# CREEP OF TECHNICAL COPPER UNDER COMBINED LOADING

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This paper gives the results of an experimental study of the creep of technical copper at constant and variable loads using thin-walled tubular specimens subjected to different combinations of tension and torsion. The test apparatus was described previously in [1]. The experiments were conducted at 150° C and lasted not more than 100 hr.

The test material was taken in the form of tube 30 mm in diameter. Before the experiments the initial isotropy was verified. For this purpose, small longitudinal and transverse specimens were cut out and tested in creep under identical loads and at the temperature of the main experiments. As shown in Fig. 1, where the continuous line represents the creep curve of a longitudinal specimen averaged over several tests, and the broken line that for a transverse specimen (p—creep strain), the material has a slight initial anisotropy. Attempts to improve the state of the material by mild heat treatment were not particularly successful. Greater heat treatment would lead to considerable softening of the material, which could not then be tested on existing apparatus.

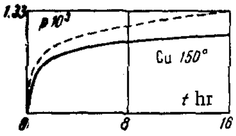


Fig. 1

Therefore it was decided to neglect the slight anisotropy detected and to test the material in its original state, if one disregards the period of almost four hours at the experimental temperature, during which the temperature was stabilized. From each tube we prepared thin sections and for the experiments selected only those with the same fine-grained structure. Figure 2 shows typical micrographs of (b) a longitudinal and (a) a transverse section (× 120). Clearly, the structure of the material is fine-grained and signs of anisotropy are scarcely noticeable. The wall thickness of the specimen was taken as not less than 15 grains.

The following program of experiments was carried out: eight specimens were tested in simple torsion at a constant twisting moment, nine in simple tension under a constant axial load was varied in steps, the condition of proportional loading always being observed, i.e., during each tests the equation

$$\tau/\sigma = \lambda = \text{const} \tag{1}$$

was satisfied.

Here $\tau$ is the tangential, and $\sigma$ the normal stress. In these tests the quantity $\lambda = 0.35$ and $0.89$. Each specimen was subjected to four stages, of loading, the length of each stage being about 24 hr. Individual tests in simple torsion and simple tension were made in accordance with the same scheme. In addition, we carried out 14 experiments at a constant rate of change of stress. Three loading rates were used $\dot{\sigma_i} \approx 8$, 0.8 and 0.08 kg/mm$^2$ · hr; here $\sigma_i = \sqrt{\sigma^2 + 3\tau^2}$.

In some experiments, after a certain interval of time the loading rate was instantaneously reduced to zero, and the specimen was tested at a constant stress, after which the loading rate was again instantaneously reduced to zero, and the specimen was tested at a constant stress, after which the loading rate was again instantaneously restored to the previous level. However, in all these cases condition (1) was satisfied. In the experiments with constant loading rate $\lambda$ was chosen in the range 0.43–0.60.

An analysis of the existing theories of creep shows that most of them involve three basic hypotheses.

1. The change in volume is elastic

$$p_{jj}^{\cdot} = 0. \tag{2}$$

The components of the creep strain tensors

$$p_{jk} = \varepsilon_{jk} - e_{jk}. \tag{3}$$

Here $\varepsilon_{jk}$ are the total, and $e_{jk}$ the instantaneous (elastic or plastic) strains. Here and in what follows we use the notations of tensor analysis. A dot denotes differentiation with respect to time.

2. The stress deviator

$$(\sigma_{jk}^* = \sigma_{jk} - \delta_{jk}\,\sigma', \quad 3\sigma' = \sigma_{jj})$$

is proportional to the creep strain rate deviator

$$p_{jk}^{\cdot} = \Lambda \sigma_{jk}^*$$

$$(\delta_{jk} \text{ is the Kronecker delta}). \tag{4}$$

3. The invariants of the stress and creep strain tensors and the tensors of the stress and strain rates are related by an expression that does not depend on the form of the stress state. For example,

$$\Phi(\sigma_i, p_i, p_i^{\cdot}) = 0, \tag{5}$$

$$p_i^{\cdot} = \int ({}^2/_3\, p_{ik}^{\cdot}\, p_{jk}^{\cdot})^{1/2} dt,$$

$$\sigma_i^2 = {}^3/_2\, \sigma_{jk}\sigma^*_{jk}{}^*. \tag{6}$$

A frequently used special case of relation (5) is

$$p_i^{\cdot} p_i^{\alpha} = f(\sigma_i). \tag{7}$$

Hence at constant stress there follows

$$p_i = (t/m)^m f^m(\sigma)$$
$$(m = 1/(1+\alpha)). \tag{8}$$

Consequently, in logarithmic coordinates lg $p_i$, lg t the experimental points must lie along parallel lines. The examples presented in Fig. 3 show that this condition is satisfactorily fulfilled. The quantity $m = 0.28$ ($\alpha = 2.57$).

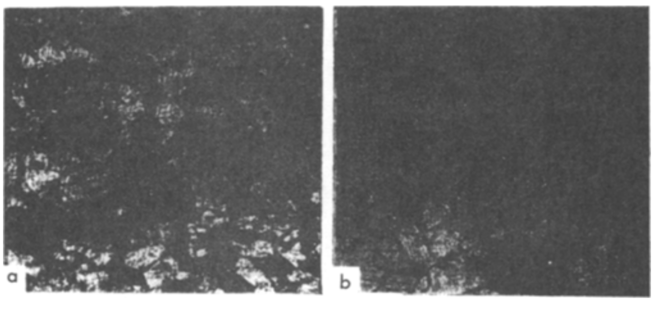


Fig. 2

At a fixed value of time in the octahedral plane $p_i\ \sigma_i$ a single curve should be obtained for all stress states. As may be seen from Fig. 4, this condition is fulfilled: the scatter of the experimental points is usual for creep.

The commonest expressions of the function

$$f = k\sigma_i^n \quad \text{or} \quad f = \varkappa \exp \sigma_i / A$$

require that in coordinates lg $p_i$ − lg $\sigma_i$ or lg $p_i$ − $\sigma_i$ a straight line be obtained. However, as may be seen from Fig. 4, in the case of a power function, this is not observed; the same result is obtained for an exponential function $f$. In what follows, the power-law approximation of the function $f$ has been used with the following values of the constants:

$$n = 3.84, \quad k = 1.067 \cdot 10^{-17} \text{ hr}^{-1} \quad \text{at} \quad \sigma \leqslant 9.34 \text{ kg/mm}^2$$

$$n = 8.23, \quad k = 5.87 \cdot 10^{-22} \text{ hr}^{-1} \quad \text{at} \quad \sigma \geqslant 9.34 \text{ kg/mm}^2.$$

It should be noted that in the stress range in which the experiments at constant loads were carried out a good approximation of the test data is given by

$$f = \varkappa \exp \frac{\sigma_i^2}{A} \qquad \left(\begin{matrix} A = 34.74 \text{ kg}^2/\text{mm}^4 \\ \varkappa = 4.37 \cdot 10^{-15} \text{ hr}^{-1} \end{matrix}\right). \tag{10}$$

However, at small values of $\sigma_i$ this expression is not correct.

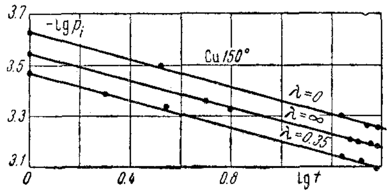


Fig. 3

We now turn to the second hypothesis. Under proportional loading (in particular, loading at constant rate and at constant loads) relation (4), under the conditions of our experiments, is reduced to

$$\gamma^p / \varepsilon^p = 3\lambda. \tag{11}$$

Here $\varepsilon^p$ is the axial creep strain, and $\gamma^p$ is the creep shear strain. In the experiments the total strains are measured; obtaining the creep strain for step loading does not present any difficulties. In order to obtain the creep strain at a stress that varies at a constant rate it is necessary to know the instantaneous strain curves or, at least, the moduli of elasticity, if one confines oneself to the elastic range, which was the case in our experiments. The following values of the elastic constants were found:

$$E = 10 \cdot 10^3 \text{ kg/mm}^2, \quad G = 3.85 \cdot 10^3 \text{ kg/mm}^2.$$

Since this hypothesis has already been examined in detail for step loading of an aluminum alloy [2], we will not dwell upon this case. We shall merely show that relation (11) is satisfied with almost the same accuracy as for aluminum alloy (in individual cases the deviations of the right and left sides reach 30%).

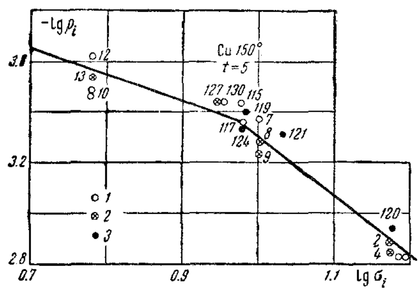


Fig. 4

Of greater interest is the case of creep under a load that varies at a constant rate (a typical example is shown in Fig. 5). On the right side of Fig. 5 the continuous straight line represents the quantity 3λ (right side of relation (11)), and the dots represent the ratio $\gamma^p/\varepsilon^p$ (left side of relation (11)). An analysis of all the results obtained showed that the hypothesis of proportionality of the deviators is satisfactorily fulfilled. The deviations of the right and left sides of (11) do not, in the main, exceed 15%. This result is similar to the result obtained for an aluminum alloy under step loading in [2].

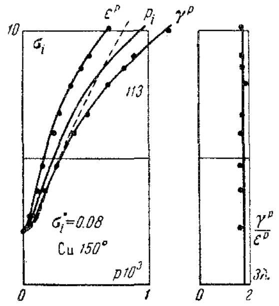


Fig. 5

We will now consider the third hypothesis. At constant stress the question is completely settled by all that has been discussed above.

For step loading (a typical example is shown in Fig. 6), after the load is increased the experimental curve lies above the curve predicted by relation (7) (broken line).

On the segment following the addition of load, the discrepancy between theory and experiment increases. This is in agreement with our previous results for other materials.

For a load that increases at a constant rate relation (7) (Fig. 5, broken line) also gives values of the creep strain that are too low compared with the experimental values. However, in this case, the discrepancy between theory and experiment is less than for step loading.

R. Rabotnov [3] has proposed the quantity

$$a = \int \sigma_{jk} \, dp_{jk} \tag{12}$$

as a measure of hardening. The integral is taken over the entire deformation path.

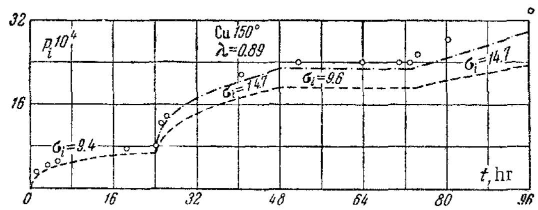


Fig. 6

The hypothesis (7) can then be replaced by

$$p_i^{\cdot} a^{\alpha} = k\sigma_i^{n+\alpha}. \tag{13}$$

It is easy to show that

$$a = \int \sigma_i dp_i. \tag{14}$$

Consequently, at constant $\sigma_i$ Eq. (13) is reduced to (7), and hence the constants in (13) are the same as in Eq. (7). In spite of the fact that the theory has apparently undergone only minor changes and no new constants have been added, the new variant of the theory shows better agreement with experiment then the old. This is clear from Fig. 6, where the dot-dash curve was calculated from relation (13).

In addition to the experiments mentioned above, six more were carried out in accordance with the following program. The specimen was tested in simple torsion (tension) at a constant value of $\sigma_i$ for $t_0$ hours. Then the load was removed and immediately restored to the same level $\sigma_i$ in tension (torsion), whereupon the test was continued for a further $t_0$ hours.

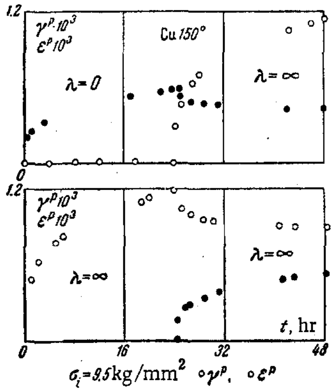


Fig. 7

Figure 7 shows some typical results of these tests. The upper part of Fig. 7 presents the data of a test in which torsion replaced tension, and the lower part, a test in which tension replaced torsion. If the second part of the upper shear strain curve is compared with the first part of the lower, it is easy to see that they coincide. In exactly the same way, the first part of the upper tension curve coincides with the second part of the lower one.

Thus, we arrive at the conclusion that preliminary torsion (tension) does not affect subsequent tension (torsion) at the same stress intensity. This result was previously obtained for EI-257 steel [4].

It is clear from Fig. 7 that when tension is replaced by torsion the elongation decreases, whereas when torsion is replaced by tension the shear strain decreases. The same thing was previously observed in connection with EI-257 steel, though to a lesser degree, but was not noted in [4].

It is interesting to remark that a similar phenomenom was observed in experiments on plastic deformation [5].

The results of the last series of experiments do not conform with any of the existing theories of creep.

REFERENCES

1. V. S. Namestnikov, "Creep at constant load in the complex stress state," Izv. AN SSSR, OTN, no. 4, 1957.

2. V. S. Namestnikov, "The hypothesis of proportional deviatiors under conditions of creep with variable loads and fixed principal axes," PMTF, no. 3, 1960.

3. Ju. N. Rabotnov "On the equation of state for creep," in: Progress in Applied Mechanics, ed, D. C. Drucker, MacMillan co., New York, 1963.

4. V. S. Namestnikov, "Creep at variable loads in the complex stress state," Izv. AN SSSR, OTN, no. 10, 1957.

5. M. Feigin, "Inelastic behavior in tension and torsion," Mekhanika (collection of translations into Russian and reviews of the foreign literature), no. 3, 1956.

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