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Progress Report
on
The Steady-State Creep Behavior of Dental Amalgam

George Dickson

Philip Oglesby

Ruth Davenport

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The Steady-State Creep Behavior
of Dental Amalgam

Abstract

The steady-state creep behavior of a dental amalgam subjected to tensile stresses of 500 to 4000 psi was investigated over the temperature range of 23 to 52°C. It was found that the creep behavior can be represented by the equation;

$$\dot{\epsilon}_V = K \sigma^m e^{-\frac{E}{RT}}$$

where $\dot{\epsilon}_V$ is the creep rate, K and m are constants of the material, σ is the stress, E is the activation energy for the process, R is the gas constant and T is the absolute temperature. Values of the constants determined for the dental amalgam were $K = 2.31 \times 10^9$, $m = 3.45$ and $E = 35{,}300$ cal/mole.

1. Introduction

In a previous study of the viscoelastic behavior of dental amalgam [1] it was shown that the viscous strain rate of amalgam at a constant temperature is a nonlinear function of stress which can be represented by an equation of the form:

$$\dot{\epsilon}_V = K \sigma^m$$

where σ is the stress and K and m are constants of the material.

The objectives of the present study were (1) to determine the steady-state creep behavior of dental amalgam over a range of temperatures occuring in the mouth, (2) to determine which of the steady-state creep equations from established theory represents the behavior of dental amalgam, and (3) to determine the activation energy of creep of amalgam in order to gain an insight into the dominant mechanism governing the steady-state creep of amalgam.

2. Theory

The steady-state creep of a metal may be controlled by such processes as (1) true frictional forces, (2) thermally activated processes, and (3) quantum mechanical tunneling effects [2]. The quantum mechanical tunneling effects appear to occur only at very low temperatures, if at all. True frictional forces give rise to viscous or quasi-viscous behavior and in examples where quasi-viscous frictional forces appear to determine the creep rate, the energy is usually dissipated by a mechanism which is thermally activiated. Thus, most steady-creep processes in metals are thermally activated processes; that is the creep rate depends on the temperature in the relation, $\exp(-E/KT)$, where T is the absolute temperature and E is the activation energy of the specific process. The steady-state creep rate may be related to the thermally activated rate processes by the following general equation:

$$\dot{\epsilon}_V = \sum_i f_i\ (\sigma,T,\beta) e^{-E_i(\sigma,T,\beta)/KT} \qquad \text{[2]}$$

where

$\dot{\epsilon}_V$ = steady-state creep rate

σ = applied stress

T = absolute temperature

β = a crystalline geometric factor

E_i = activation energy for the process

The activation processes in a metal are controlled by such micromechanisms as (1) climb-softening (climbing of dislocations) which is subgrain formation, (2) glide-softening (glide movement of dislocations) which is crystallographic slip, (3) flow of grain boundaries, (4) diffusion of vacancies (Nabarro-Herring mechanism) and (5) twinning [2].

Twinning occurs only at low temperatures and high stresses under tensile test conditions and therefore, is not ordinarily an important factor in steady-state creep [2].

The Nabarro-Herring mechanism contributes to steady-state creep only at temperatures near the melting point and at extremely low stresses [2].

The amount that flow of grain boundaries contributes to the steady-state creep is unclear, but it does contribute in some cases [2].

Glide-softening has as its main cause cross slip [3]. It can occur at low temperatures (below one half the melting temperature, T_m). Since glide-softening occurs while the dislocations are gliding, it occurs only at sufficiently high stresses and at short times in creep behavior and therefore, is not important in slow creep such as steady-state creep.

In the cases of climb-softening, the cause is vacancy creep [3]. Vacancy creep is a function only of temperature not of stress and the mobility and concentration of vacancies must be great enough for vacancy creep to occur; this critical mobility and concentration of vacancies occurs for most metallic elements at approximately 1/2 the melting temperature of the element. Thus, climb-softening occurs for most metals only above 0.5 T_m and unlike glide-softening can occur at low stresses and allows large strains to develop over long periods of time. Therefore, climb-softening is one of the principle mechanisms of steady-state creep and is pronounced at temperatures above about 0.5 T_m. The climb-softening allows edge dislocations (1) to move out of their glide surfaces, (2) to annihilate or polygonize with other dislocations and (3) to pass around obstacles. The climb of the dislocations from their glide surfaces is achieved by absorbing or emitting vacancies. The forces necessary to achieve climb are obtained from local stress fields and the interaction with other dislocations; these forces are often small enough for creep due to climb-softening to be Newtonian [3] and described by the following equation:

$$\dot{\epsilon}_v = K \sigma e^{-E/RT}$$

where

$\dot{\epsilon}_v$ = steady-state creep rate

σ = stress

E = activation energy of self-diffusion

R = gas constant

T = absolute temperature

However, even though the steady-state creep may be controlled by Newtonian vacancy creep (climb-softening) the resulting creep may be non-Newtonian due to the fact that the number of climbing dislocations, their driving stresses and their climbing distances depend on the dislocation density which is dependent on the applied stress [3]. The rate of steady-state creep in the case of many metals may be represented by either of the following equations which are non-Newtonian in the stress relation but thermally activated:

$$\dot{\epsilon}_v = K \sigma^m e^{-E/RT} \text{ (Dorn equation)} \qquad [4,5]$$

or

$$\dot{\epsilon}_v = A e^{\beta\sigma} e^{-E/RT} \text{ (Kauzmann equation)} \qquad [6]$$

3. Experimental Procedure

The material and experimental procedures were as described by Oglesby, et al [1]. Amalgam specimens were made by mixing mercury with a commercial alloy for dental amalgam (composition approximately Ag 70%, Sn 26%, Cu 3.5%, Zn 0.5%) and condensing the mixture into a metal mold. The dumbbell shaped specimens formed in the mold were 0.75 inch long, with a straight portion 0.3 inch in length having a square cross section 0.1 X 0.1 inch.

Tensile stresses ranging from approximately 500 to 4000 psi were applied to the specimens. Strain was measured to approximately 1 X 10^{-4} in. per in. with Tuckerman optical strain gages attached to the straight portion of the specimen. Creep rates were determined from the slope of the straight line portion of the loaded creep curve.

The steady-state creep rates were determined over the temperature range of 23°C to 52°C and over the stress range of 500 to 4000 psi.

4. Results and Discussion

The steady-state creep rate was found to be nonlinear as a function of the stress for any fixed temperature, Figure 1. It was further found that log of the creep rate was nonlinear as a function of stress at constant temperature. However, when the log of the creep rate was plotted as a function of the log of the stress a straight line was obtained at any given temperature, Figure 2. These log $\dot{\epsilon}_v$ vs log σ plots were made for fixed temperatures over the range 23°C to 52°C and the slope of the straight line obtained at each temperature was determined and found to be approximately 3.5 for all the linear plots as shown in Figure 2. This indicated that the steady-state creep rate could be approximated as a function of stress by the following relation:

$$\dot{\epsilon}_v = K \sigma^m f(T)$$

where m is the slope of the linear plot of log $\dot{\epsilon}_v$ vs log σ.

Next the steady-state creep rate was examined as a function of temperature at various fixed stresses. The plots of creep rate versus T(°K) and 1/T were found to be nonlinear. However, a plot of the log of the creep rate versus 1/T was found to be linear at all fixed stress values, Figure 3. The slopes of these linear plots of log $\dot{\epsilon}_v$ versus 1/T were approximately the same for the different fixed values of stress as shown in Figure 3. Thus, the steady-creep rate $\dot{\epsilon}_v$ could be related to the absolute temperature by the following relationship:

$$\dot{\epsilon}_v = K e^{-C/T} f(\sigma)$$

where C = the slope of the log $\dot{\epsilon}_v$ versus 1/T plot. Now from theory [2] the slope C of linear plots of log $\dot{\epsilon}_v$ versus 1/T where T is in degrees Kelvin, is related to the activation energy of steady-state creep for a single micromechanism by the following relation:

$$E/R = \text{slope } C$$

where R is the ideal gas constant.

However, when there are a number of micromechanisms involved the value of E is an average or combination activation energy usually representative of the dominant mechanism governing the steady-state creep process [2]. This activation energy E was calculated from the slopes in Figure 3 and found to be about 35,000 cal/mole.

Combining the results obtained from the plots of log of creep rate versus log σ at a constant temperature and the plots of log of creep rate versus $\frac{1}{T}$ at a constant stress gives the following equation for the steady-state creep of dental amalgam within the stress and temperature ranges studied:

$$\dot{\epsilon}_v = K \sigma^m e^{-\frac{E}{RT}}$$

A least squares fit of the equation,

$$\log_e \dot{\epsilon}_v = \log_e K + m \log_e \sigma - \frac{E}{RT}$$

to all of the data gave the following values for the constants:

$m = 3.45$

$E = 35{,}300$ cal/mole

$K = 2.31 \times 10^9$

In Figure 4 a plot of $\log_e \dot{\epsilon}_v + \frac{E}{RT}$ vs $\log_e \sigma$ shows a comparison of the experimental data with the curve calculated using these constants.

Since the steady-state creep rate of dental amalgam could be related to the temperature by the function $\exp(-C/T)$, it is concluded that the dominant process controlling the creep rate of amalgam is a thermally activated one.

The results suggest that the dominant micromechanism involved in the creep of dental amalgam in the temperature range studied is diffusion controlled climbing of dislocations (subgrain formation). This is supported by the evidence that the controlling process is thermally activated and by the fact that the temperature involved is above $0.5\ T_m$. (The solidus temperature of amalgam as indicated by the appearance of liquid mercury is near 355°K)

Activation energy for high temperature creep in pure metals corresponds generally to the activation energy of self diffusion [2,3]. Little quantitative information is available on diffusion in dental amalgam. It is of interest to note, however, that the activation energy found for creep of amalgam lies within the range of energies of self diffusion reported for the metals, other than mercury, contained in dental amalgam, Table 1.

Since the dominant mechanism controlling the thermally-activated steady-state creep in amalgam in the range 298-328°K is probably climb of dislocations, the activation energy of which is the activation energy of diffusion, studies of the diffusion of the components into each phase of amalgam should be made to determine the activation energies. Also studies of the steady-state creep behavior of each phase of dental amalgam should be made to determine which phase or phases of dental amalgam dominate its steady-state creep behavior.

5. Conclusions

The steady-state creep behavior of dental amalgam in the temperature range 296 to 325°K and the stress range 500 to 4000 psi can be represented by the equation:

$$\dot{\epsilon}_v = K \sigma^m e^{-\frac{E}{RT}}$$

with $m = 3.45$ and $E = 35{,}000$ cal/mole.

The creep behavior is probably controlled by a thermally activated process dominated by the mechanism of climb of dislocations.

6. References

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Table 1

Activation Energy

	Creep K cal/mole	Self Diffusion K cal/mole	Reference
Amalgam	35	--	-
Silver	-	44-46	[7]
Tin	21-26	6-10	[7]
Copper	44	48	[2]
Zinc	27	20	[2]
Mercury	1.2	1.2	[8]

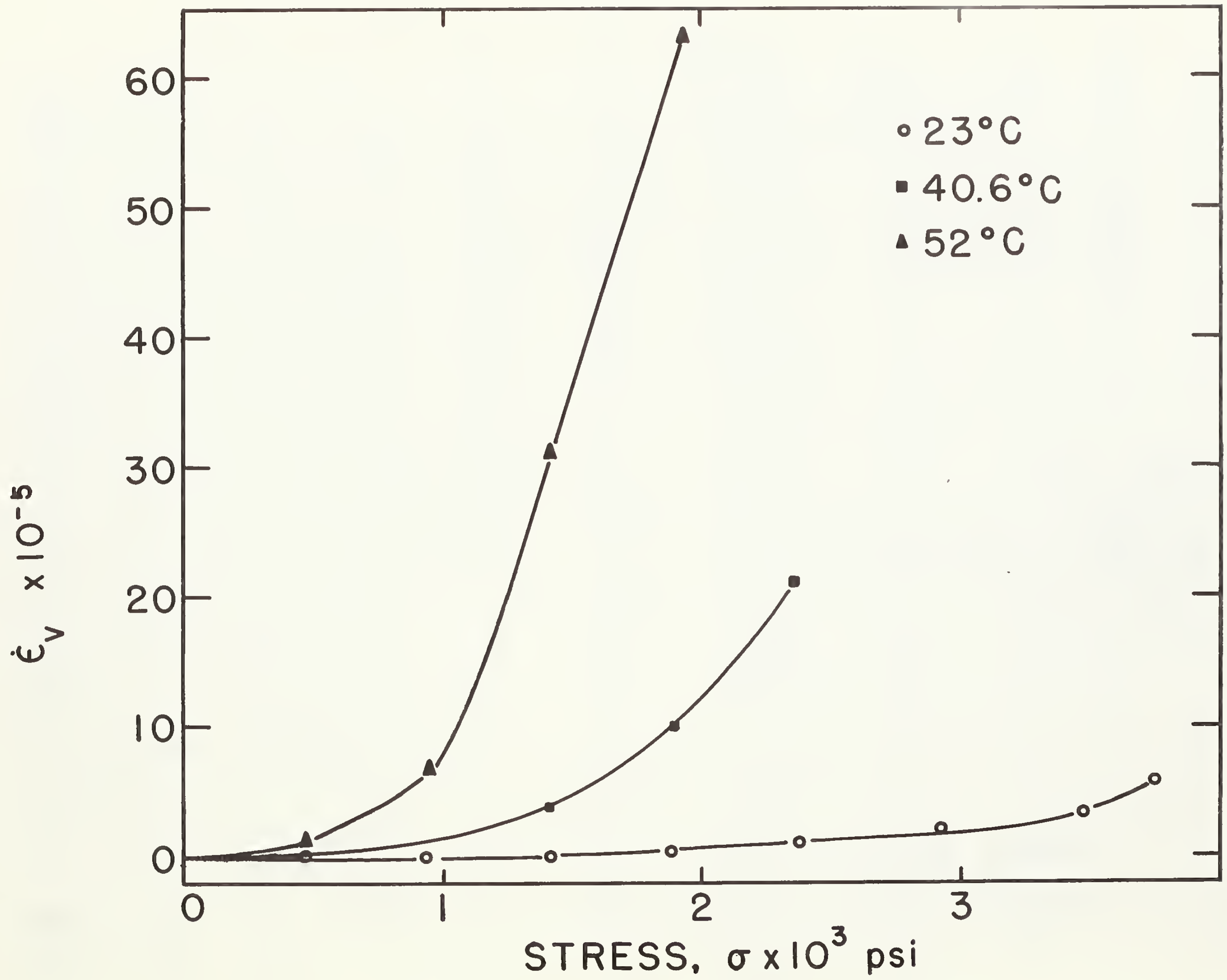

Figure 1. Steady-state creep rate, $\dot{\epsilon}_v$, of dental amalgam versus stress.

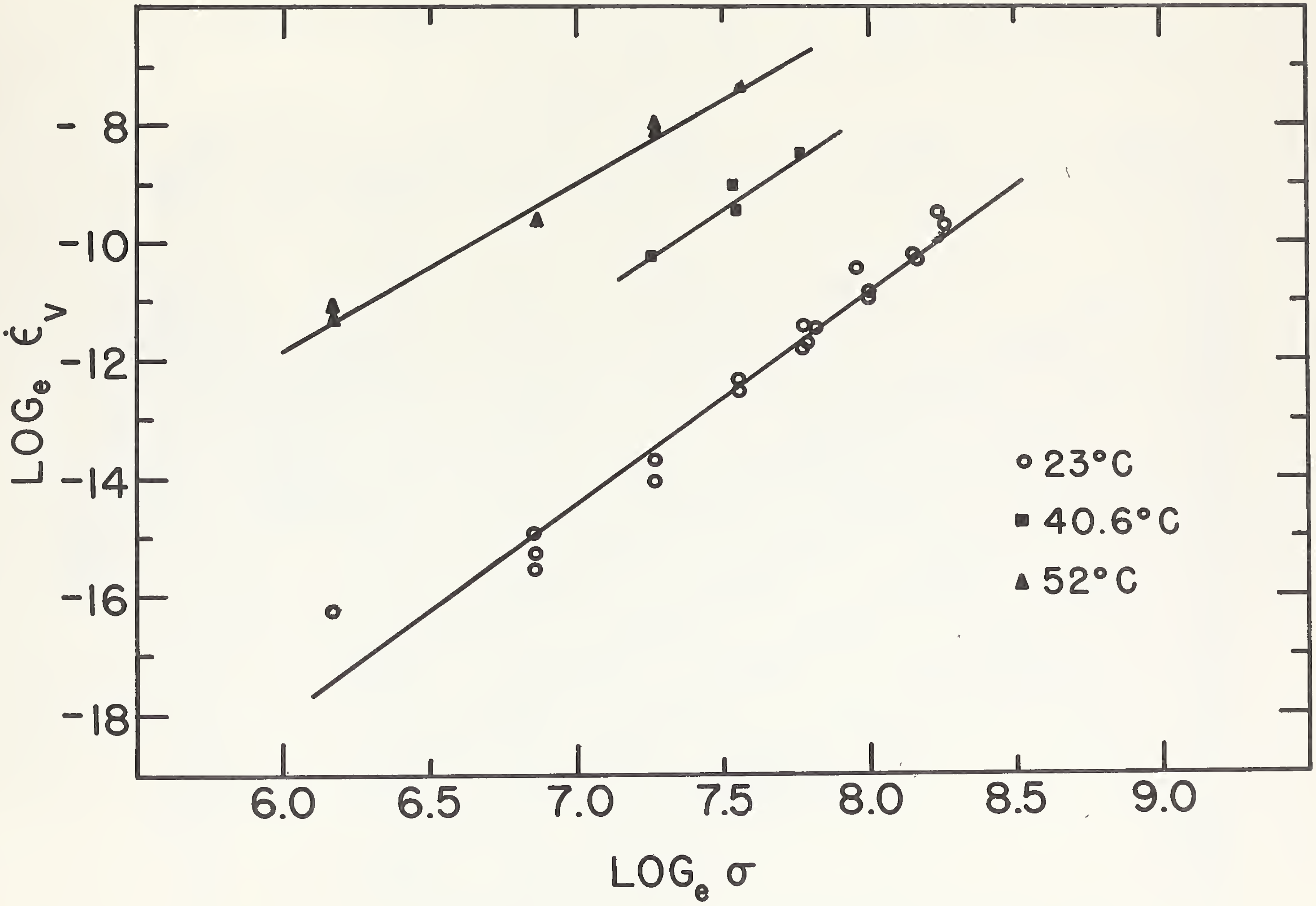

Figure 2. Log of steady-state creep rate, $\dot{\epsilon}_V$, of amalgam versus log of stress, σ.

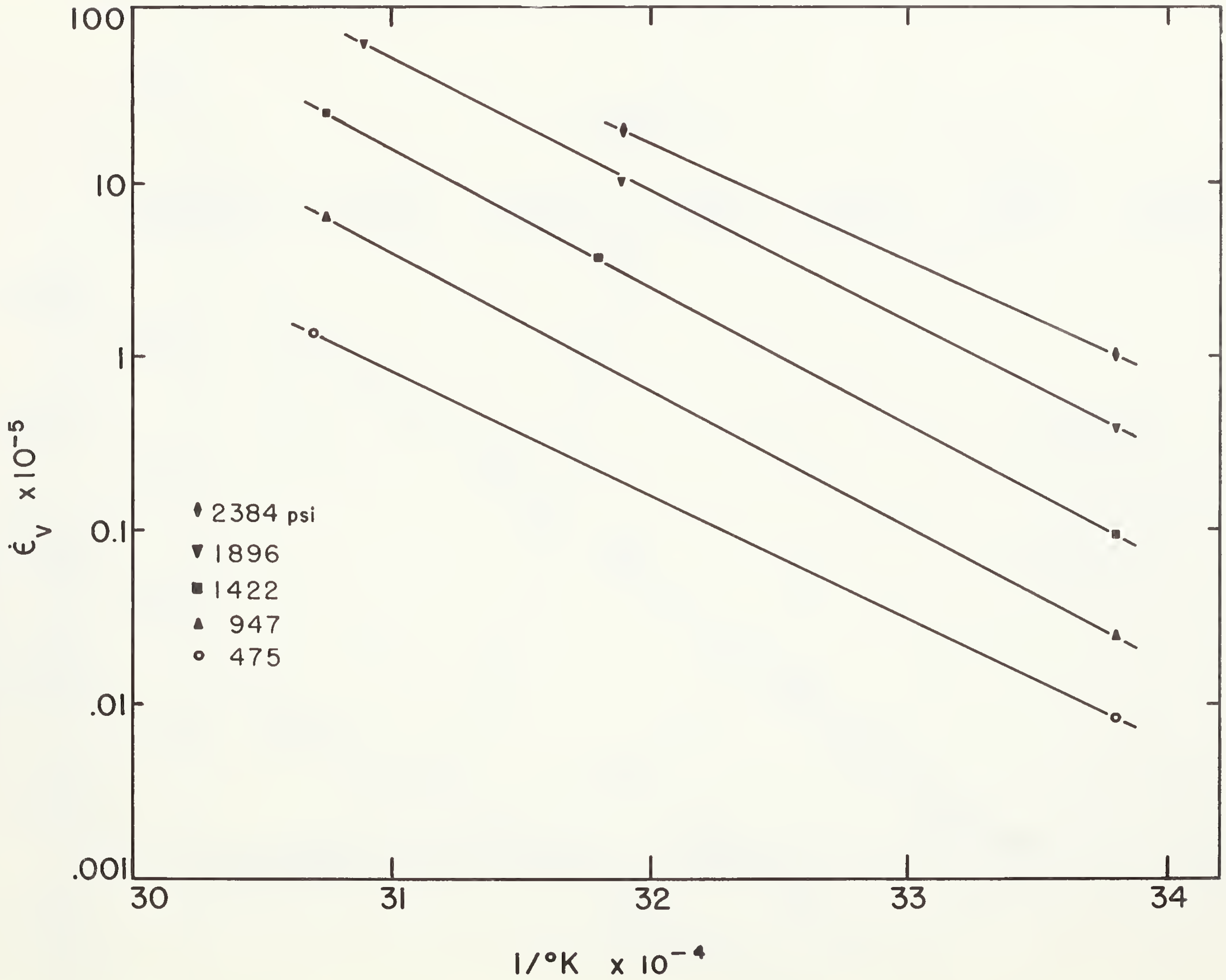

Figure 3. Steady-state creep rate, $\dot{\epsilon}_v$, of amalgam plotted on a logarithmic scale versus the reciprocal of absolute temperature, K.

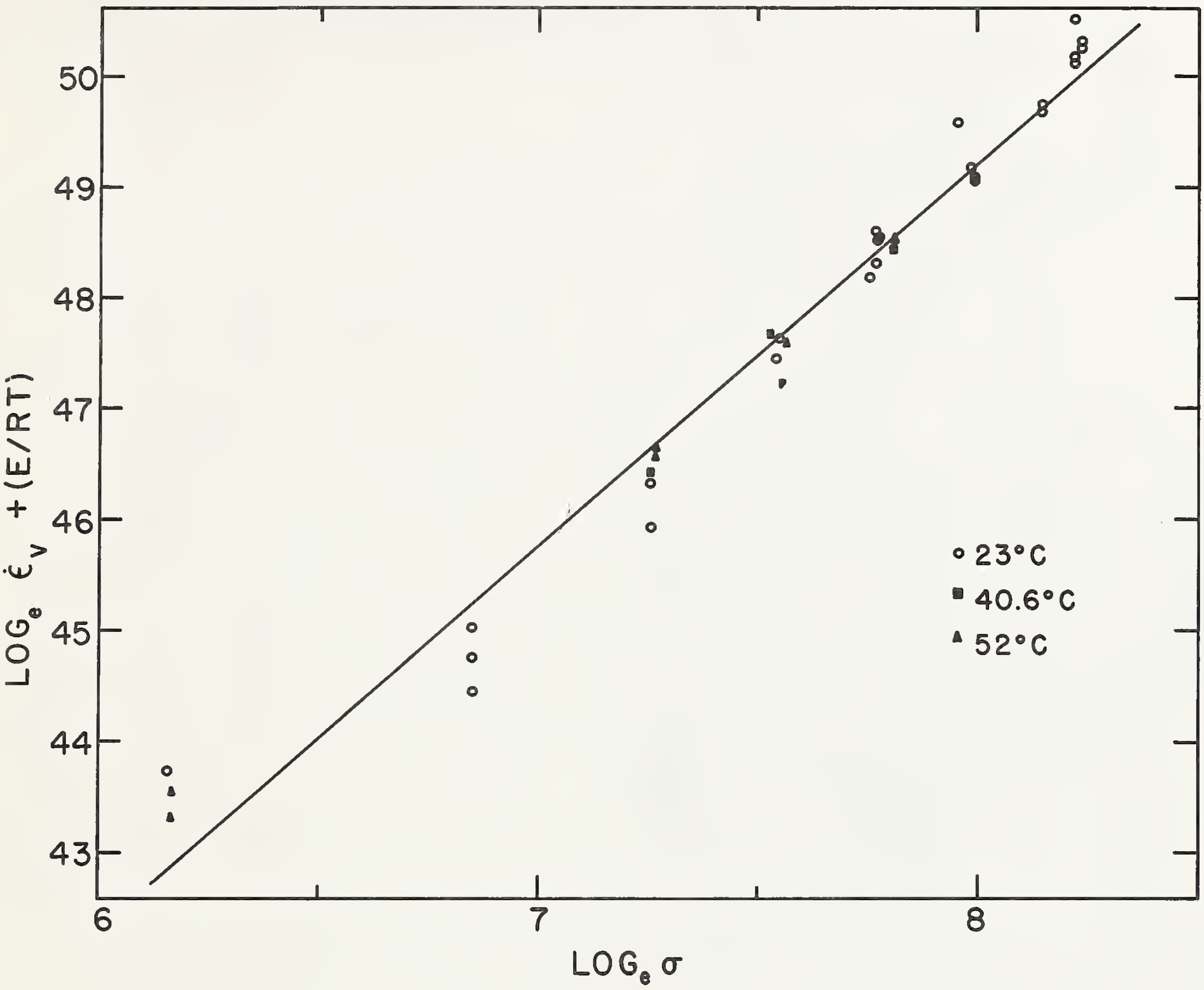

Figure 4. Comparison of experimental points with curve calculated from the constants determined for the equation

$$\dot{\epsilon}_v = K \sigma^m e^{-\frac{E}{RT}}$$

where

$\dot{\epsilon}_v$ = steady-state creep rate
K = 2.31 X 10^9
σ = stress
m = 3.45
E = 35,300 cal/mole
R = gas constant
T = absolute temperature