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COMPARATIVE ESTIMATION OF HIGH-TEMPERATURE CREEP AND RUPTURE OF STRUCTURAL MATERIALS

O. V. Sosnin, I. V. Lyubashevskaya, and I. V. Novoselya

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The possibility of comparing the rates of creep processes and times to rupture of materials is shown by the example of several structural alloys of different types. The creep equation is written in dimensionless form, which allows one to compare creep processes up to rupture in normalized quantities, to estimate their difference, and, in the case of coincidence of the normalized quantities for some materials under corresponding temperature–load conditions, to model the indicated processes using experimental data for one of these materials.

Key words: *creep, time to rupture, creep characteristics.*

Introduction. The rates of creep process of structural materials are usually estimated in the form of dependences of the creep strain rate η on the stress σ, temperature T, and some structural parameters q_i that take into account the hardening–softening characteristics of the material. In yield type creep theories, $\eta = f_1(\sigma, T, q_i)$. The energy version of creep theory uses the dependence of the energy dissipation power $W = \sigma\eta$ on similar quantities: $W = f_2(\sigma, T, q_i)$. Other versions of relationship of the creep kinematics with temperature–load and structural parameters are also possible; in this case, equivalent quantities are used for the spatial stress–strain state. For example, for isotropic materials, $\eta_e = ((2/3)\eta_{ij}\eta_{ij})^{1/2}$ and $\sigma_e = ((3/2)\sigma_{ij}\sigma_{ij})^{1/2}$. Below, in analyzing results, we use the energy version of creep theory.

At high temperatures usually exceeding nominal temperatures, the strain–strength behavior of materials is characterized by the absence of the initial creep stage (hardening stage) and the relatively short duration of the third stage (softening stage). Confining ourselves to one structural parameter q and using the dissipated creep strain energy as this parameter, we can write the basic equation as

$$W = \frac{B_1(T)\sigma_e^n}{(A_* - A)^m} = \frac{B_1(T)\sigma_e^n}{A_*^m(1-\omega)^m} = \frac{B(T)\sigma_e^n}{(1-\omega)^m}, \tag{1}$$

where $A_* = \int\limits_0^{t^*} \sigma_{ij}\eta_{ij}\,dt$ is the dissipated creep strain energy at the rupture time t^*, which, for many materials, is a characteristic and remains unchanged over a wide range of temperatures [1, 2].

Equations in the form (1) $[W = \varphi(\sigma_e, T)\psi(A)]$ assume similarity of creep diagrams $A = A(t)$ for fixed values of σ_e and T. As shown in [3], the creep time to rupture is inversely proportional to the dissipation power at the steady-state stage:

$$W_k t_k^* = W_l t_l^* = \text{const}. \tag{2}$$

This statement has been supported experimentally for many materials over a wide temperature–load range. Consequently, in the examined range of loads for each fixed value of T, we can take, as the basis, one of the creep diagrams at a stress σ_0 with the corresponding time to rupture t_0^*, and, using (2), determine t_k^* for any load σ_k.

Lavrent'ev Institute of Hydrodynamics, Siberian Division, Russian Academy of Sciences, Novosibirsk 630090; lbi@ngs.ru. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 49, No. 2, pp. 123–130, March–April, 2008. Original article submitted March 21, 2007.

Thus, in comparative estimations of the creep rupture strengths of materials, it is possible to consider only the steady-state stage and, setting $\omega = 0$ in Eq. (1), write it as

$$W = B(T)\sigma_e^n. \tag{3}$$

In this case, instead of the characteristic $B(T)$, one can use $\sigma_0(T)$ as a material characteristic related to the time t_0^* on the basic diagram. Dividing (3) by $W_0 = B(T)\sigma_0^n$ and introducing the notation $\widetilde{W} = W/W_0$ and $\widetilde{\sigma} = \sigma/\sigma_0$, we obtain

$$\widetilde{W} = \widetilde{\sigma}^n. \tag{4}$$

The normalized equation (4) has the same form over the entire temperature range considered. It is reasonable to choose the basic quantity $\sigma_0(T)$ in such a manner that its corresponding time to rupture of the material t_0^* and, hence, W_0 [see (2)] are identical over the entire temperature–load range. With this choice, the equation $W_0(T, \sigma_0) = \text{const}$ is represented on the plane (T, σ_0) by a curve of equal times t_0^*.

In some cases, as the basic quantity $\sigma_0(T)$, it is reasonable to use the minimum stress that corresponds to the conditionally admissible safe operation time of structural members under extreme conditions. In the literature, the similar notion of the creep limit has also been used earlier in determining the stress level below which creep strains can be ignored in designing structural members. For each fixed temperature T_k in the stress space, the condition $\sigma_0 = \text{const}$ corresponds to the limiting surface within which the stresses σ_{ij} are not dangerous to the operation of structures under creep conditions in the specified interval of t_0^*. For stress states $\sigma_e > \sigma_0$, the time to rupture decreases, and for a certain value of $\sigma_{\max}$, the time $t^* \to 0$, which corresponds to the limiting yield surface of an ideally viscous medium (an analog of the limiting yield surface of an ideally plastic medium).

Obviously, if the process of creep and rupture for a particular material is considered in a narrow temperature range or at a fixed constant temperature T, creep equations in the form (4) has no advantage over equations in the form (1) or the reduced form (3). An advantage is found in comparing creep processes and times to rupture over a wide temperature interval or in comparing the rates of the processes and times to rupture for materials of different types under corresponding temperature–load operation conditions.

The equations in the normalized form (4) do not describe the third stage of prerupture creep, but, over a wide temperature range, they allow one, using (2) and (3), to compare times to rupture with the time corresponding to the basic diagram:

$$W_k t_k^* = W_l t_l^* = W_0 t_0^* \quad \Longrightarrow \quad \widetilde{W}_k t_k^* = \widetilde{W}_l t_l^* = 1 \cdot t_0^*. \tag{5}$$

Using the same value of t_0^* for different materials at different temperatures and loads, it is possible to compare the creep rate and the time to rupture for structural alloys of different types, which allows one to model creep processes using simpler materials [4].

For different materials over a wide range of temperatures, the coefficients B and n in (3) can differ significantly, with the difference for the coefficient B being several orders of magnitude. A certain advantage of the equations of the form (4) is that the quantity σ_0 varies over a much narrower range with variation in the temperature T. Below, some cases of approximation of dependences in the form (3), (4) are considered for some structural materials.

1. Case of Constant Creep Exponent *n*. In (1) and (3), the creep exponent depends on temperature and stress, i.e., on the duration of the process to rupture. For many structural alloys, as the temperature increases, the exponent n decreases and then increases again. However, in a narrow range of temperatures, it can be considered constant. As σ changes, the parameter n usually changes but, in small intervals of loads, it can be considered constant.

Figure 1 show creep diagrams obtained in experiments with axial extension of standard samples of St. 45 structural steel at constant temperature and stress. In the experiment, after each increment in the axial strain $\Delta\varepsilon = 0.5\%$, the cross-sectional area of the sample $S(t)$ was recalculated from the condition of plastic incompressibility of the material $S_0 l_0 = S(t)l(t)$ and the axial load was corrected to maintain the constant stress σ. From Fig. 1, it follows that $A_* \approx 30$ MJ/m^3 over the entire range of stresses and temperatures, the third creep stage is short, and to estimate the time of the process to rupture t^* using Eqs. (2) and (3), it is sufficient to use the estimate of the dissipation power at the steady-state stage and the time t_k^* with the corresponding quantity W_k for one of the given diagrams. Figure 2a shows the results of the experiments in the coordinates $(\ln W, \ln\sigma)$ in the temperature

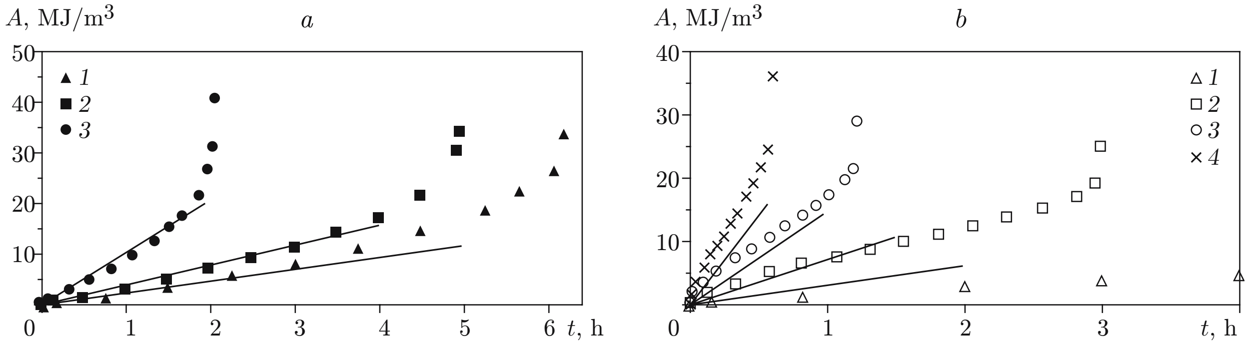

Fig. 1. Tension creep diagrams for St. 45 steel at constant temperature and stress: (a) $T = 700^\circ$C and $\sigma = 55$ (1), 60 (2), and 70 MPa (3); (b) $T = 850^\circ$C and $\sigma = 35$ (1), 40 (2), 45 (3), and 50 MPa (4).

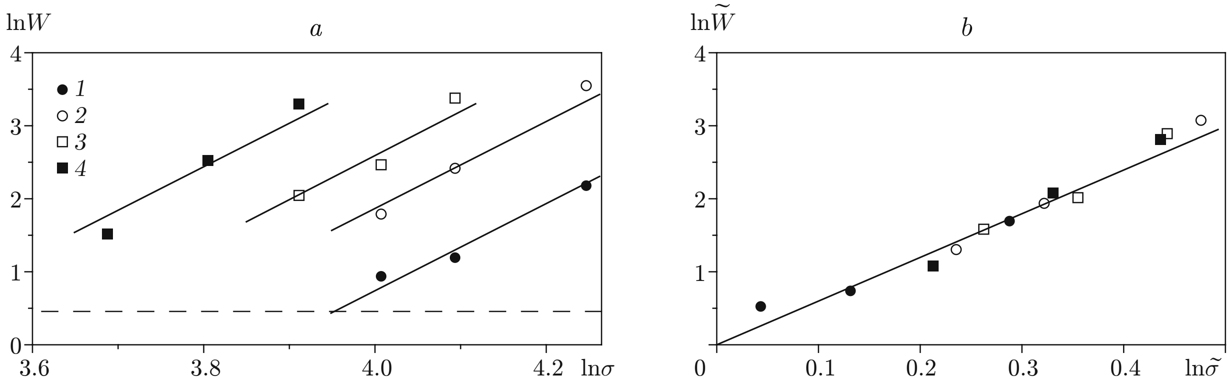

Fig. 2. Creep rate–stress relations $\ln W \sim \ln \sigma$ (a) and $\ln \widetilde{W} \sim \ln \widetilde{\sigma}$ (b) for St. 45 steel at $T = 700$ (1), 750 (2), 800 (3), and 850°C (4).

range 700°C$\leqslant T \leqslant$ 850°C. For all fixed temperatures, the experimental points lie on parallel lines, whose slope gives the quantity $n = 6$. The dependence $B(T)$ (Table 1) was determined from the relation $W_k = B(T)\sigma_k^n$ for each temperature value. The calculated values of $A(t) = Wt$ for the steady-state stage with the characteristics B and n obtained are shown in Fig. 1 (solid curves).

The value $t_0^* = 10$ h (a certain conditionally admissible critical time in an accidental situation) is used as the basic value of the time to rupture t_0^*. According to (2), from the relation $W_k t_k^* = W_0 t_0^*$ for the chosen basic time $t_0^* = 10$ h, we obtain the value $W_0 = 1.6$ MJ/(m$^3 \cdot$ h) (the dashed curve in Fig. 2a). From the relation $W_0 = B(T)\sigma_0^n$ for the known $B(T)$, n, and W_0, we find $\sigma_0(T)$ and write the creep equation in the dimensionless normalized form (4). The normalized experimental values of $\widetilde{W}$ and $\widetilde{\sigma}$ are presented in logarithmic coordinates in Fig. 2b. The corresponding values of $\sigma_0(T)$ are given in Table 1, from which it follows that the values of B change by more than an order of magnitude.

If diagrams corresponding to the temperature–load conditions (σ_0, T) for processes with the same dissipation power are constructed in the coordinates (σ, T), these lines separate the safe (below the diagrams) and dangerous (from the point of view of the duration of the process) values of T and σ.

As one might expect, for $n = \text{const}$ over the entire temperature range, the same normalized values of $\widetilde{\sigma} = \sigma/\sigma_0(T)$ correspond to the same values of the normalized dissipation power $\widetilde{W} = \widetilde{\sigma}^n$ and [by virtue of (5)] the same time to rupture, which allows the material behavior to be analyzed over the entire temperature range.

2. Case of Variable Characteristics *B* and *n*. As noted above, in the description of creep process of structural materials using dependences (1) and (3) over a wide temperature–load range, a temperature change leads to changes in both characteristics B and n and, hence, in σ_0. Figure 3 shows creep diagrams for axial tension of OT-4 titanium alloy at constant temperature and stress [5]. The dissipated energy of irreversible deformation

TABLE 1

Dependences $B(T)$ and $\sigma_0(T)$

T, °C	$B \cdot 10^{10}$, $(\text{MPa})^{1-n} \cdot \text{h}^{-1}$	σ_0, MPa
700	0.78	52.4
750	2.40	43.3
800	5.00	38.4
850	14.40	32.2

TABLE 2

Dependences $B(T)$, $n(T)$, $\sigma_0(T)$

T,°C	B, $(\text{MPa})^{1-n} \cdot \text{h}^{-1}$	n	σ_0, MPa
400	$4.4 \cdot 10^{-40}$	14.6	394
450	$3.0 \cdot 10^{-16}$	6.0	214
500	$4.5 \cdot 10^{-11}$	4.5	91
550	$1.3 \cdot 10^{-8}$	4.0	39

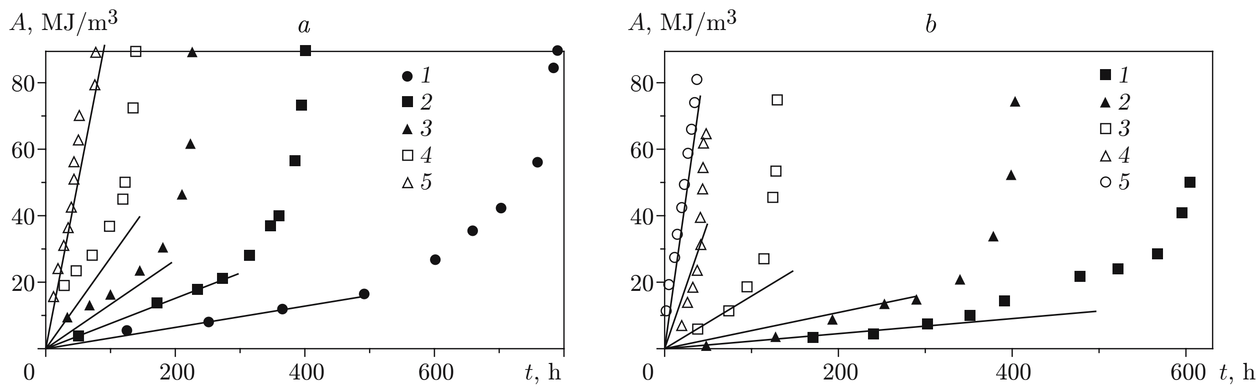

Fig. 3. Tension creep diagrams for OT-4 alloy at constant temperature and stress: (a) $T = 400°\text{C}$ for $\sigma = 392$ (1), 421.4 (2), 441 (3), 470.4 (4), and 490 MPa (5); (b) $T = 550°\text{C}$ and $\sigma = 39.2$ (1), 49 (2), 63.7 (3), 78.4 MPa (4), and 98 MPa (5).

at the rupture time changes only slightly over the entire temperature range, and it can be considered constant: $A_* \approx 85$ MJ/m^3. According to (1), setting $\omega = 0$ in the steady-state stage, for each temperature and various values of σ using experimental data, we find the values of $W = \sigma\eta$. The experimental results for the temperature range $400°\text{C} \leqslant T \leqslant 550°\text{C}$ are presented in the coordinates $(\ln W, \ln \sigma)$ in Fig. 4a. These dependences can be approximated by straight lines. The slope of these lines and, hence, the parameter n vary (the parameter n decreases with increasing T). The values of B and n for the dependence $W = B\sigma^n$ are given in Table 2, and calculated dependences $A(t) = Wt$ for the steady-state stage are shown by solid curves in Fig. 3.

The basic value of the dissipation power in the steady-state stage is taken to be the value $W_0 = 0.0291$ MJ/(m$^3 \cdot$ h^{-1}) (the dashed curve in Fig. 4a), which, according to (2), corresponds to the time to rupture $t_0^* = 1000$ h. Knowing $B = B(T)$ and $n = n(T)$, from the relation $W_0 = B(T)\sigma^{n(T)}$, we find the value $\sigma_0 = \sigma(T)$ (the corresponding values of σ_0 are given in Table 2) and write the basic equations (1) in the dimensionless normalized form (4). Results of the experiments in the normalized quantities are presented in Fig. 4b. As one might expect, we obtained a family of solid curves which intersect each other at the coordinate origin and have the same slope as in Fig. 4a. According to (2), the same values of $\widetilde{W}_k$ correspond to the same time to rupture at any temperature. For example, the value of $\widetilde{W}_k$ (the dashed curve in Fig. 4b) that is two orders of magnitude larger than $\widetilde{W}_0$ corresponds to the time to rupture t_k^* that is two orders of magnitude smaller than t_0^*, which is supported by experimental data [5]. Unlike in the case considered in Sec. 1, where $n = \text{const}$ over the entire temperature range, in this case, it is impossible to argue that the same normalized stresses $\widetilde{\sigma}_k$ correspond to the normalized powers $\widetilde{W}_k$ and, hence, the same time to rupture t_k^* [a comparison should be made for the normalized quantities $\widetilde{W}_k = \widetilde{\sigma}_k^n$ taking into account the variation in the parameter $n = n(T)$]. According to (5), the product of the normalized power $\widetilde{W}_k$ and its corresponding time to rupture is close to the value $t_0^* = 1000$ h over the entire temperature range.

3. Comparison of Times to Rupture for Materials of Different Types. Let us consider several types of structural alloys which are used in different high-temperature and load ranges. For each material, there is a set of standard creep diagrams similar to those presented in Figs. 1 and 3, which makes it possible to determine the characteristics $B(T)$ and $n(T)$ in (3), the limiting values of A_*, and the times to rupture t_k^* corresponding to some combinations of σ_k and T_k. If the creep processes and times to rupture of these materials can be described using

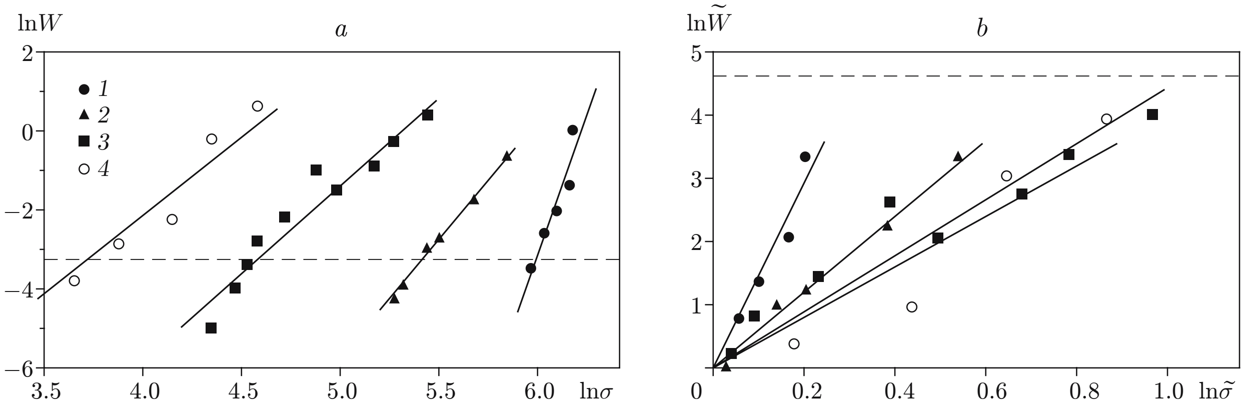

Fig. 4. Creep rate–stress relations $\ln W \sim \ln \sigma$ (a) and $\ln \widetilde{W} \sim \ln \widetilde{\sigma}$ (b) for OT-4 alloy: $T = 400$ (1), 450 (2), 500 (3) and 550°C (4).

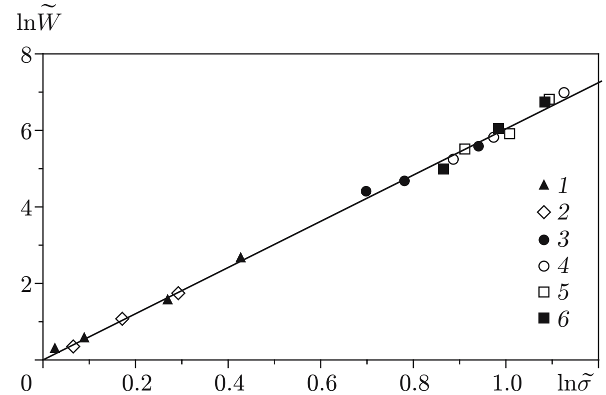

Fig. 5. Creep rate versus stress for OT-4 alloy at $T = 450$°C (1), D16 alloy at $T = 250$°C (2), and St. 45 steel for $T = 700$ (3), 750 (4), 800 (5) and 850°C(6).

the energy version of creep theory, then, according to (2), they obey the condition $W_k t_k^* = W_m t_m^* = C$. However, for each material, the values of W_k, t_k^*, and C are different. Let us specify any basic time to rupture t_0^*, the same for all materials being compared in the time interval of their operation $t_{\min}^* < t_0^* < t_{\max}^*$. Then, using the relation $W_k t_k^* = W_m t_m^* = W_0 t_0^*$ for each material, we find the basic value of the dissipation power W_0 in the steady-state stage. Knowing the characteristics $B(T)$, $n(T)$, and W_0 for each material, from the relation $W_0 = B(T)\sigma_0^{n(T)}$, we find $\sigma_0(T)$ and obtain the dimensionless normalized creep equation $\widetilde{W}_k = \widetilde{\sigma}_k^n$ (4), where $\widetilde{\sigma} = \sigma/\sigma_0(T)$; $n = n(T)$ [with different values of $\sigma_0(T)$ and $n = n(T)$ for each material]. In the normalized quantities for all materials being compared, relation (2) becomes $\widetilde{W}_k t_k^* = t_0^*$, i.e., instead of the constants $C_1, C_2, \ldots$ we have one constant t_0^* — the chosen basic time of comparison. If we represent the normalized quantities $\widetilde{W}$ and $\widetilde{\sigma}$ in logarithmic coordinates, then, for each material considered, we obtain a family of straight lines which intersect each other at the coordinate origin, as in Fig. 4b; in this case, for all materials being compared, the same values of $\widetilde{W}$ correspond to the same time of the process to rupture.

Thus, if, for all materials being compared, there are diagrams similar to those presented in Fig. 4b, it is possible to choose temperature–load intervals in which the exponents n of these materials are equal. Then, the diagrams $\widetilde{W} \sim \widetilde{\sigma}$ represent the same straight line.

Table 3 gives temperature–load conditions for three materials with the same creep exponent $n(T) = 6$, i.e., for the case described in Sec. 1. Figure 5 gives experimental data in the normalized logarithmic coordinates $(\ln \widetilde{W}, \ln \widetilde{\sigma})$ for the basic time $t_0^* = 500$ h for the materials indicated in Table 3.

TABLE 3

Temperature–Load Conditions and Rate and Time Parameters of Creep Process

Material	T, °C	σ, MPa	t^*, h	W, MJ/(m$^3\cdot$h)	$\widetilde{W}t^*$, h
D16T alloy	250	98.10	90	0.0138	512
		88.26	170	0.0073	513
		78.48	340	0.0036	507
		68.67	720	0.0016	482
OT-4 alloy	450	196.0	1080	0.0145	412
		205.8	700	0.0197	363
		230.3	400	0.0525	553
		245.0	340	0.0681	609
		294.0	100	0.1839	484
		343.0	40	0.5517	580
St. 45 steel	700	70	2.08	8.392	542
		60	4.92	3.250	496
		55	6.17	2.613	500

The materials considered are greatly different, and, hence, the temperature–load ranges of their operation are also different. Nevertheless, the approach proposed here can be used to compare the creep rates of different materials and to estimate their creep times to rupture.

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