rupt}}^{\text{app}} = t_{\text{rupt}}^{\text{exp}}$ is used for the total error (6).

3. Experimental data

To compare the total errors between dependences (1) and (3), as well as between dependences (2) and (4), the experimental data reported in [15] are used. These experimental data (Tables 1 and 2) have been obtained for two different titanium alloys (Tables 3 and 4) at the same high temperature, where $v_{\text{sec}}^{\text{exp}}$ is elongation rate at the secondary creep in the experiment, $t_{\text{rupt}}^{\text{exp}}$ is rupture time in the experiment.

Table 1. Experimental dependences of elongation rate at secondary creep and rupture time on nominal stress for the VT6 titanium alloy at 650 °C

σ_{nom} (MPa)	25	30	35	40	45	50	55	60	65
$v_{\text{sec}}^{\text{exp}}$ (mm/h)	0.22	0.34	0.37	0.57	0.66	1.16	1.07	1.67	1.37
$t_{\text{rupt}}^{\text{exp}}$ (h)	181.4	65.4	37.2	35.0	28.6	13.5	14.0	6.7	9.0
σ_{nom} (MPa)	70	75	80	85	90	100	110	120	120
$v_{\text{sec}}^{\text{exp}}$ (mm/h)	2.00	1.57	2.01	2.22	3.85	3.67	3.93	3.47	4.41
$t_{\text{rupt}}^{\text{exp}}$ (h)	3.7	6.4	4.8	4.0	2.5	2.5	1.7	2.1	1.4

Table 2. Experimental dependences of elongation rate at secondary creep and rupture time on nominal stress for the VT5 titanium alloy at 650 °C

σ_{nom} (MPa)	80	100	120	140	160
v_{sec}^{exp} (mm/h)	0.05	0.29	0.94	2.57	5.88
t_{rupt}^{exp} (h)	112.2	11.8	9.7	7.4	1.2

Table 3. The chemical composition of the VT6 titanium alloy

Ti	Al	V	Fe	Zr	O	C	Si
86.6	6.8	5.3	0.6	0.3	0.2	0.1	0.1

Table 4. The chemical composition of the VT5 titanium alloy

Ti	Al	V	Mo	Fe	Zr	O	Si	C
90.8	6.2	1.2	0.8	0.3	0.3	0.2	0.1	0.1

4. Material parameters and total errors

For the experimental data (Table 1), the total errors (5) and (6) and the material parameters (Table 5) of dependencies (1) and (3), as well as dependencies (2) and (4), have been calculated for 18 experimental values, where Δ_1, Δ_2, Δ_3 and Δ_4 are the total errors of dependencies (1), (2), (3), and (4).

Table 5. Material parameters and minimum total errors for the VT6 titanium alloy at 650 °C

$\lg A_1$ (h/mm)	n_1	Δ_1	A_2 (h/mm)	n_2	σ_{start} (MPa)	σ_{break} (MPa)	Δ_3
3.6	2.1	1.2	0.33	0.9	17	180	1.1
$\lg B_1$ (h)	m_1	Δ_2	B_2 (h)	m_2	σ_{start} (MPa)	σ_{break} (MPa)	Δ_4
6.2	2.9	1.5	2.54	1.2	21	180	1.4

The analysis of the values of σ_{start} and σ_{break} (Table 5) shows that the relative difference of σ_{start} is 19% and the relative difference of σ_{break} is 0%.

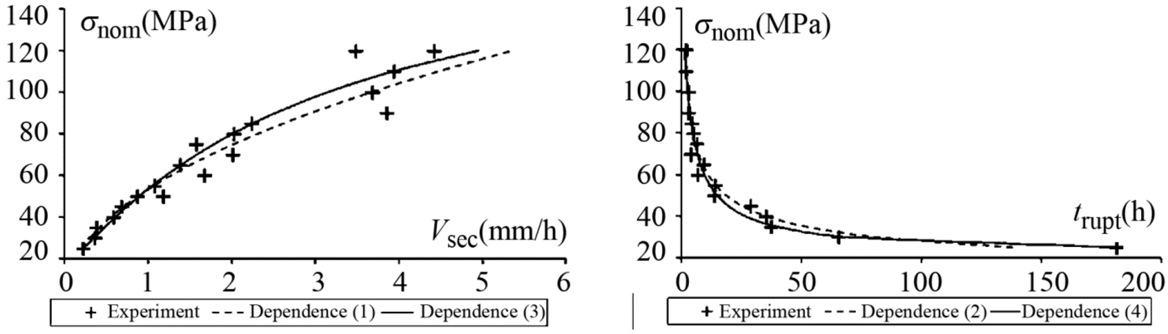
For the experimental data (Table 2), the total errors (5) and (6) and the material parameters (Table 6) of dependences (1) and (3), as well as dependences (2) and (4), have been calculated for only 5 experimental values.

Table 6. Material parameters and minimum total errors for the VT5 titanium alloy at 650 °C

$\lg A_1$ (h/mm)	n_1	Δ_1	A_2 (h/mm)	n_2	σ_{start} (MPa)	σ_{break} (MPa)	Δ_3
14.6	7.0	0.2	0.56	1.7	64	202	0.1
$\lg B_1$ (h)	m_1	Δ_2	B_2 (h)	m_2	σ_{start} (MPa)	σ_{break} (MPa)	Δ_4
14.0	6.3	0.9	5.51	1.7	60	200	0.7

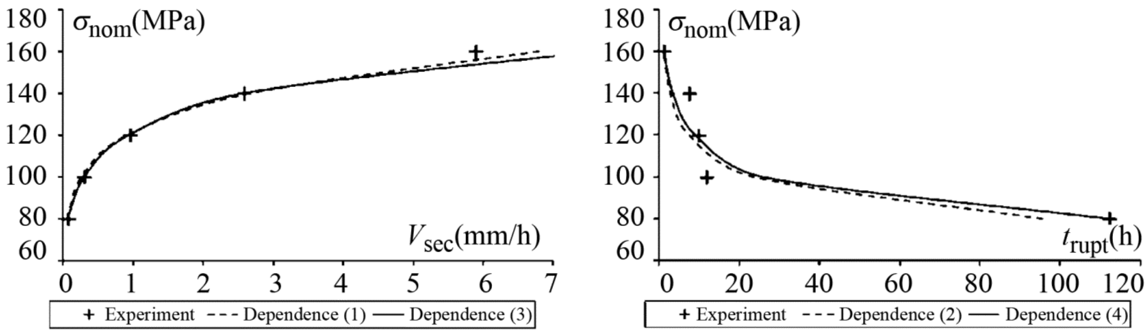
The analysis of the values of σ_{start} and σ_{break} (Table 6) shows that the relative difference of σ_{start} is 6% and the relative difference of σ_{break} is 0.1%. The comparison of the values of σ_{start} and σ_{break} (Tables 5 and 6) shows that the VT5 alloy resists creep better than the VT6 alloy.

The differences between dependences (1) and (3) and dependences (2) and (4) proves to be insignificant (Figs. 2 and 3).



a b

Fig. 2. Approximations of experimental data on secondary creep (a) and creep rupture strength (b) for the VT6 titanium alloy at 650 °C



a b

Fig. 3. Approximations of experimental data on secondary creep (a) and creep rupture strength (b) for the VT5 titanium alloy at 650 °C

5. Conclusion

An attempt has been made to solve the problem of choosing an approximation for describing secondary creep and creep rupture strength. For this purpose, two empirical approximations reported in [1, 2] and [3] have been considered. From a comparison of the minimum total errors of the difference between the experimental and approximating values of elongation rate at secondary creep and rupture time, it has been found that both approximations are almost equally well confirmed by the experimental data obtained in [15] for two different titanium alloys at the same high temperature. The approximation discussed in [3] is more physically justified than that discussed in [1, 2], and it has the following indisputable advantages: the total error is still less, and its material parameters assume relatively small values (Tables 5 and 6). The starting creep stress and the breaking creep stress, calculated from minimizing the total error of the difference between the experimental and approximating values, take values (Tables 5 and 6) almost insignificantly different from the approximations of the experimental data for elongation rate at secondary creep and rupture time. This result gives grounds to consider the calculated values of the ultimate creep stresses to be correct, and this can be useful in determining the values of starting creep stress and breaking creep stress without performing a special experiment.

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