# EXPERIMENTAL INVESTIGATION OF THE EFFECT OF SHORT-TERM PLASTIC DEFORMATION ON THE TRANSIENT CREEP RATE OF A TITANIUM ALLOY VT-6 IN UNIAXIAL TENSION

Yu. P. Kaptelin

In this article the author describes the results of an experimental investigation of the transient creep of a titanium alloy VT-6 (with reduced aluminum and vanadium contents) at 400°C; the creep tests were carried out on sheet specimens both in the as-supplied condition and work-hardened to various degrees by short-term plastic deformation in tension.

It was established that previous short-term plastic deformation of 0.5-1.6% has no effect on the creep relaxation phenomena taking place in this alloy in the entire range of stress studied; in other words, relatively light plastic deformation increases the proportionality limit $\sigma_*$ and conditional yield point $\sigma_{0.2}$ of the alloy in question without affecting its conditional creep strength. On the other hand, heavy short-term plastic deformation (more than 2%) weakens the alloy and reduces its resistance to creep.

Comparison of the results of a study of the influence of short-term plastic deformation on the resistance of materials to creep and relaxation described in [1-5] with the results of this investigation led to the conclusion that in the case of certain metals (e.g., grade M-1 copper) a short-term strain-hardening treatment has a substantial effect on their creep but only at relatively high stress levels; in other cases (e.g., in the case of titanium alloys) the creep properties are practically unaffected by previous short-term plastic deformation. However, even if the creep strength is affected by such a short-term treatment [4], the resulting increase in strength differs from that produced by previous creep. These facts support the view that the mechanisms of short-term deformation and deformation in creep are different.

## NOTATION AND DIMENSIONS

$\sigma$ – stress, kg/mm$^2$
$\sigma_+$ – stress reached during short-time plastic deformation
$\varepsilon^0$ – total strain during short-time plastic deformation, %
$\varepsilon_+$ – plastic strain due to deformation, %
$\sigma_i$ – stresses at which creep tests are carried out ($i = 1, 2, 3, 4$)
$\varepsilon$ – creep strain, %
$\sigma_0$ – initial relaxation stress
t – time, hr
$l°$ – specimen gauge length, mm
d – specimen diameter, mm
$\sigma_*$ – proportionality limit
$\sigma_{**}$ – U.T.S.
$\sigma_{0.2}$ – conditional yield point
$\delta$ – relative residual elongation in tension, %
$\psi$ – reduction in area in tensile tests, %
T – temperature, °C

1. Experimental Procedure. The creep tests in uniaxial tension were carried out on an IP-2 machine equipped with a redesigned tensometric device [6]. The stress relaxation tests were carried out on the same machine with the aid of an attachment described in [7]. Cylindrical specimens with a gauge portion 100 mm long and 5 mm diameter were used.

The short-term strain-hardening treatment was applied by stepwise loading of the specimens to a predetermined level of the real stress (taking into account the reduction in specimen cross-section area due to

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Leningrad. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, Vol. 10, No. 3, pp. 179-183, May-June, 1969. Original article submitted March 9, 1967.

TABLE 1

| Specimen No. | $\sigma_*$ | $\sigma_i$ | $\sigma_i/\sigma_*$ | $\sigma_2$ |
|---|---|---|---|---|
| 7 | 23.5 | 11.65 | 0.496 | 12.82 |
| 8 | | 19.35 | 0.823 | — |
| 12 | | 20.20 | 0.858 | 23.4 |
| 33 | | 23.45 | 1.00 | 25.8 |

TABLE 2

| Specimen No. | $\sigma_+$ | $\varepsilon_+$ | $\sigma_i$ | $\sigma_i/\sigma_+$ |
|---|---|---|---|---|
| 13 | 39.90 | 1.556 | 39.90 | 1.00 |
| 4 | 37.10 | 0.606 | 37.10 | 1.00 |
| 10 | 34.87 | 0.399 | 34.87 | 1.00 |
| 14 | 29.30 | 0.038 | 29.30 | 1.00 |

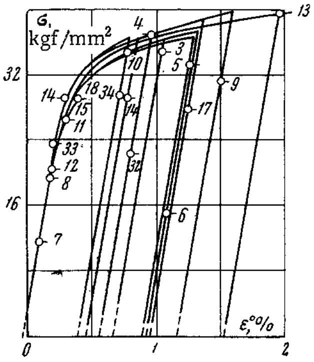

Fig. 1

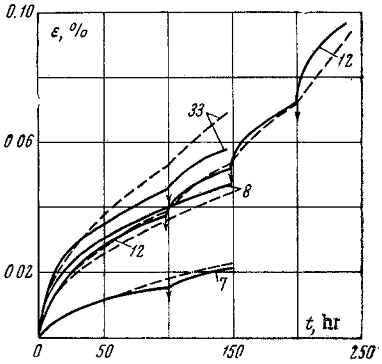

Fig. 2

Fig. 1. Tensile stress-strain diagrams based on data obtained during short-term strain-hardening treatment applied to alloy VT-6 specimens before creep tests at 400°C. Points on each diagram indicate stress levels at which creep tests were subsequently carried out on the corresponding specimens. Numbers ascribed to these points denote here and henceforth the specimen numbers.

Fig. 2. Creep curves of alloy VT-6 specimens not subjected to previous strain-hardening treatment. Test temperature T = 400°C, $\sigma_i \leq \sigma_* = 23.5$ kg/mm$^2$; for specimen No. 12 $\sigma_1 = 20.20$, $\sigma_2 = 23.4$, $\sigma_3 = 26.2$, and $\sigma_4 = 29.3$ kg/mm. Arrows on creep curves in this and other figures indicate changes in the applied load (arrows pointing downward indicate an increase and those pointing upward a reduction in load).

deformation) on the creep testing machine IP-2 at 400°C immediately before the commencement of a creep test; the method used was previously described in [4]. Data obtained during the loading and unloading stages of this short-term treatment were used to plot a graph showing the dependence of strain $\varepsilon^0$ on real stress $\sigma$.

The temperature gradient over the specimen length did not exceed ±1.0° and the temperature was maintained constant during tests accurate to ±2°C.

Tensile properties (average results of n tests, where n = 3 and 5) determined for the titanium alloy studied by short-term tensile tests are given below (d = 5 mm, $l_0$ = 25 mm):

| $T$ | $\sigma_{**}$ | $\sigma_{0.2}$ | $\delta$ | $\psi$ | |
|---|---|---|---|---|---|
| 20 | 75.0 | 66.3 | 16.4 | 27.2 | $(n=5)$ |
| 400 | 44.5 | 33.0 | 16.4 | 56.4 | $(n=3)$ |

2. Experimental Results and Discussion. Stress-strain diagrams obtained during the short-term strain-hardening treatment (Fig. 1) and data collected when specimens were unloaded after creep tests were used to calculate the elasticity modulus E = $0.936 \cdot 10^4$ kg/mm$^2$ (an average of 32 determinations) and the proportionality limit $\sigma_*$ = 23.5 kg/mm$^2$ at 400°C.

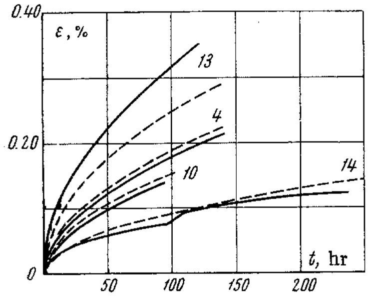

Fig. 3

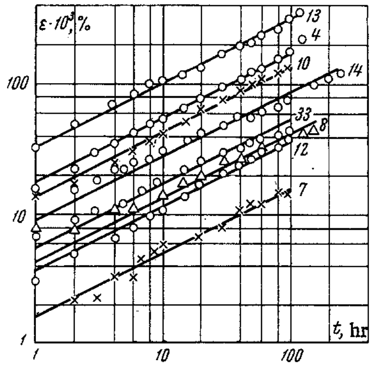

Fig. 4

Fig. 3. Creep curves of work-hardened specimens at $\sigma_i = \sigma_+$ and T = 400°C.

Fig. 4. Results of creep tests at 400°C plotted in logarithmic coordinates.

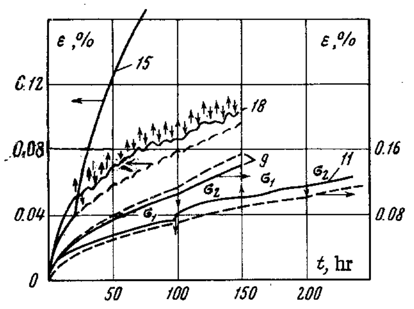

Fig. 5

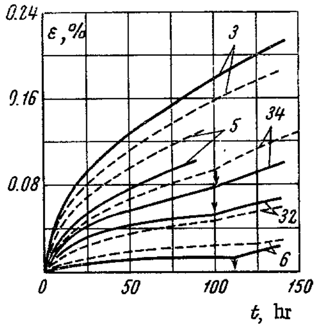

Fig. 6

Fig. 5. Creep curves of specimens tested at step-like varying stresses. Left scale: specimen No. 11) $\sigma_1 = 26.35$, $\sigma_2 = 27.70$; specimen No. 9) $\sigma_+ = 39.95$; $\sigma_1 = 31.52$; $\sigma_2 = 34.67$. Right scale: specimen No. 18) $\sigma_1 = \sigma_+ = 28.3$; $\sigma_2 = 23.66$; specimen No. 15) $\sigma_1 = \sigma_+ = 29.3$; $\sigma_2 = 29.22$ at t = 20 hr after short-term deformation $\varepsilon_+ = 6.2\%$ at $\sigma_+ = 41.7$ kg/mm$^2$.

Fig. 6. Creep curves of specimens work-hardened at $\sigma_+ = 37$ kg/mm$^2$, T = 400°C.

Two series of creep tests were carried out. The aim of the first series of tests was to study the effect of work-hardening on subsequent creep; the relations established as a result of these tests were verified by the second series of tests which included stress relaxation tests and creep tests with step-by-step variation in stress.

The first series of tests included creep tests at $\sigma_i \leq \sigma_* = 23.5$ kg/mm$^2$ on specimens that had not been work-hardened (Table 1, Fig. 2) and several tests on work-hardened specimens (Table 2, Fig. 3). Experimental results are reproduced in the figures as solid curves.

The elastic strains and short-term plastic strains (produced when the load applied to specimen No. 12 was increased to $\sigma_4 = 23.3$ kg/mm$^2$, $\varepsilon_+ = 0.013\%$) were taken into account in plotting the creep curves.

If creep test results are plotted in logarithmic coordinates (log t, log ε), it is found that transient creep at constant loads can be satisfactorily represented by a set of parallel straight lines (Fig. 4). The slope of these lines is m = 0.500. If the logarithm of creep strain recorded one hour after the start of a test is denoted by z, then the experimental data presented in (z, σ) coordinates are in good agreement with

TABLE 3

| Specimen No. | $\sigma_+$ | $\varepsilon_+$ | $\sigma_i$ | $\sigma_i/\sigma_+$ | $\sigma_2$ |
|---|---|---|---|---|---|
| 6 | 37.6 | 0.950 | 15.0 | 0.399 | 16.50 |
| 32 | 37.0 | 0.587 | 22.2 | 0.600 | 24.42 |
| 34 | 37.1 | 0.415 | 29.6 | 0.800 | 32.56 |
| 5 | 37.1 | 0.930 | 33.4 | 0.901 | — |
| 3 | 36.9 | 0.702 | 35.1 | 0.951 | — |

the linear distribution law. All this points to the possibility of approximating the relationship studied by the equation of state of the theory of strain hardening in the form

$$\dot{\varepsilon}\varepsilon^{\alpha} = K \exp\frac{\sigma}{A} \qquad \left(\alpha = \frac{1-m}{m}\right) \tag{1}$$

Here K, A, and $\sigma$ are constant in the entire range of stress applied in the tests:

$$\alpha = 1,\ K = 0.179 \cdot 10^{-10},\ A = 5.36\ \text{[kg/mm}^2 \tag{2}$$

The theoretical creep curves in Figs. 2 and 3 are shown by dashed lines.

Creep test results showed that the creep behavior of alloy VT-6 at 400°C is practically unaffected by previous short-term plastic deformation at this temperature, while step-by-step creep, i.e., creep taking place after straining the alloy in creep at a different stress, is in good agreement with the theory of strain-hardening (Fig. 2).

This supports the view that short-term deformation and deformation in creep have different mechanisms and different effects on subsequent creep [1-4].

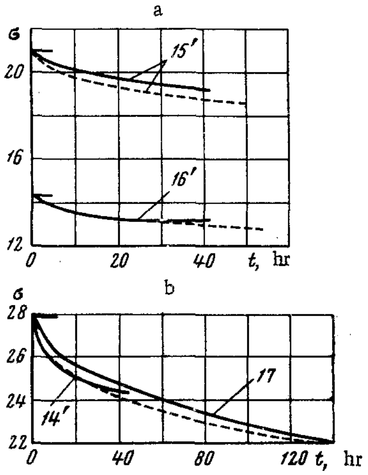

Fig. 7. Stress relaxation curves: a) in the as-received condition; b) after work-hardening.

To find whether the strengthening effect of previous creep is destroyed by short-term plastic deformation applied at a certain instant during a creep test, we carried out the following experiment. Specimen No. 14 after 97 hr in creep at $\sigma$ = 29.3 kg/mm$^2$ was plastically strained by short-term step-like loading to $\sigma_+$ = 36.7 kg/mm$^2$ (which produced a residual plastic strain $\varepsilon_+$ = 0.446%) and then unloaded to $\sigma$ = 29.3 and tested in creep for additional 150 hr. Data in Fig. 3 show that in this case the short-term plastic deformation had little effect on the rate of subsequent creep. On the other hand, when specimen No. 15 was subjected to short-term plastic deformation of 6.2% ($\sigma_+$ = 41.7) after 20 hr creep at $\sigma_1$ = 29.3 kg/mm$^2$, its subsequent creep rate at $\sigma$ = 29.22 kg/mm$^2$ was substantially higher than that before the short-term plastic deformation (Fig. 5). Evidently, the degree of short-time plastic deformation was in this case sufficiently high to produce a substantial reduction in the alloy strength (in this case $\sigma_+$ was close to $\sigma_{**}$ at 400°C).

To verify the conclusions reached and the validity of the approximating expressions used, we carried out a second series of creep tests on specimens work-hardened at $\sigma_+ \simeq$ 37 kg/mm$^2$; the tests were carried out at a constant stress, at a stress which was increased once (Table 3, Fig. 6), and at a cyclically varying stress (Fig. 5). In the case of specimen No. 11 the stress after 100 hr creep at $\sigma_1$ = 26.35 kg mm$^2$ was increased thrice at 50-hr intervals to 27.70 kg/mm$^2$; specimen No. 18 was tested in creep at $\sigma_1$ = 29.3 kg/mm$^2$ for the first 20 hr after which the stress was periodically varied (at 5-hr intervals) from 23.66 to 29.3 kg/mm$^2$.

In addition to creep tests we carried out four stress relaxation tests: two specimens were tested in the as-received condition at initial stresses of 20.9 and 14.15 kg/mm$^2$ (Fig. 7a, specimens No. 15' and 16'); the other two specimens were tested at an initial stress of 27.9 kg/mm$^2$, one after previous short-time tensile plastic deformation at 39.25 kg/mm$^2$ producing $\varepsilon_+$ = 0.942% (Fig. 7b, specimen No. 17) and the other after a similar treatment at $\sigma_+$ = 27.9 kg/mm$^2$ (Fig. 7b, specimen No. 14').

Theoretical curves in Figs. 5, 6, and 7 were plotted with the aid of the equation of state (1) and constants (2) obtained from the results of creep tests on specimens in the as-received condition. The good agreement between theoretical and experimental curves (for the second series of tests) proves that short-term plastic deformation of about 1.0% has no effect on the creep of the titanium alloy studied at stresses of up to $\sigma_+$. It should be borne in mind that each experimental curve was plotted from the results of tests on one specimen; as is known, creep and stress relaxation tests carried out on twin specimens under identical conditions can produce widely scattered results.

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