CREEP OF D16T DURALUMIN UNDER CONSTANT, CYCLIC, AND STEP-WISE VARIABLE LOADS

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The results of creep tests on D16T duralumin under certain types of variable and constant loads were described and compared with data calculated on the basis of a number of hypotheses of creep under variable stresses in [1–8]. This article reports the results of an experimental study of the creep of D16T duralumin sheet under constant, cyclic, and step-wise variable loads at 155, 207, and 255° C and the results of creep tests on D16T duralumin rods under constant and step-wise variable loads at 207° C. In addition, formulas describing creep at constant loads were derived and some of the hypotheses of creep at variable stresses were verified.

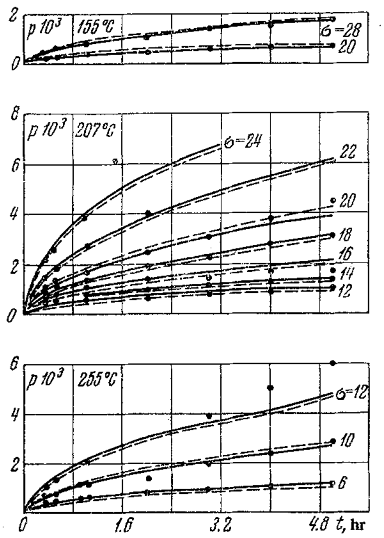

Fig. 1

Flat specimens were tested on DST-5000 machines with special devices for applying cyclic and step-wise variable loads [8].

Specimens were made of D16T duralumin sheet as supplied from the factory; they were 2 mm thick, their gauge portion length and width being 100 and 10 mm, respectively.

Cylindrical specimens were tested on Zst 3/3 machines; the step-wise variable loads were applied by hand.

Cylindrical specimens (made from rods) had a gauge portion 100 mm long and 8 mm in diameter.

The gauge portion of both the flat and cylindrical specimens terminated in flanges to which the extensometer drawbars were attached for strain measurements.

Each specimen was heated to a given test temperature in approximately one hour and held at the temperature for 1–2 hours, after which the load was applied. In the case of tests at constant loads, 20–30 cylindrical and 5–8 flat specimens were tested at each stress level. Averaged test results are plotted in Fig. 1, where t denotes time and σ stress (kg/mm²). The experimental creep curves obtained for both flat and cylindrical specimens can be described by

$$p = A\sigma^n t^m, \quad \text{or} \quad p = B\,\mathrm{sh}\,(\sigma / k)\, t^m, \tag{1}$$

where t is time, σ is stress, and p is creep strain; the values of constants A, B, n, k, and m are given in the table.

Curves representing formulas (1.1) and (1.2) are represented in Fig. 1 by solid and dashed lines, respectively. Both curves adequately describe the experimental creep curves obtained for flat specimens. However, formula (1.1) is simpler for solving problems of creep at stresses which do not appreciably vary. Formula (1.2) is more convenient for solving problems associated with stresses that vary within wide limits since with the same constants it describes all the creep curves in each of the stress intervals studied. Creep curves of cylindrical specimens, which pass through a steady-state creep range, are less adequately described by formulas (1).

Several different step-wise loading programs were used in creep tests at variable loads. Thus, in tests on flat specimens at 155° C the initial stress of 20 kg/mm² was raised at various times to 28 kg/mm²; the initial stress of 18 kg/mm² at 207° C was raised to 24 kg/mm², the corresponding figures for 255° C being 6 and 12 kg/mm². The results of tests on flat specimens are reproduced in Fig. 2, where the experimental points show creep strain values averaged for 4–8 specimens to which a higher load was applied at the same instant. Six step-wise loading programs with the load increased or reduced at various time intervals were used in tests on cylindrical specimens, 10–20 specimens being tested according to each program. The averaged results of one series of tests are shown by circles in Fig. 3.

Several hypotheses for describing transient creep under time-dependent loads have been postulated; of these, mathematically correct for step-wise variable loads are the hypotheses of strain-hardening, flow, and after-effect. We were unable to verify the

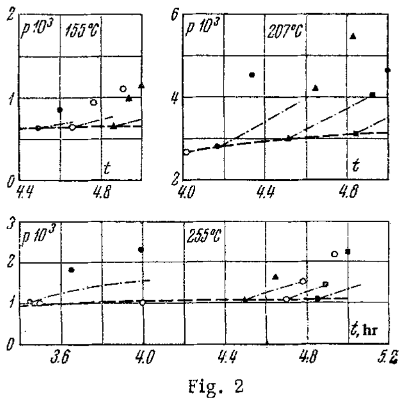

Fig. 2

applicability of the after-effect hypothesis in the case under consideration, since to carry out computations with the aid of this hypothesis it is necessary to obtain creep curves at several stress levels,

T, °C	σ, kg/mm²	m	n	A, mm²/kgⁿhrᵐ	k, kg/mm²	B, 1/hrᵐ
155	σ ⩾ 20	0.515	2.9	$4.7\cdot10^{-8}$	8.3	$5.10\cdot10^{-5}$
207	σ ⩽ 20 σ ⩾ 20	0.542	2.67 4.44	$5.4\cdot10^{-7}$ $2.86\cdot10^{-9}$	5.5	$9.45\cdot10^{-5}$
255	σ ⩽ 10 σ ⩾ 10	0.55	1.57 3.2	$2.85\cdot10^{-5}$ $6.75\cdot10^{-7}$	4.5	$2.52\cdot10^{-4}$
207	σ ⩽ 16 σ ⩾ 16	0.5	1.20 3.3	$1.04\cdot10^{-5}$ $3.35\cdot10^{-8}$	5.5	$3.29\cdot10^{-5}$

to use them to construct isochronous curves and to derive formulas describing the latter. This could not be done because an insufficient number of creep curves was obtained at 155 and 255° C, while in the case of creep at 207° C the similarity of isochronous curves, which is necessary for the application of the after-effect hypothesis, is observed only in limited time intervals.

There is no need to derive formulas describing the starting creep curves for verifying the strain-hardening and flow hypotheses under step-wise variable load conditions. According to the strain-hardening hypothesis, the rate of creep at a given time depends only on the stress and creep strain at this instant. According to the flow hypothesis, the rate of creep is determined only by stress and the time elapsed from the beginning of a given test. To construct creep curves based on either of these hypotheses it is therefore sufficient to have creep curves obtained at constant stresses equal to each stress level of a step-wise variable loading program.

Dot-dash lines in Figs. 2 and 3 represent curves obtained on the basis of the strain-hardening hypothesis directly from the starting creep curves. It will be seen that in the case of increasing loads the theory gives strains much lower than those determined by experiment. Theoretical values obtained on the basis of the flow hypothesis are even lower in the case of increasing loads and similar to those obtained on the basis of the strain-hardening hypothesis in the case of decreasing loads.

It was suggested in [5] that a new parameter $q = \int \sigma dp$ be introduced in the strain-hardening hypothesis instead of parameter p. Generally speaking, the introduction of the parameter q reduces the above-noted systematic divergence. Calculations showed, however, that this produces a negligible improvement in the degree of agreement between theory and experiment. Better results are obtained if instead of q one uses a parameter $q_1 = \int \sigma^s \, dp$, where $s > 1$ is obtained from the results of a test at a step-wise variable stress.

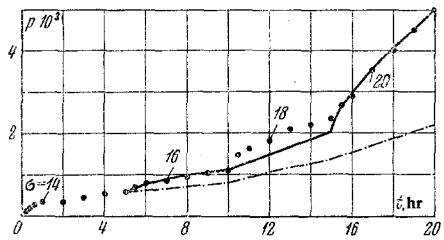

Fig. 3

It was postulated in [2] that the strain-hardening hypothesis can be made applicable to creep at variable loads by introducing an additional parameter

$$\frac{\theta}{R} = \frac{1}{R} \int p d\sigma,$$

where R is determined from the results of one or several tests at step-wise variable loads. Let us describe the creep of cylindrical specimens by a formula

$$\dot{p} p^{\mu-1} = (B^{\mu} m) \operatorname{sh}^{\mu} (\sigma / k + \theta / R) \qquad (\mu = 1/m), \tag{2}$$

which becomes (1.2) when the applied stress is constant. Values of B, m, and k are taken from the table, while $R = 3.57 \cdot 10^{-3}$ kg/mm² is obtained by processing results reproduced in Fig. 3. The theoretical creep curves for a step-wise variable load are obtained in the following way. Formula (2) is used to plot a number of curves corresponding to constant values θ, after which curves for step-wise variable loads are obtained graphically as is done when the ordinary strain-hardening hypothesis is used. A curve obtained by this method is represented by the solid line in Fig. 3. Data in Fig. 3 and similar comparisons made for the remaining loading programs showed that the introduction of the parameter θ leads to a considerable improvement in the extent of agreement between theory and experiment in the case of increasing loads; the improvement in the case of decreasing loads is smaller but still substantial. In the case of creep following a complex variable loading program, the introduction of the parameter θ should therefore, generally speaking, give a closer agreement between calculated and experimental results.

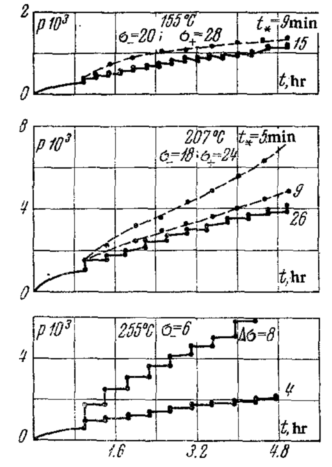

Fig. 4

Creep tests under cyclically variable loads were carried out on sheet specimens. The following load cycle form was used: to a specimen under a certain stress σ_- a higher stress σ_+ was periodically applied, after which the stress was reduced to σ_-; the time at stress σ_+ was one minute in all of the experiments, the time at the lower stress level varied from experiment to experiment between 1.5 and 25 minutes; the first cycle was applied one hour after the start of the test.

Some of the test results are plotted in Fig. 4, where each point represents an average of 4–5 results. Graphs in Fig. 4 relate either to experiments carried out at the same values σ_- and σ_+ and different cycle times t_*, or at the same $t_* = 26$ min and at a constant σ_- but at different σ_+. Analysis of data in Fig. 4 shows that each of the curves obtained lies between curves obtained at constant stresses σ_- and σ_+. It will be seen also that as time at the lower stress level increases or as the difference $(\sigma_+ - \sigma_-)$ decreases, the curves relating to cyclically variable stress are shifted toward the curve obtained for a constant stress σ_-. Some of the curves show evidence of recovery, i.e., a reduction in the creep strain after the application of a lower stress: the magnitude of this effect is quite small, however. It is therefore quite likely that creep under cyclically variable loads (with the cycle form and frequency studied) can be satisfactorily described by the strain-hardening hypothesis; after the introduction of additional parameters this hypothesis would probably give results in good quantitative agreement with experimental data.

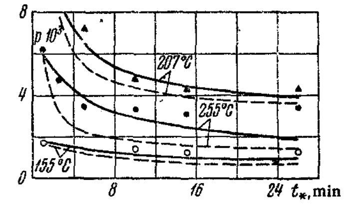

Fig. 5

In Fig. 5 average creep strains produced by 5 hr tests are plotted against the cycle duration t_*. Triangles relate to tests at 207° C, $\sigma_- = 18$ kg/mm² and $\sigma_+ = 24$ kg/mm²; black circles represent the results of tests at 255° C, $\sigma_- = 6$ kg/mm² and $\sigma_+ = 12$ kg/mm², while open circles relate to tests at 155° C, $\sigma_- = 20$ kg/mm² and $\sigma_+ = 28$ kg/mm². It should be noted that points obtained at $t_* = 26$ min lie above those obtained at $t_* = 15$ min and sometimes even above points obtained at $t_* = 9$ min. This is owing to the fact that increasing the holding time at the lower stress level leads to an increase in the initial creep rate after the application of σ_+, this being true for all the test temperatures studied.

Average creep strain values recorded in 5 hr tests at $t_* = 26$ min are plotted against the difference $(\sigma_+ - \sigma_-)$ in Fig. 6. Black circles represent the results of tests at 207° C and $\sigma_- = 12$ kg/mm², open circles relate to the same temperature and $\sigma_- = 18$ kg/mm², while triangles represent the results of tests at 255° C and $\sigma_- = 6$ kg/mm².

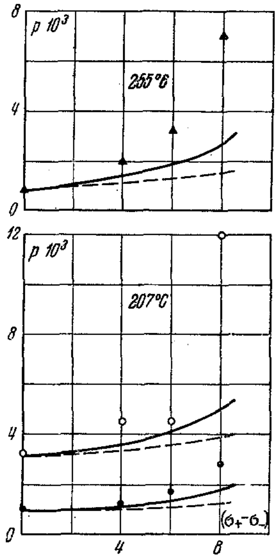

Fig. 6

Dashed lines in Figs. 5 and 6 represent theoretical creep curves obtained from the initial curves with the aid of the strain-hardening hypothesis, while continuous lines represent theoretical results obtained by the above-described graphical method using the additional parameter θ (in the strain-hardening hypothesis). Values of R in the appropriate formula were determined from experimental results reproduced in Fig. 2; the values actually obtained were $R = 9.0 \cdot 10^{-3}$ kg//mm² at 155° C, $R = 22.7 \cdot 10^{-3}$ kg/mm² at 207° C, and $R = 0 \cdot 10^{-3}$ kg/mm² at 255° C.

Comparison of the experimental and calculated data shows that the strain-hardening hypothesis often gives underestimated results. When, however, the parameter θ is introduced into this hypothesis, quantitatively satisfactory agreement between theory and experiment is obtained in Fig. 5 (except at $t_* = 26$ min) and a better qualitative agreement in Fig. 6; neither case produced quantitative agreement in the latter.

Thus, the above described results lead to the conclusion that the creep curves of D16T duralumin under constant loads may be described by a relation in the form of a hyperbolic sine function of stress. In the case of step-wise variable loads, creep may be described by the strain-hardening hypothesis containing the additional parameter $\theta = \int p d\sigma$. The strain-hardening hypothesis modified in this way may also be used to describe creep under cyclically variable loads, if the holding time at the higher stress level is not too short relative to the holding time at the lower stress level. If, however, the holding time at σ_- is much larger than that at σ_+, the effect of time at the lower stress on the creep rate after application of the higher stress must be taken into account in the calculations.

It may be postulated on the basis of our experimental results that certain processes take place when a specimen is held at the lower stress level, as a result of which the process of creep after application of the higher stress does not continue from point C (characterizing the creep strain at the instant of increasing the stress) along the curve BD transferred so that its origin is at point C (curve CD' in Fig. 7), but along the curve AD, where point A is nearer to the origin than point B (curve CD"). The longer t_*, the nearer to the origin point A and, consequently, the faster the initial creep rate at the instant of applying σ_+. Under our experimental conditions a noticeable shift of point A toward the origin is observed at $t_* = 15$ min; at $t_* = 0$, point A evidently coincides with point B.

Extending the above reasoning to creep in the presence of loading discontinuities ($\sigma_- = 0$), we find that—in the absence of strains due to recovery after unloading—the loading discontinuities can only increase the creep strain (if the creep curve is plotted only for the time under load) to an extent which increases with increasing duration of discontinuities and decreasing time under load. On the other hand, a reduction in the creep strain can be obtained with cycles of a certain form, if the strain due to recovery is taken into account. The validity of these conclusions can be proved only by special experiments.

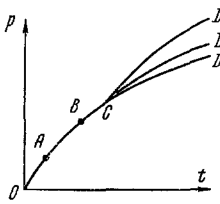

Fig. 7

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