ON RUPTURE ATTRIBUTABLE TO CREEP

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The results of creep rupture tests carried out in a plane-stressed state are presented; the experiments confirm the validity of an earlier energy approach as regards the time to rupture under creep conditions [1].

It was shown in an earlier paper [1] that, in the case of a uniaxial stressed state, the A = A(t) diagrams, where $A = \int_0^t \sigma\eta dt$, η is the rate of creep deformation, were very similar in form for a wide range of stress levels and that the duration of the creep process up to the point of rupture t^* was comparable with the specific dissipated power $W^\circ = \sigma\eta$ under the steady-state conditions

$$W_k^\circ / W_n^\circ = t_n^* / t_k^* \quad (1)$$

In this paper we shall present some results obtained in a plane-stressed state: tension with torsion and compression with torsion.

The experiments were carried out at T = 275°C on tubular samples with internal and external diameters of 18 and 20 mm and a length of the working part equal to 80 mm. The samples were made from Duralumin D16T rods in the as-supplied state and were not subjected to any heat treatment after preparation. From each rod of the chosen batch we made two samples and subjected these to tensile creep tests in order to establish the statistical scatter of the results due to possible inhomogeneities of the rods. In this way we selected rods for which the scatter of the experimental deformation data remained within a band of ±10% of the mean value.

The creep experiments were carried out in four series.

The first series consisted of tensile, compressive, and torsional tests; in the experiments with torsion the tangential stress τ was determined from the relation $M = \tau S R_0$, where M is the external torque, S is the cross-sectional area of the sample, R_0 is the mean radius of the circular cross section. The majority of the experiments were taken up to the complete rupture of the sample, but some of them were stopped when the creep process intensified sharply, a phenomenon which may have been associated with a loss of stability under compression or torsion. (Control experiments with rest periods at various levels of the third creep stage showed that a corrugated or oval structure appeared in the samples in the third creep stage immediately before rupture.) During the experiments we measured the axial elongation of the sample and the angle of twist, from which we determined the axial deformations ε and shears γ, while in the steady-state sections we measured the deformation rates $\eta = d\varepsilon/dt$, $\theta = d\gamma/dt$.

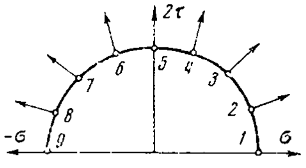

Fig. 1

It should be noted that in all the experiments of both this series and the succeeding series, the initial transient stage of creep was practically absent and the process passed very rapidly into the steady-state stage with a constant deformation velocity. At the instant of passing into the third stage the axial creep deformations were no greater than 1%, and at the instant of rupture ~ 5%. During the experiments no corrections were made to the load in respect to changes in the cross-sectional area of the

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TABLE 1

t, h	1	2		3		4		5	6		7		8		9
	$\varepsilon \cdot 10^3$	$\varepsilon \cdot 10^3$	$\gamma \cdot 10^3$	$\varepsilon \cdot 10^3$	$\gamma \cdot 10^3$	$\varepsilon \cdot 10^3$	$\gamma \cdot 10^3$	$\gamma \cdot 10^3$	$-\varepsilon \cdot 10^3$	$\gamma \cdot 10^3$	$-\varepsilon \cdot 10^3$	$\gamma \cdot 10^3$	$-\varepsilon \cdot 10^3$	$\gamma \cdot 10^3$	$-\varepsilon \cdot 10^3$
5	3.06	2.94	1.97	2.38	4.00	0.85	6.60	5.58	0.63	3.95	1.87	3.09	3.18	1.35	2.96
10	6.40	5.70	3.80	4.05	7.29	1.54	12.40	11.50	1.20	8.34	3.26	5.31	7.30	4.00	5.66
15	12.60	9.80	6.60	6.66	12.12	2.58	19.60	19.48	1.80	12.60	5.20	8.48	12.50	7.60	10.63
20	23.60	17.10	12.20	10.38	19.31	3.77	30.20	33.45	2.45	19.30	7.09	11.56	21.00	12.50	16.80
25	46.69	33.50	22.50	17.10	32.54	5.27	51.43	65.00	3.90	31.36	10.93	18.21	34.50	19.65	32.31
30	—	—	—	35.00	65.00	—	—	—	6.50	48.75	17.10	29.30	—	—	—

TABLE 2

Expt. No.	σ	τ	$\varepsilon \cdot 10^3$	$\gamma \cdot 10^3$	$W \cdot 10^3$
1	8.00	0	0.50	—	4.00
2	7.39	1.64	0.45	0.38	3.95
3	5.66	3.02	0.33	0.66	3.85
4	3.00	3.80	0.13	0.95	3.00
5	0	3.92	—	1.00	3.90
6	−3.00	3.80	−0.15	0.80	3.50
7	−5.87	2.75	−0.33	0.67	3.70
8	−7.67	1.46	−0.50	0.27	4.25
9	−8.30	0	−0.47	—	3.90
10	10.00	0	1.50	—	15.00
11	9.51	1.65	1.41	0.73	14.60
12	8.09	3.14	1.27	1.63	15.40
13	5.88	4.33	0.73	2.35	14.50
14	3.00	4.77	0.34	3.05	15.50
15	0	4.88	—	3.20	15.60
16	−3.20	4.78	−0.35	2.60	13.55
17	−8.40	2.87	−1.15	1.50	14.00
18	−9.60	1.79	−1.30	0.95	14.20
19	−9.87	1.49	−1.50	0.65	15.80
20	−10.38	0	−1.45	—	15.05
21	12.00	0	3.75	—	45.00
22	10.39	3.21	4.00	4.00	54.40
23	6.00	5.55	1.90	8.00	55.80
24	0	5.85	—	6.80	39.80
25	−6.15	5.15	−1.40	6.35	41.30
26	−10.79	2.92	−3.10	3.00	42.20
27	−12.46	0	−3.60	—	44.85

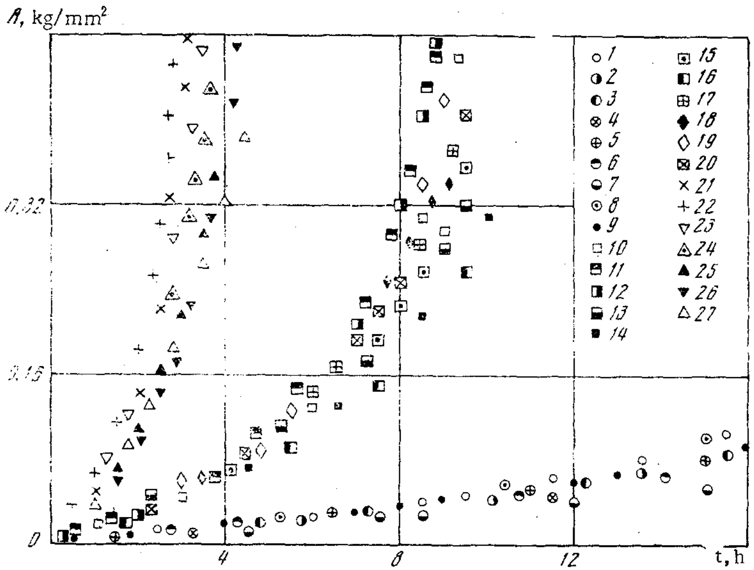

Fig. 2

sample. This necessarily led to a slight monotonic deviation in the sense of retarding the creep processes under compression, as was indeed observed in the third stage.

Earlier [2] one of us showed that material of the D16T type subject to creep tests behaved in the same way in both tension and compression. Subsequent investigations showed that this conclusion was only valid for moderate intensities of the creep process, extending over tens and hundreds of hours. For short-term processes the deformation rate in tension increases considerably more rapidly than the deformation rate in compression for equal stresses in the two cases. This difference cannot be explained by a change in the cross-sectional area of the samples; the same effect occurs when the loads are adjusted to allow for the change in cross section, this area being recalculated for every 0.3% axial deformation during the experiment from the incompressibility condition. Analogous conclusions may be drawn from a number of other investigations [3].

The experiments of the first series showed that the test material D16T was anisotropic and exhibited slight differences in its properties under tension and compression.

These experimental results enabled us approximately to estimate the creep properties of the material and construct contours in the σ, τ stress plane; at any point of these contours the specific dissipated power $W^\circ = \sigma\eta_0 + \tau\Theta$ in the steady-state stage was the same. The geometrical locus of points in the σ, τ plane with constant W° values was refined experimentally. The next three series of experiments were aimed at determining three $W^\circ(\sigma, \tau)$ = const contours intersecting the positive σ axis at the points $\sigma_1 = 8$ kg/mm^2, $\sigma_2 = 10$ kg/mm^2, $\sigma_3 = 12$ kg/mm^2.

In Fig. 1 (plotted in coordinates of σ, 2τ) the points indicate the stresses at which the value of $W_1^\circ \approx 4 \cdot 10^{-3}$ kg/mm$^2 \cdot$h was obtained in the experiments. Table 1 indicates the creep deformations (strains) ε and γ for various values of time. We see from the data presented in the table that the deformation ratio ε/γ remains practically constant during the experiment until the sample actually ruptures. The arrows in Fig. 1 indicate the directions of the resultant increments in creep deformation, which are plotted in components of 2ε, γ measured in the corresponding experiments. The directions indicated agree excellently with the directions of the normal to the contour drawn through the stress points for which $W^\circ(\sigma, \tau)$ = const, and, as already mentioned, these directions remain constant up to the rupture point. It follows that the relationship between the creep deformation velocity components and the stresses (as expressed, for example, in the form of a similarity between the corresponding deviators

$$\eta_{kn} = \lambda\partial\sigma^i/\partial\sigma_{kn}, \quad \sigma_i^2 = {}^3/_2\, \mathring{\sigma}_{kn}\mathring{\sigma}_{kn}$$

for isotropic materials, or in the more general form

$$\eta_{kn} = \lambda\partial T/\partial\sigma_{kn}, \quad T^2 = a_{ijkn}\sigma_{ij}\sigma_{kn}$$

for certain kinds of anisotropy of the material), which has been repeatedly verified by experimental observations in the first stages of creep, remains valid in the third stage right up to the rupture point.

Analogous results were obtained for the two other levels of the stressed state, corresponding to the values $W_2^\circ \approx 15 \cdot 10^{-3}$ and $W_3^\circ \approx 45 \cdot 10^{-3}$ kg/mm$^2 \cdot$h.

Table 2 gives the values of the stresses σ and τ in kg/mm^2 and the deformation rates $\eta \cdot 10^3$ and $\Theta \cdot 10^3$ h^{-1} corresponding to the foregoing three values of W° = const.

Figure 2 shows the results of these experiments in the form of A = A(t) diagrams where $A = \sigma\varepsilon + \tau\gamma$. The numbers in the figure correspond to the numbers of the experiments in Table 2. We see from the diagrams that the average times to rupture for the various stress levels corresponding to the foregoing dissipated powers in the steady stages are $t_1^* \approx 30$ h, $t_2^* \approx 10$ h, $t_3^* \approx 3$ h, respectively.

The following conclusions may be drawn from the foregoing results: the surfaces of the stressed states equivalent in the sense of time-to-failure coincide with the surfaces of constant dissipated powers for the steady-state stages of creep W° = const, while the latter are similar to the yield surfaces, the shape of which remains constant until the material ruptures.

Equations (1), which were verified earlier [1] in experiments carried out under uniaxial loading, are also reasonably satisfactory in a complex stressed state.

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