TEMPERATURE AFTEREFFECT IN METALS

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The creep of solids has for long attracted the attention of research workers as one of the most fundamental phenomena. The traditional methods of investigating the physical nature and laws of creep are usually limited to tests on materials at a constant stress and temperature and to the investigation of the characteristics of structural elements of materials subjected to such tests. The basic phenomenological laws of creep have been established and many microscopic mechanisms of this phenomenon have been postulated. Structures and their elements calculated for creep strength on the basis of formal concepts are successfully exploited.

A complete physical theory of creep should correctly interpret not only the facts pertaining to isothermal creep at a constant stress but also the laws of a more complex behavior of materials, e.g., creep at varying temperatures or stresses. The latter requirement is dictated by both general physical considerations and operational experience. Real structures never work under those ideal conditions that obtain in standard creep tests. It is obvious that a physical theory of creep should correctly predict the properties of materials under widely differing external conditions.

Experiment shows that creep of metals and alloys under varying external conditions often obeys laws which cannot be directly determined from available data on ordinary creep. Neither do these laws follow (see, e.g., [1-7]) from the widely known physical models postulated for the explanation of creep [3]. Thus, the creep rate at a varying temperature often undergoes a substantial increase [5] or decrease [6, 7], while in isolated instances it is not affected by temperature variations [8]. The difference between experimental creep rates and their values calculated on the basis of various theories is sometimes of several orders of magnitude, being often qualitative in character [4].

This situation is intolerable not only from the practical point of view but also from the standpoint of understanding the nature of the phenomenon in question. Due to large discrepancies between experimental and theoretical creep rate values it is often pointless to carry out design calculations with the aid of accepted standards. Moreover, the question of the validity of the starting theoretical concepts presents a real problem. This means that either the known theories about the probable mechanisms of creep are incorrect, or they are correct but the stress or temperature variations introduce singularities (e.g., in the structural state of the material) which cannot be inferred directly from conventional test results.

Thus, investigations of creep of materials under varying external conditions bring twofold benefits: firstly, they make it possible to determine the load-carrying capacity of materials under conditions approaching those that obtain in practice; secondly, creep tests in nonstationary force and temperature fields give more comprehensive information about material properties. Creep under varying external conditions may serve as one of the criteria of the validity of theories dealing with the nature of creep and with the structural state of materials in creep.

This article describes the results of an investigation of creep of metals and alloys in variable temperature fields.

EXPERIMENTAL METHOD

The most widely used method of creep testing at varying temperatures [4] consists in measuring the creep strains accumulated during a specified number of thermal cycles. The total strain obtained in this

way is then compared with the value calculated by trivial averaging over a thermal cycle. Data on iso-
thermal creep rates are used in the calculations. If the results of calculations agree with experimental
data, it is concluded that temperature variations do not affect the issue. Otherwise the opposite conclu-
sion is reached. Detailed information on the method of calculation is given in [4], while the results of
original investigations are reported in [1, 2, 5-8].

However, the above described approach gives no information about the kinetics of the accumulation
of "nonisothermic" strains. Questions regarding the precise stage of the temperature variation in which
complications arise can be answered only from various indirect symptoms, e.g., from the character of
the influence of frequency, form, and amplitude of the thermal cycle, etc.

In this investigation the nonisothermal creep strain was measured directly at each thermal cycling
stage, i.e., during the heating and cooling stages, during the isothermal stage, etc. The temperature was
varied during the steady-state creep stage. It was established by a series of special tests, however, that
analogous results are obtained when the temperature is varied during the first creep stage. Special atten-
tion was paid to the way in which the creep strain is affected by a single thermal cycle; it was estab-
lished that this strain does not depend on the number of thermal cycles preceding the cycle under consid-
eration. Nevertheless, all the creep specimens were subjected to several preliminary thermal cycles identi-
cal to that used in a given test; henceforth these preliminary cycles will be called "idle."

The conclusions of this investigation are based on the results of torsional creep tests. Tests in uni-
axial tension were also carried out and gave qualitatively analogous results. The torsion tests were car-
ried out on thin-walled tube specimens under the influence of a constant twisting moment. The specimen
gage length was 100 mm, the o.d. and i.d. being 10 and 7 mm. The strain was measured accurate to ±2
× 10^-5, the temperature being controlled accurate to ±1.0°C. Before testing all the specimens were given
a 3 h annealing treatment at a temperature equal to T_m/2, where T_m is the melting point, °K.

Analysis of the test results showed that one must clearly distinguish between two (different in their
nature) effects accompanying temperature variations.

The first effect is associated with the following facts. It is known that the structural state of a ma-
terial (in the widest meaning of this term) depends on temperature and the stress state; it may become a
stationary-nonequilibrium state if the steady-state stage of creep is reached in a test. As a result, the
material structure characteristic of the steady-state creep should be a function of temperature (and stress),
i.e., it should be different for various isothermal creep curves. If the temperature (stress) is increased
or decreased during a test, this immediately produces a corresponding redistribution of the structural
elements, even if the transition from one temperature (stress) level to another takes place during the
steady-state creep stage. The reverse temperature change should, naturally, promote the regression of
the structure to its initial state, and so on.

Since the structural state of a material determines (for given external conditions) the rate of creep,
the strain–time curves should show an additional transitional strain accompanying each temperature
change; we shall call it the strain of temperature aftereffect or simply the aftereffect strain.

The second effect, which is not considered in this article though it should be borne in mind, was ob-
erved in investigations [9, 10] of low-temperature nonisothermal creep. It is associated with the fact that
cooling a specimen during a creep test may produce irreversible structural changes substantially reducing
the subsequent creep rate, i.e., increasing the strength of the material.* Tests in our investigation were
carried out in such a way that this effect was absent.

RESULTS AND DISCUSSION

One must clearly distinguish between the temperature aftereffect in metals with noncubic and cubic
symmetries. Many experiments have shown that the temperature aftereffect in metals with noncubic sym-
metry is mainly due to thermal stresses of the second kind. These stresses are produced as a result of
anisotropy of the thermal expansion coefficient. They may reach the crystal yield point as a result of tem-
perature variations of a few degrees not only in polycrystals but also in single crystals with a strongly
pronounced mosaic structure.

*This increase in strength differs from the aftereffect in that the aftereffect is due to reversible structural
changes while the increase in strength is characterized by the appearance of stable structural elements
which remain when the temperature is raised again. Moreover, the increase in strength takes place only
during the first few thermal cycles and is caused only by cooling the specimens.