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THE NATURE OF THE CREEP CURVE

Ninth Technical Report

by

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under

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Vast strides have been made in the development of high temperature creep resistant alloys, but no sound understanding of the mechanism of this phenomena exists to date. Consequently, creep resistant alloys are still developed by the "cut and try" methods which were formerly so successful but are now yielding diminishing returns for the moneys expended. It is apparent to all workers in the field that if the mechanism of creep were understood much fruitless labor could be eliminated. Even though such an understanding is not yet available, numerous theories of creep have been proposed. A critical review of these theories reveals that there are some general areas of agreement between the majority of the workers, but there are many fundamental questions yet to be resolved. (1)*

It is generally conceded that theoretical speculation is far in advance of experimental evidence and it is the need for additional reliable creep data that now hinders more rapid progress in the theoretical field. It is essential that the effects of different stresses and temperatures on the creep characteristics of metals be quantitatively defined. Once this has been accomplished, it will then be possible to evaluate the effects of alloying additions, and it is hoped to provide a firm basis of facts for theoretical treatment of the phenomena. The work reported herein was undertaken to determine the effects of such variables as stress, temperature, alloying, and structure on the creep characteristics of some metals.

Nickel was selected as the base material for the current investigation and an experimental program was initiated to determine the effects of temperature and stress on the creep characteristics of this material.

* Numbers refer to bibliography at end of report.

Since the ultimate goal of the study was to provide data which would be of value for theoretical studies, all tests were performed under conditions of constant stress rather than the more conventional constant load; the test facilities have been described previously.⁽²⁾ The data which were obtained from this original program were plotted in the usual manner on rectangular coordinates and the "secondary" or "steady state" creep rate determined for each as illustrated in Fig. 1. This concept of a steady state creep rate has long been accepted and used by both designers and theorists as a reliable parameter to define the creep behavior of materials under given conditions.

However, as pointed out by Lubahn,⁽³⁾ such a concept may be unjustified. When the data of Fig. 1 are replotted on a vastly expanded time scale, as shown in Fig. 2, an apparent constant strain rate is again evidenced, but of a different magnitude than that previously obtained.

Subsequent work by the General Electric Research group demonstrated that in many cases, creep data obtained from constant stress tests showed a continuous decrease of creep rate up to the point of initiation of failure.⁽⁴⁾ This is illustrated by Fig. 3, which shows that when the logarithm of the strain (ϵ) is plotted against the logarithm of the time (t), the resulting creep curve is linear. Consequently, the data may be represented by the following empirical relationship.

$$\epsilon = A t^b \quad (1)$$

where A and b are constants.

A critical re-examination of all available constant stress creep data substantiated the thesis that the creep rate does continuously

FIG. 1 TYPICAL CONSTANT STRESS CREEP CURVE
FOR HIGH PURITY NICKEL

FIG. 2 EXPANDED INITIAL PORTION OF CREEP CURVE
SHOWN IN FIG. 1

decrease as postulated by Fisher and Holloman.⁽⁴⁾ Consequently, it was concluded that the concept that the creep rate eventually becomes and remains constant is incorrect, and the use of such a parameter for correlating constant stress creep data is unjustified.

Since it is highly desirable, if not essential, to utilize some specific parameters when comparing results of creep tests, Equation (1) was adopted with considerable success as shown by the creep curves for nickel in Fig. 4. This was further substantiated by Lubahn's data on mild steel⁽⁴⁾, Correker's results on platinum⁽⁵⁾, and by one of Andrade's constant stress creep curves for copper.⁽⁶⁾ However, as the stress and temperature test range for nickel was expanded, it was found that some data did not conform to this simple relationship, but instead produced curved lines which were concave upward on the logarithmic plot. The lack of linearity on the log-log plot was also evident in the data obtained by Andrade for lead and that for aluminum obtained by N. J. Grant at M.I.T.⁽⁷⁾ These curves are shown in Figs. 5 and 6.

The nickel curve of Fig. 5 which exhibits this behavior is shown plotted on rectangular coordinates in Fig. 7, together with a curve obtained from a test performed at 700°C. It may be noted that the total creep strain for the lower temperature test appears to consist of two parts; first, an instantaneous strain and second, a time dependent strain. The region of rapidly decreasing creep rate usually associated with the early portions of the creep curve is not pronounced in the 550°C data, but rather large strains do occur at the time the load is applied. This is more clearly portrayed in the expanded scale plots of the same data shown in Fig. 8. The more typical 700°C curve is again shown for

FIG. 4 CONSTANT STRESS CREEP CURVES FOR
HIGH PURITY NICKEL AT 700 °C

FIG. 5 NON - LINEAR LOGARITHMIC CREEP CURVES
FOR NICKEL AND ALUMINUM

FIG. 6 NON - LINEAR LOGARITHMIC CREEP CURVES
FOR LEAD AND ALUMINUM

FIG. 7 CREEP CURVES FOR HIGH PURITY NICKEL
ON RECTANGULAR COORDINATES

FIG. 8 INITIAL PART OF CREEP CURVES OF FIG. 7
WITH EXPANDED COORDINATES

comparison. It can be seen that the 550°C curve may be extrapolated to a finite strain at zero time with reasonable certainty, but for the 700°C curve the strain rate is increasing so rapidly with decreasing time that the strain at zero time is very indefinite.

On the basis of data exemplified by the 550°C curve, it was found that if the instantaneous strain upon loading was subtracted from the total strain, the resulting time dependent deformation plotted linearly with time on logarithmic coordinates as shown in Fig. 9.

Thus it appears that Equation (1) should be modified to the form

$$\epsilon - \epsilon_0 = At^b \quad (2)$$

where

ϵ = total true strain

ϵ_0 = instantaneous strain at loading

t = time

A, b = constants.

However, this does not explain the linearity of the high temperature curves such as the 700°C curves of Fig. 4 since it would appear from Fig. 8 that the zero time intercept of the 700°C curve is of the same order of magnitude as the 550°C curve.

In order to clarify this situation, special high speed strain recording equipment was constructed to determine accurately the initial part of the curve. For times greater than one hour, the logarithmic plot of these data yields a straight line as shown in Fig. 10. However when data at very short times are plotted the line shows a pronounced curvature as illustrated in the upper curve of Fig. 11. Here it may be seen that the

FIG. 9 LINEARITY OF LOW TEMPERATURE CREEP CURVES FOR HIGH PURITY NICKEL WHEN TIME DEPENDENT STRAIN ONLY IS USED.

FIG. 10 LINEARITY OF NICKEL ALLOY CREEP CURVE AFTER FIRST HOUR OF TEST WHEN TOTAL STRAIN (ϵ) IS USED.

FIG. 11 LOGARITHMIC PLOTS OF COMPLETE CREEP CURVES SHOWING EFFECT OF ϵ_0 CORRECTION

linearity from one hour on is merely a very close approximation, the curvature increasing as the time decreases. A value of $\epsilon_o = 0.0070$ is required to make the total curve straight as shown in the lower curve of Fig. 11. The rectangular plot of these data is given in Fig. 12, including a greatly expanded initial portion. It may be observed from this curve that the total strain at the time the load was fully applied is $\epsilon = 0.0080$. This is considered very good agreement with the value of 0.0070 determined graphically from Fig. 11. The small discrepancy between the two values may be due to the time dependent strain which occurred during loading even though this represents a time period of only 3.5 seconds.

Thus it appears that the value of ϵ_o obtained graphically is a real quantity having physical significance; i.e., it is the instantaneous total strain at the moment of loading, and the time dependent strain, $\epsilon - \epsilon_o$, is linear on a logarithmic plot. Further evidence of this fact is presented in Figs. 13 and 14 which are replots of the curves of Figs. 5 and 6 in which the time dependent strain only is plotted.

The relationship between strain and time of Eq. 2 is further substantiated by the creep curves shown in Fig. 15 obtained from a series of solid solution nickel alloys. All of these specimens were tested at the same temperature and applied stress. It may be noted that the degree of curvature increases as the alloy content increases. However, when the instantaneous strain is subtracted from the total strain, all of these curves become linear as shown in Fig. 16. In these cases, the ϵ_o was determined graphically. It should also be observed that the slope of the time dependent strain curves, b in Eq. 2, increase as the alloy content increases. Similarly, the slope varies with grain size as indicated in

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FIG. 12 RECTANGULAR COORDINATE PLOT OF CREEP CURVE
 SHOWN IN FIG. 11

FIG. 13 TIME DEPENDENT STRAIN CREEP CURVES
FOR NICKEL AND ALUMINUM

FIG. 14 TIME DEPENDENT STRAIN CREEP CURVES
FOR LEAD AND ALUMINUM

FIG. 15 EFFECT OF ADDITIONS OF TITANIUM IN
SOLID SOLUTION ON CREEP CURVES
OF HIGH PURITY NICKEL.

FIG. 16 TIME DEPENDENT STRAIN CREEP CURVES
FOR Ni - Ti ALLOYS

Fig. 17. Observations to date have not revealed any regular variation of $\dot{\epsilon}$ with applied stress and the variation with temperature is not clear at the present time. The parameter A of Eq. 2 on the other hand, does vary in a regular manner with stress and also varies with structure, alloy content, and temperature.

Since all of the foregoing data were obtained for polycrystalline materials, it was deemed desirable to determine whether the continuously decreasing creep rate required the presence of grain boundaries. In order to resolve this question, creep data on zinc single crystals tested in shear was generously offered the writers by O.N.R. project workers of this laboratory. In the typical results shown in Fig. 18, the upper curve (Fig. 18a) is the total strain and Fig. 18b is the time dependent strain. It is apparent that single crystals too follow the behavior required by Eq. 2, indicating that the phenomena of continuously diminishing creep rate is not necessarily dependent upon the presence of grain boundaries.

Results obtained to date may be summarized as follows:

1. The creep rate for structurally stable metals tested under conditions of constant stress decreases continuously until the initiation of failure. There is no region of constant creep rate.
2. The creep curve may be accurately represented by the empirical equation

$$\epsilon - \epsilon_0 = At^b$$

in which

ϵ = total true strain

ϵ_0 = instantaneous strain which occurs at the moment of loading

FIG. 17 EFFECT OF GRAIN SIZE ON SLOPE OF LOGARITHMIC CREEP CURVES

(a) TOTAL DEFORMATION

(b) TIME DEPENDENT DEFORMATION

FIG. 18 LOGARITHMIC CREEP CURVES FOR ZINC
SINGLE CRYSTAL TESTED AT 24.5 °C
AND 35 psi

t = time

A, b = constants.

3. The parameter ϵ_0 is a quantity having real physical significance, denoting an instantaneous strain upon loading. The parameter A varies in a regular manner with stress, alloy content and temperature. The parameter b also varies over a wide range but the correlation of b with temperature etc. will require many additional tests.

4. The empirical equation given above is applicable to both single crystals and polycrystalline materials indicating that the continuously decreasing creep rate is not solely a grain boundary phenomena.

5. Accurate determination of the parameters A , b , and ϵ_0 requires strain measurements beginning at very short times after applying the load. In many cases readings must begin only seconds after loading.

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