A proposed model for high temperature creep of tantalum

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A PROPOSED MODEL FOR HIGH TEMPERATURE CREEP OF TANTALUM

by

Robert E. Uhrig

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A PROPOSED MODEL FOR HIGH TEMPERATURE CREEP OF TANTALUM

Robert E. Uhrig

Abstract--A model for the creep of tantalum at elevated temperature has been presented in which the increase in strain rate with strain is related to the reduction of the cross-sectional area accompanying strain. Comparison of experimental data with the proposed theory indicates that the dominant creep mechanism beyond the second stage of creep starts at a point of highest temperature or at a stress concentration, spreads throughout the volume in the immediate vicinity, and eventually results in localized "necking down."

INTRODUCTION

Observations on creep of tantalum at 800°C by Murphy and Uhrig indicate that the creep curve (strain vs time) can be separated into four stages: the initial stage in which strain hardening occurs and the strain

(1) G. Murphy and R. E. Uhrig, U. S. Atomic Energy Report IS-26,
Iowa State University, Ames, Iowa.
rate decreases, the secondary stage in which the strain rate remains constant, the exponential stage in which strain and strain rate both increase exponentially, and the final stage in which the creep rate increases with time at a rate greater than in the exponential stage. Since the strain and strain rate both vary exponentially with time during the exponential stage of creep, the strain rate is proportional to the strain. This indicates that the strain rate is influenced by the amount of strain in the material and that high temperature creep may involve progressive damage.

One form of change which continually takes place during straining is the reduction of the cross-sectional area of the specimen as it elongates. As most creep machines are constant load rather than constant stress devices, the stress increases as the cross-sectional area decreases. For purposes of analysis the reduction of area is generally assumed to be uniform throughout the gage length of the specimen. However, a considerable amount of "necking down" in a relative small portion of the specimen does occur immediately prior to failure. In examining several specimens for which the test was discontinued when it became evident that failure was eminent, the usual necked down region was found. However, the diameter of the specimen along the rest of the specimen was relatively constant, usually 0.004 or 0.005 in. less than the original diameter.
ANALYSIS

Let us consider the behavior of a specimen undergoing a creep test. The specimen has been machined to a tolerance of ± 0.001 in. in diameter and then polished to a fine finish. The furnace controls have been adjusted to give as uniform a temperature distribution as possible along the gage length. Generous fillets at the end of the gage length have been used to eliminate stress concentrations. However, somewhere along the specimen there is one spot which is hotter than any other spot, or there is one point at which the stress is greater due to the inclusion of an impurity or a machining scratch which causes a stress concentration. Since the creep rate \( \frac{d\varepsilon}{dt} \) is quite sensitive to both stress \( \sigma \) and temperature \( T \) as indicated in the relationship given by Dorn \(^2\)

\[
\frac{d\varepsilon}{dt} = K' e^{B\sigma} e^{-\Delta H/RT}
\]

(1)

where \( K' \) is a structure sensitive parameter, \( \Delta H \) is the activation energy for creep and \( R \) is the gas constant. If the strain takes place in the vicinity of the point where the stress or temperature is a maximum, the cross-sectional area will be reduced locally. This causes the stress to increase at this point and in turn increase the localized strain and strain rate. In the absence of some sort of strain-hardening (or

---

stress-relieving) mechanism, the specimen would fail almost immediately at this point. If an effective strain-hardening mechanism were present, the strength of the material at this point would increase, causing the localized straining to cease and probably start elsewhere. If a partially effective strain-hardening mechanism were present, it is possible that the strain could be confined to a local area without causing immediate failure. The existence of such a partially effective strain-hardening mechanism at the high temperature (800°C) under consideration is postulated for the analysis which follows.

Another factor which contributes to the increasing strain rate is the use of nominal (engineering) strain $\varepsilon$ rather than true strain $\varepsilon$. Since the original gage length is less than the actual gage length at any time during the test, the use of engineering strain gives strains and strain rates which are higher than the corresponding true strains and strain rates. True strain $\varepsilon$ can be shown to be

$$\varepsilon = \ln (1 + \varepsilon). \quad (2)$$

The derivative of Eq. (2) gives the true strain rate

$$\frac{d \varepsilon}{dt} = \frac{1}{1 + \varepsilon} \cdot \frac{d \varepsilon}{dt} \quad (3)$$

which is less than nominal strain rate by a factor $(1 + \varepsilon)$. True stress is defined as

$$\sigma = \frac{P}{A} = \frac{P}{A_0} \cdot \frac{A_0}{A} = S \frac{A_0}{A} \quad (4)$$
where \( P \) is the load, \( A \) is the area at any time (or strain), \( A_o \) is the original area and \( S \) is the engineering stress. For a constant volume straining process occurring uniformly over the entire gage length

\[
L_o \frac{A_o}{A} = L A
\]

(5)

or

\[
\frac{A_o}{A} = \frac{L}{L_o} = \frac{L_o}{L_o} = \frac{L_o + \varepsilon L_o}{L_o} = (1 + \varepsilon) \quad (6)
\]

Substitution of (4) and (6) into (1) gives

\[
\frac{d \varepsilon}{dt} = K \varepsilon^{BS}(1 + \varepsilon) \cdot \varepsilon^{-\Delta H/RT} \quad (7)
\]

This indicates that the strain rate is increased by a factor \( \varepsilon^{BS\varepsilon} \) due to the reduction in area of the specimen. The use of true strain or division of the creep rates by \( \varepsilon^{BS\varepsilon} \) does not significantly change the numerical values of strain or strain rate. Hence the use of true strain does not explain the observed increase of strain rate with strain.

If it is assumed that all of the plastic flow (or creep) occurs in a fraction \( \alpha \) of the original gage length \( L_o \), a relationship between the strain rate and strain can be derived. Consider the specimen of Fig. 1 where all the deformation occurs in a fraction \( \alpha \) of the gage length \( L_o \). By definition:

\[
\text{Engineering strain} \quad \varepsilon = \frac{\delta}{L_o} \quad (8)
\]

"True" strain \( \varepsilon = \ln(1 + \varepsilon) \) \quad (9)
Fig. 3. Strain rate vs strain for specimen with previous history
Actual engineering strain $\varepsilon' = \frac{\delta}{\alpha \bar{L}_0}$

(10)

Actual "true" strain $\varepsilon' = \ln(1 + \varepsilon')$

(11)

Engineering stress $S = \frac{P}{A_0}$

(12)

"True" stress $\sigma = \frac{P}{A}$

(13)

where $A$ is the area of the specimen at the reduced section, and $\delta$ is the total elongation of the specimen. Eqs. (8) and (10) can be combined to give

$$\varepsilon' = \frac{\varepsilon}{\alpha}$$

(14)

and hence

$$\varepsilon' = \ln\left[1 + \frac{\varepsilon}{\alpha}\right].$$

(15)

Fig. 2 is a sketch of the reduced portion of the specimen. If the equation of the profile of the specimen is assumed to be

$$x = \frac{r_0 + r}{2} - \frac{r_0 - r}{2} \cdot \cos \frac{2y}{L'},$$

(16)

the volume in which deformation occurs is

$$V = \int_{-\frac{L'}{2}}^{\frac{L'}{2}} \pi x^2 dy = \int_{-\frac{L'}{2}}^{\frac{L'}{2}} \pi \left[\frac{r_0 + r}{2} - \frac{r_0 - r}{2} \cdot \cos \frac{2y}{L'}\right]^2 dy.$$

(17)

Integration of Eq. (17) gives

$$V = \frac{\pi}{8} \frac{L'}{8} \left[3r_0^2 + 2rr_0 + 3r^2\right].$$

(18)

If a constant volume straining process is assumed for the portion of the specimen $\alpha \bar{L}_0$

$$V = \alpha \bar{L}_0 A_0 = L'A$$

(19)
where \( L_o \) and \( L' \) are lengths shown in Fig. 1. Combination of Eqs. (18) and (19) gives

\[
\pi \frac{L'}{8} \left[ 3r_o^2 + 2rr_o + 3r^2 \right] = \alpha L_o \pi r_o^2 \tag{20}
\]

which can be rearranged to give

\[
\left( \frac{r}{r_o} \right)^2 + \frac{2}{3} \left( \frac{r}{r_o} \right) + \left( 1 - \frac{8}{3} \frac{L_o}{L'} \right) = 0 \tag{21}
\]

Use of the quadratic equation gives

\[
\frac{r}{r_o} = -\frac{1}{3} \pm \sqrt{\frac{1}{9} - \left( 1 - \frac{8}{3} \frac{L_o}{L'} \right)} \tag{22}
\]

When \( \alpha L_o = L' \), \( r/r_o = 1 \) and hence the plus sign gives the proper solution. Since

\[
\frac{\alpha L_o}{L'} = \frac{\alpha L_o}{\alpha L_o + \delta} = \frac{\alpha L_o}{\alpha L_o + \varepsilon L_o} = \frac{\alpha}{\alpha + \varepsilon} \tag{23}
\]

Equation (22) can be rearranged to give

\[
\frac{r}{r_o} = \frac{1}{3} \left\{ -1 + 4 \left[ \frac{\alpha - \varepsilon}{\alpha + \varepsilon} \right]^{1/2} \right\} \tag{24}
\]

If \( M \) is defined as

\[
M = \left[ \frac{\alpha - \varepsilon}{\alpha + \varepsilon} \right]^{1/2} \tag{25}
\]

then

\[
\frac{r}{r_o} = \frac{1}{3} \left[ 4M - 1 \right] \tag{26}
\]

and the ratio of the areas
Fig. 1. Sketch of creep specimen showing reduced section

Fig. 2. Reduced section of specimen
\[ \frac{A}{A_0} = \left( \frac{r}{r_0} \right)^2 = \frac{1}{9} \left( 4M - 1 \right)^2 . \]  

(27)

The true stress at the point of greatest reduction is now given by

\[ \sigma = \frac{P}{A} = \frac{P}{A_0} \cdot \frac{A_0}{A} = \frac{9S}{(4M - 1)^2} \]  

(28)

and the actual "true" strain rate is

\[ \frac{d \varepsilon'}{dt} = K' e^{-\frac{\Delta H}{RT}} \frac{9BS}{(4M - 1)^2} \]  

(29)

Since Eq. (11) gives

\[ \varepsilon' = \ln (1 + \varepsilon' ) \]  

(30)

\[ \frac{d \varepsilon'}{dt} = \frac{1}{1 + \varepsilon'} \cdot \frac{d \varepsilon'}{dt} = \left( \frac{1}{1 + \varepsilon'/\alpha} \right) \frac{1}{\alpha} \frac{d \varepsilon}{dt} = \frac{1}{\alpha + \varepsilon} \frac{d \varepsilon}{dt} \]  

(31)

and Eqs. (29) and (31) can be combined to give the engineering strain rate

\[ \frac{d \varepsilon}{dt} = (\alpha + \varepsilon) K_1 e^{-\frac{\Delta H}{RT}} \left( \frac{9BS}{(4M - 1)^2} \right) \]  

(32)

The constant \( K_1 \) can be evaluated from a boundary condition.

Equation (32) was derived for the case in which the strain rate was increasing due to the reduction of area. Therefore, the boundary condition used to evaluate \( K_1 \) cannot be chosen from the first or second stage of creep where the creep rate is decreasing or remains constant.

It was readily found that a single set of values for \( \alpha \) and \( K_1 \) would not fit Eq. (32) to the experimental data, even in the exponential stage of creep. Since \( K_1 \) is a constant, it appeared that the fraction of
the gage length \( \alpha \) in which deformation occurs changed as the test progressed. In order to determine the variation of \( \alpha \) with strain, plots of strain vs strain rate were drawn for several values of \( \alpha \). The constant \( K \) for each \( \alpha \) was calculated using as a boundary condition the values of strain and strain rate obtained when the exponential stage of creep is extrapolated back to time \( t = 0 \).

The plots of strain rate vs strain for six values of \( \alpha \) are shown in Figs. 3 and 4 for the two tests. Experimental data from the two tests are superimposed on the families of calculated curves. The intersection of the experimental and calculated curves gives the fraction \( \alpha \) of gage length in which strain occurs as the strain increases. Fig. 5 shows that the fraction \( \alpha \) increases as the strain increases.

If it is postulated that the exponential stage of creep extends back to time \( t = 0 \) and that the first and second stages of creep are respectively transient and constant in nature, then it would appear that the initial plastic action of the exponential creep phenomenon takes place in a very small volume. As the strain increases, the portion of the specimen in which plastic action takes place continues to increase in an almost linear manner as indicated in Fig. 5. This increase in the volume participating in creep during the exponential stage gives credence to the hypothesis that the exponential stage of creep starts at a
Fig. 4. Strain rate vs strain for specimen without previous history
Fig. 5. Fraction of gage length vs strain
point where the temperature is the highest or the stress is the greatest. The partially effective strain-hardening mechanism postulated in this theory then causes the straining to spread throughout the volume in the immediate vicinity and eventually results in localized "necking down".

CONCLUSIONS

A model for the creep of tantalum at elevated temperatures is presented. The increase in strain rate with strain is related to the increase in stress caused by the reduction in cross-sectional area accompanying strain. Since it is believed that creep beyond the second stage is confined to a local area, it was assumed in the model that only a small fraction of the gage length actively participated in the yielding. The presence of a partially effective strain-hardening mechanism is also postulated.

Comparison of the experimental data with the proposed theory indicated that the participating fraction of the gage length increased as the strain increased. It is concluded that the dominant creep mechanism beyond the second stage of creep actually starts at a point of highest temperature or at a stress concentration, spreads throughout the volume in the immediate vicinity, and eventually results in localized "necking down".