FEATURES CONTROLLING THE EARLY STAGES OF CREEP DEFORMATION OF WASPALOY

by

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and

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ABSTRACT

A model has been presented for describing primary and second stage creep. General equations were derived for the amount and time of primary creep. It was shown how the model can be used to extrapolate creep data. Applicability of the model was demonstrated for Waspaloy with gamma prime particle sizes from 75 - 1000 Å, creep tested in the temperature range 1000 - 1400°F (538 - 760°C). Equations were developed showing the dependence of creep parameters on dislocation mechanism , gamma prime volume fraction and size.

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8 Iso-creep strain curves at 1200°F (649°C) for two heat treatments of Waspaloy. A longer time was required for 0.1 and 0.2 percent creep for the material aged at 1400°F (760°C) (dislocation mechanism of shearing), than for that aged at 1700°F (927°C) (dislocation mechanism of by-passing).

9 The dependence of the rate coefficient K_1 on γ' particle size for Waspaloy at 1200°F (649°C). The linear relationships shown are in accordance with the theory presented.

NOMENCLATURE

$\dot{\epsilon}$ = primary creep rate (Greek eta)

$\dot{\epsilon}_i$ = initial creep rate (Greek eta)

$\dot{\epsilon}_m$ = steady state creep rate (Greek eta)

$\dot{\epsilon}_m^c$ = steady state creep rate compensated for temperature and particle size (Greek eta)

K_1 = rate coefficient

K_1^c = rate coefficient compensated for temperature and particle size

T = absolute temperature

R = Gas constant

k = Boltzman's constant

b = Burgers vector

v = mean dislocation velocity

v_m = minimum dislocation velocity

ϵ = creep deformation (Greek eta)

μ = shear modulus (Greek mu)

λ = mean planar particle separation (Greek lamda)

d = average particle diameter

V_f = precipitate volume fraction

D = self-diffusion coefficient

σ = applied stress (Greek sigma)

E_D = activation energy

t = time

n = numerical stress exponent

f_1, f_2, f_3, f_4 = functions of temperature and stress

A_o, A, B, B', C, E = constants

INTRODUCTION

Engineers are increasingly aware that primary and second stage creep characteristics must be considered in design for many high temperature applications. The importance of the early stages of creep was highlighted by research carried out at The University of Michigan under sponsorship of The National Aeronautics and Space Administration, Washington, D. C. Studies of Waspaloy [1]* and Inconel 718 [2] sheet demonstrated that severe time-dependent edge-notch sensitivity occurred when notched specimens were loaded below the yield strength and when smooth specimen tests showed that 0.1 or 0.2 percent creep consumed large rupture life fractions. Thus, the notch sensitive behavior was dependent on the creep characteristics, particularly those at small strains.

A correlation also has been established between time-dependent notch sensitivity and the dislocation motion mechanism [2, 3]. Precipitate particles, γ' - $Ni_3(Al, Ti)$ in Waspaloy and γ' and γ'' - Ni_3Cb(bct) in Inconel 718, smaller than a critical size were sheared by dislocations. Under these conditions, the deformation was localized and time-dependent notch sensitivity occurred. Particles larger than the critical size were by-passed by dislocations, the deformation was homogeneous and no time-dependent notch sensitivity was observed.

The presently reported study was directed at developing an understanding of the factors controlling primary and second stage creep behavior. Emphasis was on γ' strengthened nickel-base superalloys for conditions where dislocations sheared and by-passed the precipitate particles. The approach, however, can be applied to other systems in which different dislocation motion mechanisms may occur.

* Numbers in brackets designate References at end of paper.

EXPERIMENTAL DATA

The creep data used in the study were from the previous reported [1] creep-rupture testing program of Waspaloy at 1000° - 1400°F (538 - 760°C).

The heat treatments evaluated were:

(a) 1/2 hr. at 1975°F (1080°C) + 10 hrs. at 1700°F (927°C)

(b) 1/2 hr. at 1975°F (1080°C) + 24 hrs. at 1550°F (843°C)

(c) 1/2 hr. at 1975°F (1080°C) + 16 hrs. at 1400°F (760°C)

Aging 24 hours at 1550°F (843°C) and 10 hours at 1700°F (927°C) resulted in γ' about 600Å and 1000Å in diameter respectively. These are larger than the critical size, and thus, the dislocations by-passed the γ' particles under all test conditions [3]. After aging 16 hours at 1400°F (760°C) the γ' was about 75Å which was smaller than the critical size. Consequently, at the lower test temperatures, the dislocations sheared the precipitate particles. The by-pass mechanism became operative at the higher temperatures and longer times due to γ' growth.

DATA ANALYSIS

Theories for primary and second stage creep were applied to the data. Evaluation of the nature of tertiary creep was beyond the scope of the study and therefore was not considered.

Based on dislocation multiplication, motion and immobilization, Li [4] derived the following relationship for primary creep rate:

$$\dot{\varepsilon} = \dot{\varepsilon}_m \left[1 - \frac{\dot{\varepsilon}_i - \dot{\varepsilon}_m}{\dot{\varepsilon}_i} \exp - (K_1 t) \right]^{-1} , \qquad (1)$$

where $\dot{\varepsilon}_m$ is the steady state creep rate, $\dot{\varepsilon}_i$ the initial creep rate, t the time and the rate coefficient K_1 represents the following function [5]:

$$K_1 = A_o \, b \, v \, \exp - (E / RT) , \qquad (2)$$

where b is the Burgers vector, v is the mean dislocation velocity, T is the absolute temperature, R is the Gas constant, A_o and E are constants.

Integrating equation (1) allows expression of primary creep deformation as:

$$\varepsilon = \frac{\dot{\varepsilon}_m}{K_1} \ln \left[1 + \frac{\dot{\varepsilon}_i - \dot{\varepsilon}_m}{\dot{\varepsilon}_m} \left(1 - \exp - (K_1 t) \right) \right] + \dot{\varepsilon}_m t . \qquad (3)$$

Equations (1) and (3) require that plots of $\ln(1 - \dot{\varepsilon}_m / \dot{\varepsilon})$ versus t to be linear with slope K_1. In all cases, the creep data were consistent with this relationship for a wide range of values of $\dot{\varepsilon}_m / \dot{\varepsilon}$ (fig. 1). The values of the rate coefficient K_1 are presented in Table 1.

In order to make most effective use of the above equations, relationships must be established to describe the dislocation velocity and the steady state creep rate. These are dependent on the dislocation motion mechanism.

Dislocation By-Passing of γ'

For the materials aged 10 hours at 1700°F (927°C) and 24 hours at 1550°F (843°C), and creep-rupture tested, dislocations were observed bowing between γ' particles leaving pinched off dislocation loops [3]. Ansell and

Weertman [6] proposed a theory indicating that this mechanism occurs for stresses above $\mu b / \lambda$ where μ is the shear modulus and λ is the mean planar separation. λ can be calculated from the average particle diameter d and the volume fraction V_f (about 0.22 in this case - [7]) using the relationship [8]:

$$\lambda = d \left(\pi / 4 V_f \right)^{1/2} - d \quad . \qquad (4)$$

The experimental observations were consistent with the theory in that all of the test stresses were greater than $\mu b / \lambda$. Under these conditions, the dislocation velocity and the steady state creep rate are given by [6]:

$$v = \frac{2 b D \lambda}{\mu k T} \sigma^2 \quad \text{and} \quad \dot{\varepsilon}_m = \frac{2 \pi D \lambda^2}{d \mu^3 k T} \sigma^4 \quad , \qquad (5)$$

where D is the self-diffusion coefficient and k is Boltzman's constant. Thus, K_1 varies with σ^2 [equations (2) and (5)] while $\dot{\varepsilon}_m$ depends on σ^4. For test stresses below the approximate yield strength (figs. 2, 3), the creep data conformed very well to these relationships. However, at higher stresses, larger exponents occurred. This was not unexpected since at high stresses v and $\dot{\varepsilon}_m$ reportedly depend exponentially on stress [6].

A useful representation of the data can be obtained if it is compensated for variations in temperature and particle size. From equations (2), (4) and (5), compensated K_1 coefficients can be obtained as follows:

$$K_1^c = K_1 \frac{d_c}{d} \frac{T}{T_c} \exp - B \left(\frac{1}{T_c} - \frac{1}{T} \right) \quad . \qquad (6)$$

Using values taken at constant stress for the material aged at 1700°F (927°C), the constant B was determined to be 3.3×10^4 and 2.2×10^4 above and below the yield strength, respectively. Using these values, the K_1 values were compensated to 1200°F (649°C) and a particle size of 1000Å. For the material aged at 1550°F (843°C) compensation was made for both temperature and particles size. No allowance was made for γ' growth during test exposures (for the times and temperatures involved the γ' growth was negligible.) The results (Table 1, fig. 4) show little scatter and therefore are well represented by the master curve.

Minimum creep rates can be compensated in a similar manner. Using equations (4), (5) and the relationship $D = \exp - (E_D / RT)$, where E_D is the activation energy (for diffusion), the following equation is obtained.

$$\dot{\varepsilon}_m^c = \dot{\varepsilon}_m \frac{d_c}{d} \frac{T}{T_c} \exp - \frac{E_D}{R}\left(\frac{1}{T_c} - \frac{1}{T}\right) \quad . \quad (7)$$

The apparant activation energies (for creep) were determined to be 83 and 92 K cal/mole for stresses above and below the yield strength respectively. These values are close to the value for diffusion ($E_D \sim 65$ k cal/mole). Plotted against stress, the creep rates compensated to 1200°F (649°C) and a particle size of 1000Å deviated only slightly from the single master curve.

Dislocation Shearing of γ'

During primary and second stage creep of the material aged 16 hours at 1400°F (760°C) the dislocations sheared the γ' particles in tests at 1000° - 1300°F (538 - 704°C). Rapid γ' growth occurred in tests at 1400°F (760°C) so that, even at relatively short times, the looping mechanism became operative. Analysis was carried out only for the lower temperature test data.

Detailed theories for the shearing mechanism were not found in the literature. However, the dependence of dislocation velocity on variables of interest can be formulated. The velocity of a dislocation varies according to its position. The minimum value V_m which controls the deformation rate, occurs when the dislocation is adjacent to γ' particles [9]. Gleiter derived the following relationship between this velocity and temperature [9]:

$$V_m \propto \frac{\mu}{T} \exp - (E_D / RT) \quad . \quad (8)$$

The mean velocity v of a dislocation must be dependent on the amount of time that it moves at v_m and, therefore, on the number of dislocation-particle interactions. Hence:

$$v \propto \frac{d}{V_f} v_m \quad . \qquad (9)$$

The stress dependence of the velocity was derived from the experimental data. For constant temperature (assuming V_f and d also constant) K_1 varied according to σ^n where n = 11 and 5 for stresses above and below the yield strength respectively (fig. 5). Thus, the dislocation velocity for the shearing mechanism can be expresses as follows:

$$v \propto \frac{d \mu}{V_f T} \sigma^n \exp - \left(E_D / R T \right) \quad . \qquad (10)$$

Using equations (2) and (10) an equation can be derived to compensate K_1 values for temperature and particle size:

$$K_1^c = K_1 \frac{d}{d_c} \frac{T_c}{T} \exp - B' \left(\frac{1}{T_c} - \frac{1}{T} \right) \quad . \qquad (11)$$

Constant B' values of 2.6×10^4 and 5.1×10^4 were derived for stress above and below the yield strength respectively (for constant d). K_1 values compensated to 1200°F (649°C) are presented in Table 1. Again, no allowance was made for the relatively small amount of γ' growth that occurred during the test exposures.

No well-defined equation was available describing the dependence of minimum creep rate on stress and temperature. Consequently, the following general expression was utilized:

$$\dot{\varepsilon}_m = A \sigma^n \exp - \left(E_D / R T \right) \quad . \qquad (12)$$

The stress exponent n was 20 and 6 for stresses above and below the yield strength respectively. The data were compensated for temperature by:

$$\dot{\varepsilon}_m^c = \dot{\varepsilon}_m \exp - \frac{E_D}{R}\left(\frac{1}{T_c} - \frac{1}{T}\right) \quad . \qquad (13)$$

The apparent activation energies (for creep) were about 73 and 105 K cal/mole above and below the yield strength respectively. The data compensated to 1200°F (649°C) using these values are presented in Table 1.

Time for Primary Creep.

The primary creep rate decreases with time until it equals the minimum creep rate. Thus, $\dot{\epsilon} = C\dot{\epsilon}_m$ $(C > 1)$ during primary creep. Substituting in equation (1), one obtains:

$$t = -\frac{1}{K_1} \ln\left[\frac{\dot{\varepsilon}_i}{\dot{\varepsilon}_i - \dot{\varepsilon}_m}\left(1 - 1/c\right)\right] \quad . \qquad (14)$$

From the experimental data, $\dot{\epsilon} >> \dot{\epsilon}_m$. Thus, equation (14) reduces to:

$$t = -\frac{1}{K_1} \ln\left(1 - 1/c\right) \quad . \qquad (15)$$

From a practical point of view, primary creep can be considered complete when C is less than about 2.5. Based on this value, the times for primary creep were taken from the $\ln(1 - \dot{\epsilon}_m / \dot{\epsilon})$ versus time plots for each set of creep data evaluated. These results (fig. 6) show excellent agreement with the curve calculated using equation (15). Therefore, the equation is a good representation of the time for primary creep. Note especially that the correlation is independent of the dislocation motion mechanism.

Amount of Primary Creep

From equations (3) and (14), the amount of primary creep is given by:

$$\varepsilon = \frac{\dot{\varepsilon}_m}{K_1} \ln\left[\frac{\dot{\varepsilon}_i - \dot{\varepsilon}_m}{\dot{\varepsilon}_m} \; \frac{1}{c-1}\right] \quad . \qquad (16)$$

To utilize this relationship, the ratio $\dot{\epsilon}_i / \dot{\epsilon}_m$ must be known. Examination of the plots of $\ln(1 - \dot{\epsilon}_m / \dot{\epsilon})$ versus time at $t = 0$ showed that 10 is a good average value for $\dot{\epsilon}_i / \dot{\epsilon}_m$. Hence:

$$\epsilon = \frac{\dot{\epsilon}_m}{K_1} \ln\left(\frac{9}{C-1}\right) \quad . \qquad (17)$$

Using the times for primary creep, values for primary creep deformation were read from the creep curves. These were plotted as a function of $\dot{\epsilon}_m / K_1$ along with the curve derived from equation (17) (fig. 7). Some of the data scatter probably reflects experimental difficulty in determining creep deformation in the very early stages. Again, the correlation is independent of the dislocation mechanism.

PRACTICAL IMPLICATIONS

The model presented permitted correlations to be extablished for primary and second stage creep. Based on these relationships, several conclusions of practical importance can be drawn. A number of these are discussed in the following sections.

Extrapolation of Creep Characteristics:

An important factor in high temperature design is the long time creep-rupture characteristics. It is usually impractical to conduct prolonged time tests to verify the applicability of a material for service. Consequently, the characteristics must be determined from shorter time tests. Extrapolation of creep data can be accomplished using equation (3). Relationships between K_1 and σ and also $\dot{\epsilon}_m$ and σ must first be established using relatively short time tests. These can then be extrapolated to the stress (and time) of interest and the primary and second stage creep characteristics calculated. It should be noted that this is a general technique and requires no knowledge of the dislocation motion mechanism. However, if theories are available describing the stress dependence of K_1 and $\dot{\epsilon}_m$, then the extrapolation can be made with either greater certainty or less data. In other words, dislocation theories offer a basis for improving the accuracy of extrapolation of creep data.

Creep data for Waspaloy aged at 1400°F (760°C) and at 1700°F (927°C) were extrapolated at 1200°F (649°C). The results are presented as iso-creep strain curves (fig. 8). Curves were determined only for 0.1 and 0.2 percent creep since for this particular alloy, tertiary creep begins at relatively low creep strains. This entailed calculation of the time and deformation for primary creep [equations (15) and (17)]. The amounts of primary creep calculated were <0.1 percent. The remainder of creep deformation was, therefore, assumed to be second stage, i.e. $\dot{\epsilon}_m t$. As predicted by the equations, the iso-strain curves were linear on plots of log σ versus log t (fig. 8). It is clear that a longer time is necessary to attain a given creep strain for aging at 1400°F (760°C) (shearing mechanism) than for aging at 1700°F (927°C) (looping mechanism).

Two additional factors can influence creep characteristics, particularly in the extrapolated range. (a) Many nickel-base superalloys, including Waspaloy, exhibit "negative creep". This feature becomes evident when test stresses are low enough so that little or no "creep deformation" is expected. Negative creep (which may be associated with an ordering reaction) is little understood and presently is being studied at The University of Michigan. It is probable that this phenomenon has little influence on the results reported, since in this work, the stresses are high enough so that "negative creep" was small relative to the total creep deformation. As the analysis was applied to actual creep data ("positive" plus "negative" creep), the results are applicable within and probably somewhat beyond the range of test stresses. (b) No allowance was made for growth of γ' during the test exposures. Little or none occurs for the test conditions considered. When extrapolating to higher temperatures and longer times, structural instabilities could become a significant factor. Allowance for γ' growth could be incorporated into the analysis, but this was beyond the scope of the present investigation.

Creep Characteristics and γ' Morphology

The influence of variations in size and volume fraction of γ' on creep deformation characteristics can be derived from the equations presented. When the dislocation motion mechanism is looping:

$$K_1 = f_1(T, \sigma)\, d / V_f^{1/2} \quad , \qquad (18)$$

while for shearing:

$$K_1 = f_2(T, \sigma)\, d / V_f \quad . \qquad (19)$$

In either case, K_1 varies linearly with d. This is shown in Figure 9 using data for Waspaloy (V_f = .22) at 1200°F (649°C). The figure is drawn with a mechanism change at about 200Å (reasonable estimate for this critical particle size). Near the critical value, both mechanisms presumably contribute so the curves are smooth.

Using the equations (18), (19) and (15), it is evident that the time for primary creep for either mechanisms increases with decreasing d or increasing V_f.

The dependence of the amount of primary creep on d and V_f can be derived for the looping mechanism. Using equations (4) and (5):

$$\dot{\varepsilon}_m = f_3(T, \sigma)\ d / V_f \quad . \qquad (20)$$

Substituting equations (20) and (18) into (17) the following relationship for the amount of primary creep is obtained:

$$\varepsilon = f_4(T, \sigma)\ V_f^{-1/2} \quad . \qquad (21)$$

As ϵ decreases with increasing V_f, alloys with high γ' volume fractions will exhibit very little deformation in primary creep. For constant volume fraction , the amount of primary creep can be expected to be independent of particle size.

CONCLUSIONS

1. Primary and second stage creep can be described analytically in terms of two important parameters, a rate coefficient K_1 and the minimum creep rate $\dot{\epsilon}_m$. These can be determined from experimental data. Extrapolation as a function of stress permits determination of creep characteristics at prolonged times.
2. The time for primary creep depends only on K_1 while the amount of primary creep varies according to $\dot{\epsilon}_m / K_1$.
3. Knowledge of the dislocation motion mechanism permits theoretical determination of the manner in which K_1 and $\dot{\epsilon}_m$ (hence the creep characteristics) vary with test stress, precipitate morphology, etc. Dislocation theories can, therefore, be used to improve extrapolations of creep characteristics or to indicate the influence of varying precipitate size, volume fraction, etc.
4. Creep data for Waspaloy at 1000° - 1400°F (538 - 760°C) for test stresses below the yield strength were in good agreement with models derived for dislocations either shearing and by-passing γ' particles. The creep characteristics depended on the dislocation mechanism. K_1 and $\dot{\epsilon}_m$ were shown to vary with the γ' particle size for both mechanisms. They depended inversely on the γ' volume fraction to various powers.

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TABLE I

PRIMARY AND SECONDARY STAGE CREEP CHARACTERISTICS OF THREE HEAT TREATMENTS OF WASPALOY AT 1000° - 1400°F (538 - 760°C)

Temperature (°C)	Temperature (°F)	Stress (MN/m^2)	Stress (ksi)	Minimum Creep Rate $\dot{\varepsilon}_m$ (%/hr.)	Coefficient K_1 (1/hr.)	Compensated Minimum Creep Rate $\dot{\varepsilon}_m$ (%/hr.)	Compensated Coefficient K_4^c (1/hr.)
1/2 hr. at 1975°F (1080°C) plus 10 hrs. at 1700°F (927°C)							
760	1400	183	26.6	$7.7 \cdot 10^{-5}$	$1.3 \cdot 10^{-2}$	$5.0 \cdot 10^{-7}$	$1.0 \cdot 10^{-3}$
		262	38.0	$8.2 \cdot 10^{-4}$	$2.9 \cdot 10^{-2}$	$5.3 \cdot 10^{-6}$	$2.3 \cdot 10^{-3}$
704	1300	265	38.5	$8.5 \cdot 10^{-5}$	$7.9 \cdot 10^{-3}$	$5.8 \cdot 10^{-6}$	$2.2 \cdot 10^{-3}$
		414	60.0	$8.9 \cdot 10^{-4}$	$2.4 \cdot 10^{-2}$	$6.0 \cdot 10^{-5}$	$6.8 \cdot 10^{-3}$
649	1200	552	80.0	$1.8 \cdot 10^{-4}$	$1.6 \cdot 10^{-2}$	$1.8 \cdot 10^{-4}$	$1.6 \cdot 10^{-2}$
		690	100.0	$6.9 \cdot 10^{-2}$	$2.2 \cdot 10^{-1}$	$6.9 \cdot 10^{-2}$	$2.2 \cdot 10^{-1}$
593	1100	690	100.0	$2.8 \cdot 10^{-3}$	$9.0 \cdot 10^{-3}$	$5.0 \cdot 10^{-2}$	$8.4 \cdot 10^{-2}$
		862	125.0	$5.2 \cdot 10^{-2}$	$4.1 \cdot 10^{-2}$	$9.3 \cdot 10^{-1}$	$3.9 \cdot 10^{-1}$
538	1000	758	110.0	$3.5 \cdot 10^{-4}$	$3.7 \cdot 10^{-3}$	$1.7 \cdot 10^{-1}$	$4.6 \cdot 10^{-1}$
		862	125.0	$2.7 \cdot 10^{-3}$	$6.0 \cdot 10^{-3}$	$13.0 \cdot 10^{-1}$	$7.5 \cdot 10^{-1}$
1/2 hr. at 1975°F (1080°C) plus 24 hrs. at 1550°F (843°C)							
760	1400	262	38.0	$8.2 \cdot 10^{-4}$	$2.0 \cdot 10^{-2}$	$8.4 \cdot 10^{-6}$	$2.6 \cdot 10^{-3}$
		310	45.0	$3.3 \cdot 10^{-3}$	$2.3 \cdot 10^{-2}$	$3.4 \cdot 10^{-5}$	$2.8 \cdot 10^{-3}$
649	1200	655	95.0	$1.3 \cdot 10^{-3}$	$1.8 \cdot 10^{-1}$	$2.1 \cdot 10^{-3}$	$2.9 \cdot 10^{-1}$
593	1100	827	120.0	$5.9 \cdot 10^{-3}$	$3.2 \cdot 10^{-2}$	$1.7 \cdot 10^{-1}$	$5.4 \cdot 10^{-1}$
538	1000	931	135.0	$3.6 \cdot 10^{-3}$	$6.0 \cdot 10^{-3}$	$28.0 \cdot 10^{-1}$	$12.4 \cdot 10^{-1}$
1/2 hr. at 1975°F (1080°C) plus 16 hrs. at 1400°F (760°C)							
704	1300	241	35.0	$3.5 \cdot 10^{-5}$	$1.5 \cdot 10^{-3}$	$1.5 \cdot 10^{-6}$	$7.5 \cdot 10^{-5}$
		379	55.0	$4.2 \cdot 10^{-4}$	$1.5 \cdot 10^{-2}$	$1.8 \cdot 10^{-5}$	$7.5 \cdot 10^{-4}$
		448	65.0	$9.8 \cdot 10^{-4}$	$3.9 \cdot 10^{-2}$	$4.1 \cdot 10^{-5}$	$2.0 \cdot 10^{-3}$
		552	80.0	$3.4 \cdot 10^{-3}$	$1.7 \cdot 10^{-1}$	$1.4 \cdot 10^{-4}$	$8.5 \cdot 10^{-3}$
649	1200	552	80.0	$1.2 \cdot 10^{-4}$	$1.0 \cdot 10^{-2}$	$1.2 \cdot 10^{-4}$	$1.0 \cdot 10^{-2}$
		621	90.0	$1.3 \cdot 10^{-4}$	$2.0 \cdot 10^{-2}$	$1.3 \cdot 10^{-4}$	$2.0 \cdot 10^{-2}$
		758	110.0	$1.0 \cdot 10^{-3}$	$3.6 \cdot 10^{-2}$	$1.0 \cdot 10^{-3}$	$3.6 \cdot 10^{-2}$
593	1100	827	120.0	$1.6 \cdot 10^{-4}$	$8.5 \cdot 10^{-3}$	$2.1 \cdot 10^{-3}$	$4.8 \cdot 10^{-2}$
		931	135.0	$1.3 \cdot 10^{-3}$	$2.0 \cdot 10^{-2}$	$1.7 \cdot 10^{-2}$	$1.1 \cdot 10^{-1}$
538	1000	896	130.0	$1.7 \cdot 10^{-4}$	$4.5 \cdot 10^{-3}$	$4.4 \cdot 10^{-2}$	$1.8 \cdot 10^{-1}$
		931	135.0	$5.6 \cdot 10^{-4}$	$9.5 \cdot 10^{-3}$	$1.4 \cdot 10^{-1}$	$3.8 \cdot 10^{-1}$
		1000	145.0	$5.8 \cdot 10^{-3}$	$1.9 \cdot 10^{-2}$	$15.0 \cdot 10^{-1}$	$7.6 \cdot 10^{-1}$
		1034	150.0	$7.4 \cdot 10^{-3}$	$2.7 \cdot 10^{-2}$	$19.0 \cdot 10^{-1}$	$10.8 \cdot 10^{-1}$

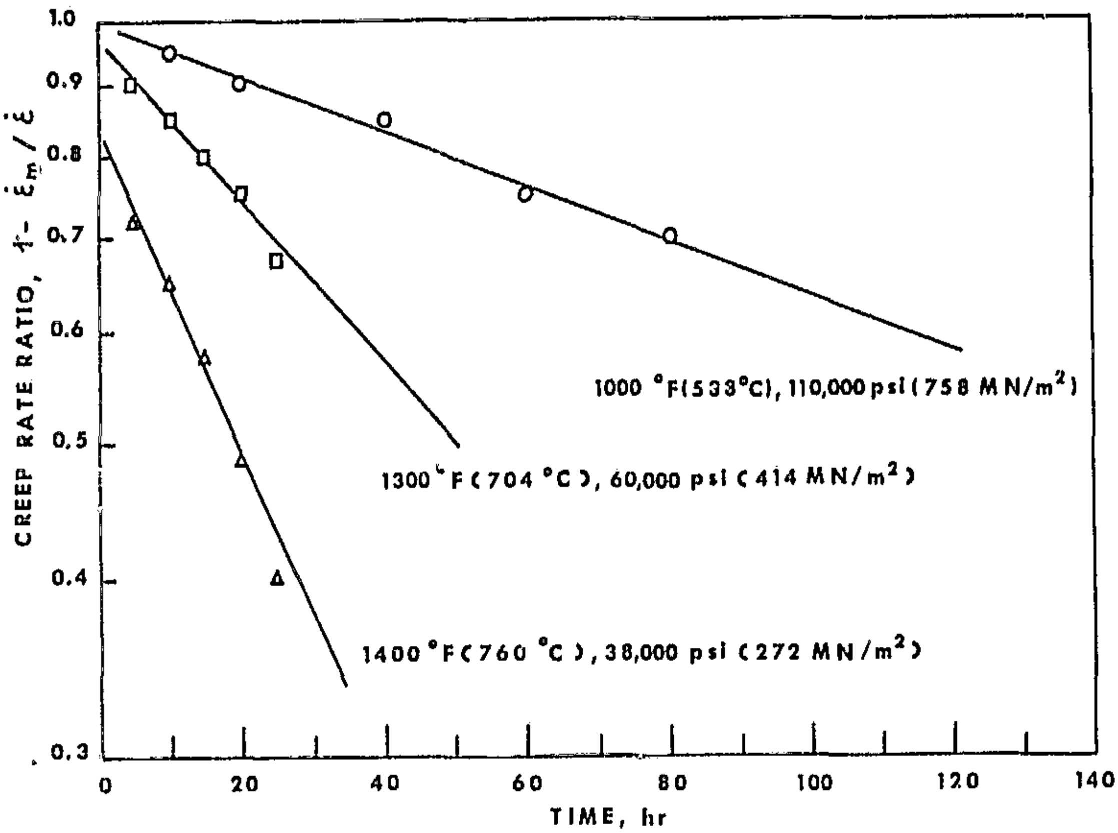

Figure 1 Dependence of primary creep rate, expressed as $\ln(1-\dot{\varepsilon}_m/\dot{\varepsilon})$, on time for several test conditions of Waspaloy aged 10 hrs. at 1700°F(927°C). Linearity for almost the entire primary creep range permits its description in terms of the slope K_1.

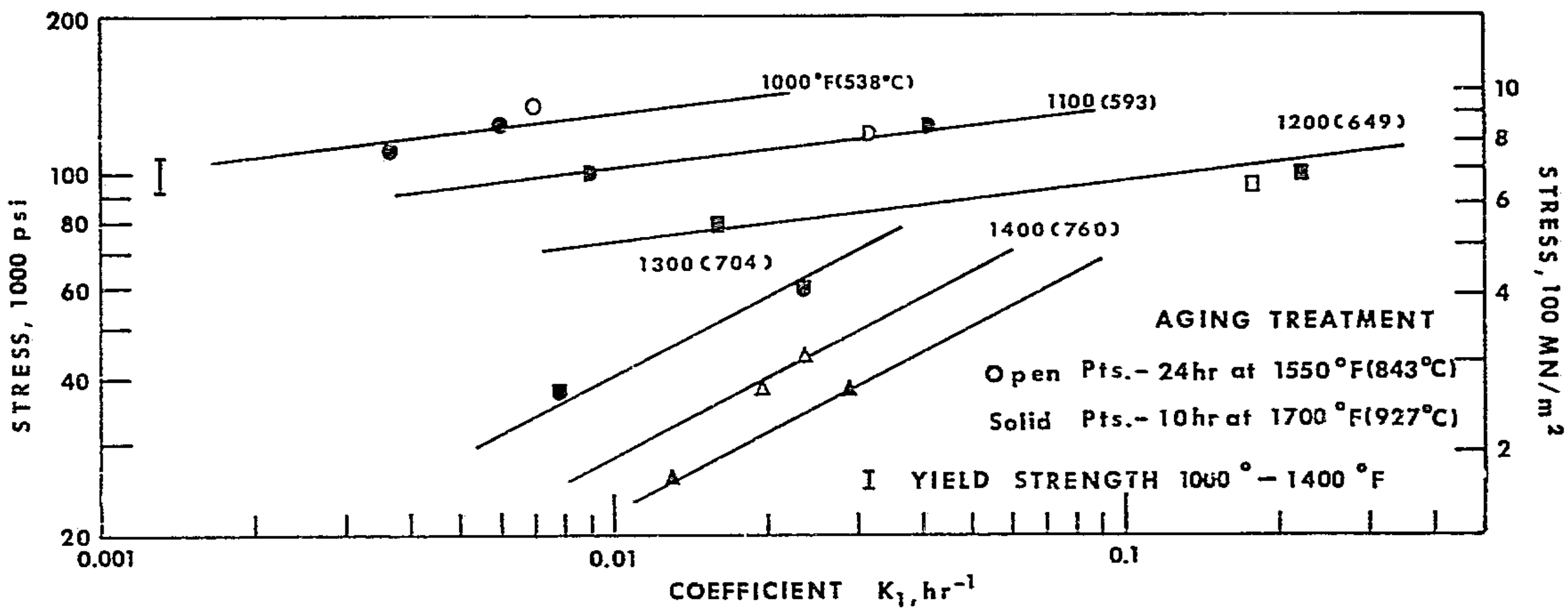

Figure 2 The dependence of the coefficient K_1 on stress σ in the temperature range of 1000° - 1400°F (538 - 760°C) for Waspaloy aged at 1700°F (927°C) and at 1550°F (843°C). For stresses below the yield strength, the data are consistent with theory in that K_1 depends on σ^2. At higher stresses, a stress exponent of about 10 occurs.

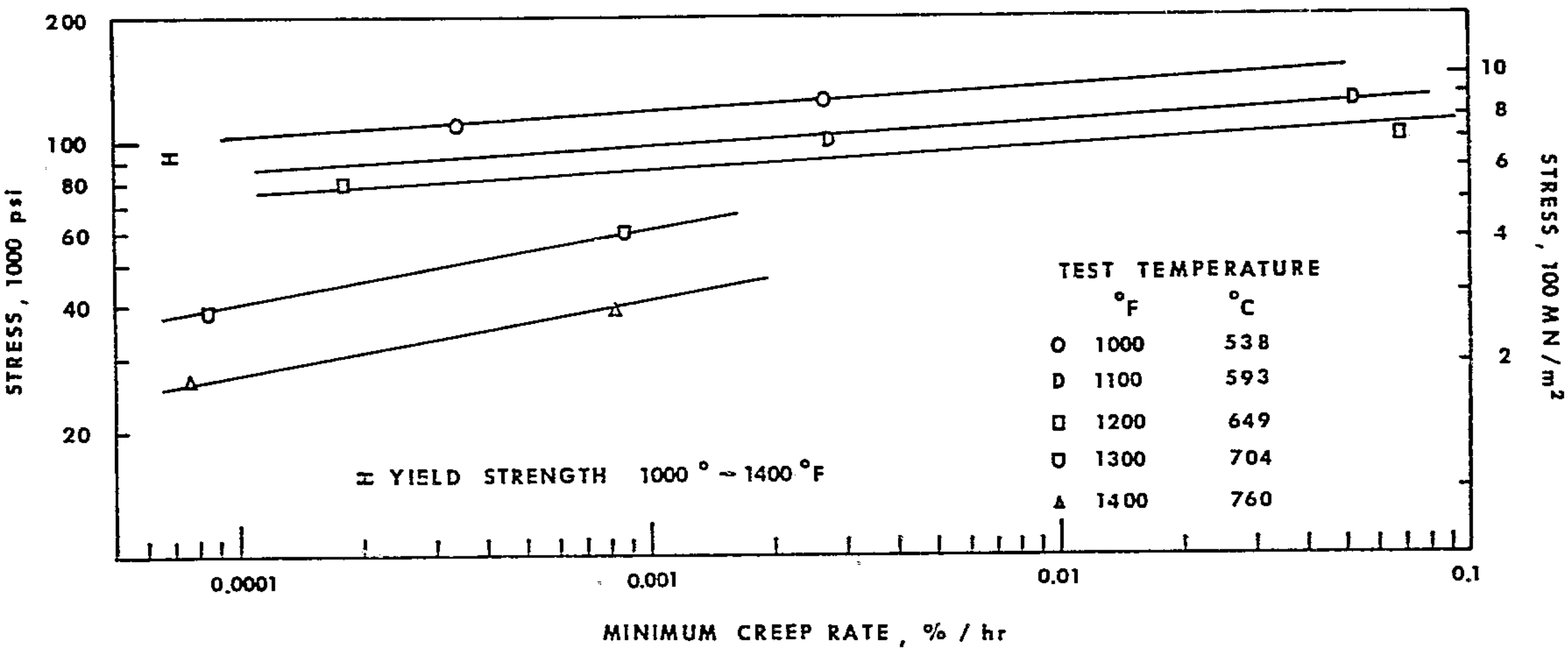

Figure 3 The dependence of the minimum creep rate $\dot{\epsilon}_m$ on stress σ at temperatures from 1000° - 1400°F (538 - 760°C) for Waspaloy aged 10 hrs. at 1700°F (927°C). At stresses below the yield strength, $\dot{\epsilon}_m$ depends on σ^5 (similar to the theoretical σ^4). At higher stresses, the exponent is about 20.

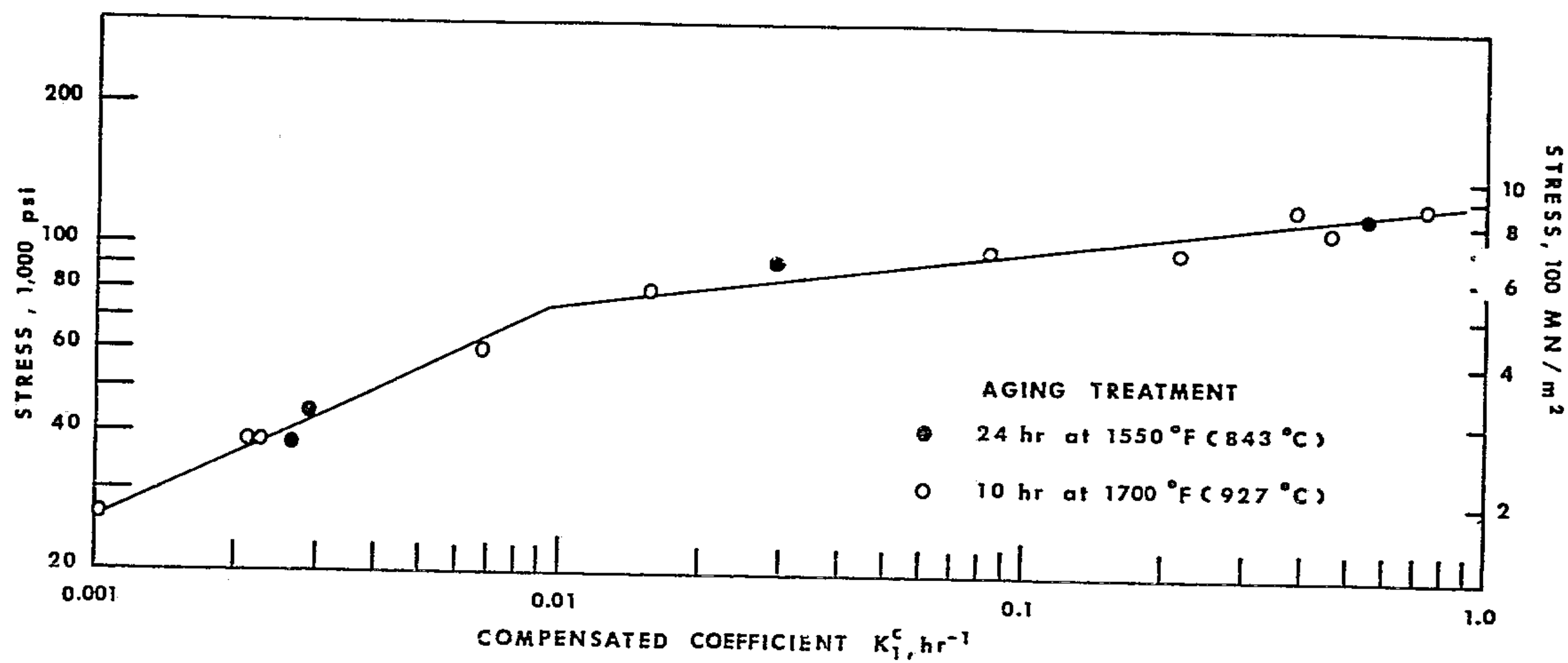

Figure 4 Coefficients K_1 compensated to 1200°F (649°C) and a particle size of 1000Å for Waspaloy aged at 1700°F (927°C) and at 1550°F (843°C) and tested in the temperature range 1000° - 1400°F (538 - 760°C). The data shows little scatter and are well represented by the master curve.

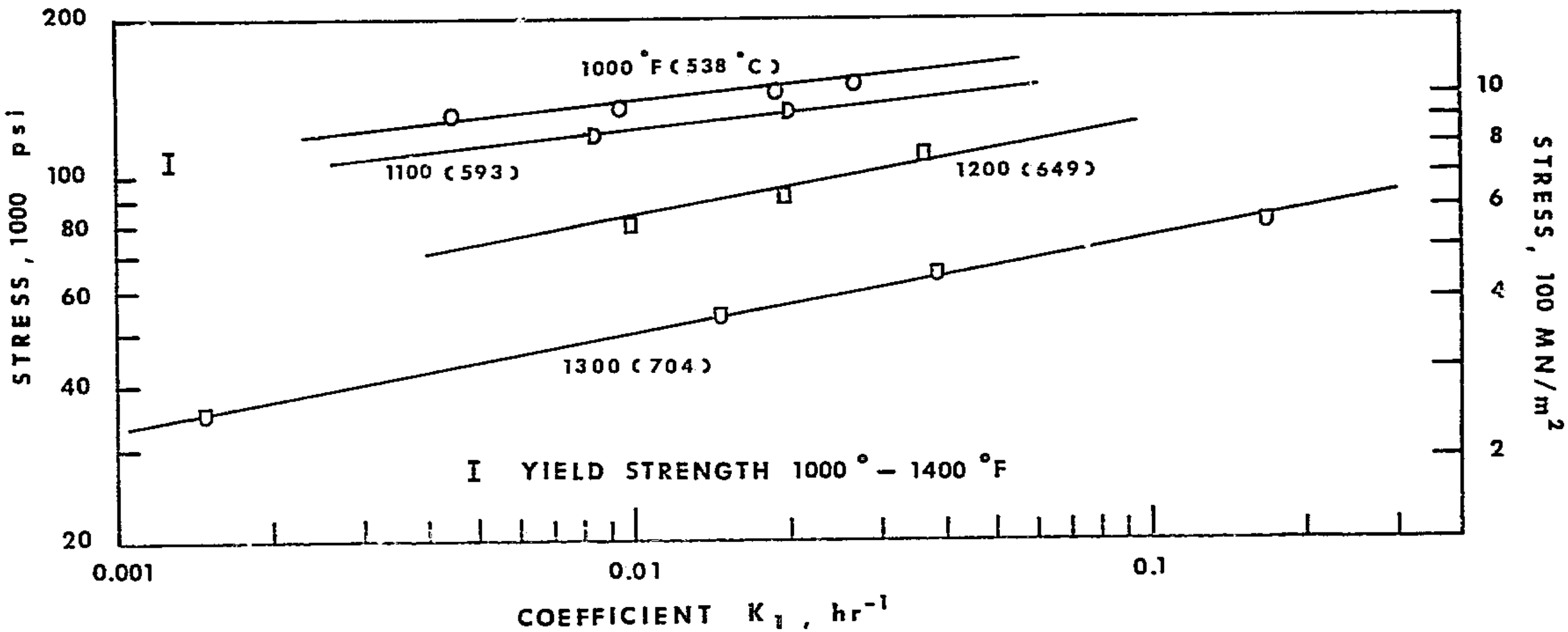

Figure 5 The dependence of the coefficient K_1 on stress σ in the temperature range of 1000° - 1400°F (538 - 760°C) for Waspaloy aged 16 hrs. at 1400°F (760°C). For stresses below the yield strength, K_1 depends on σ^5. At higher stresses, the exponent is about 11.

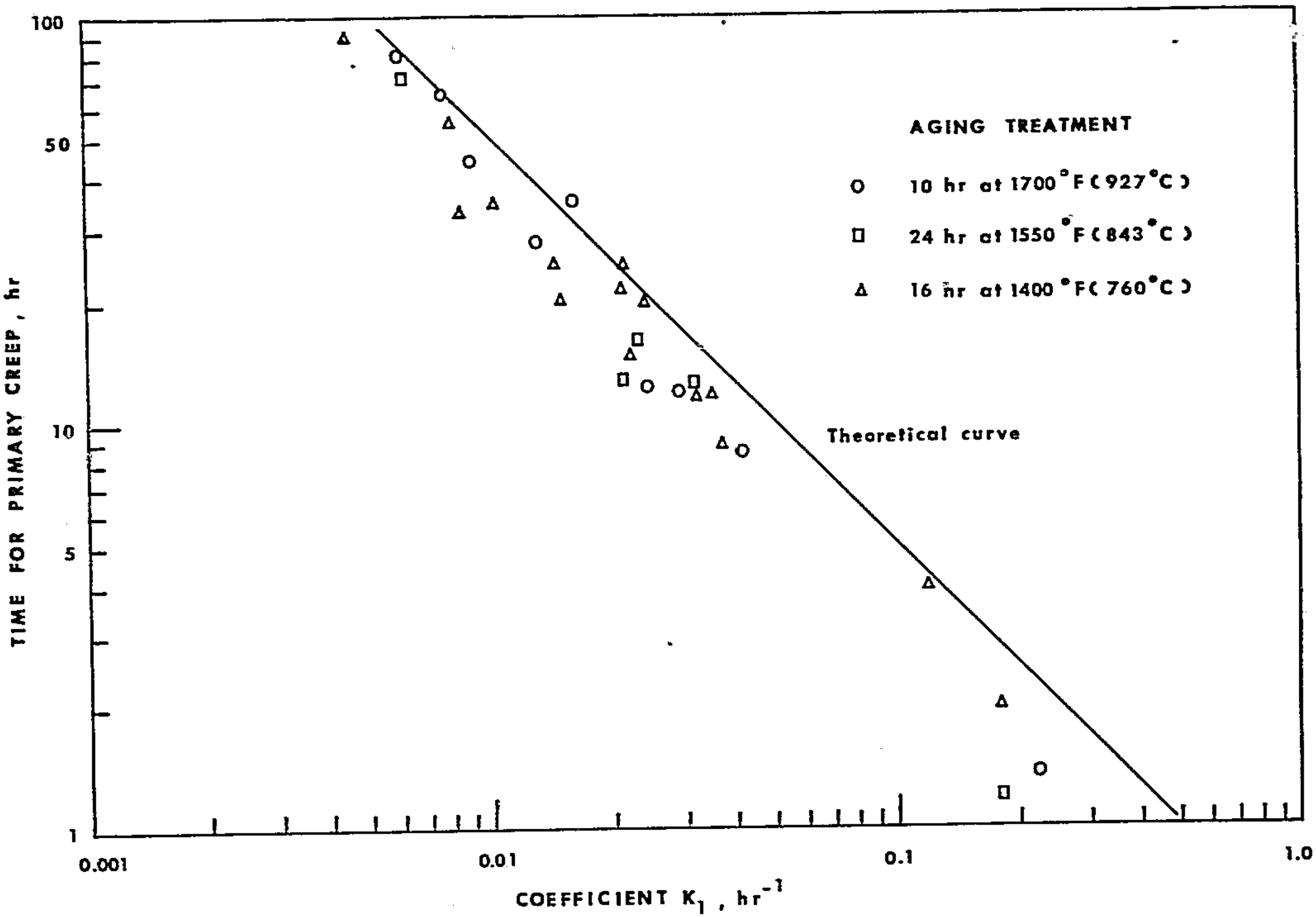

Figure 6. Time for primary creep as a function of K_1 for a range of heat treatments and test conditions of Waspaloy. The experimental data conform very well to the theoretically derived curve.

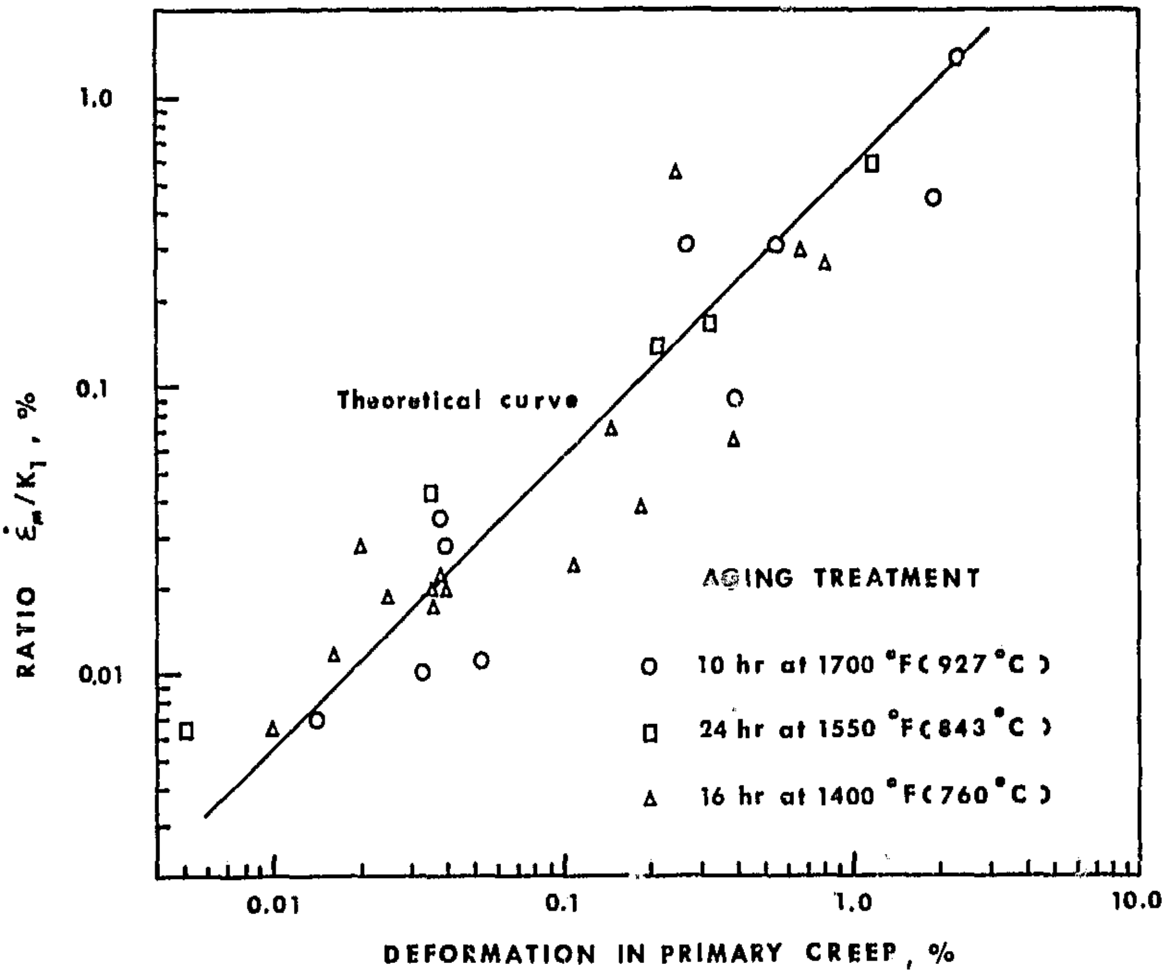

Figure 7. Amount of primary creep as a function of $\dot{\epsilon}_m / K_1$ for a range of heat treatments and test conditions of Waspaloy. The data are in good agreement with the theoretical curve.

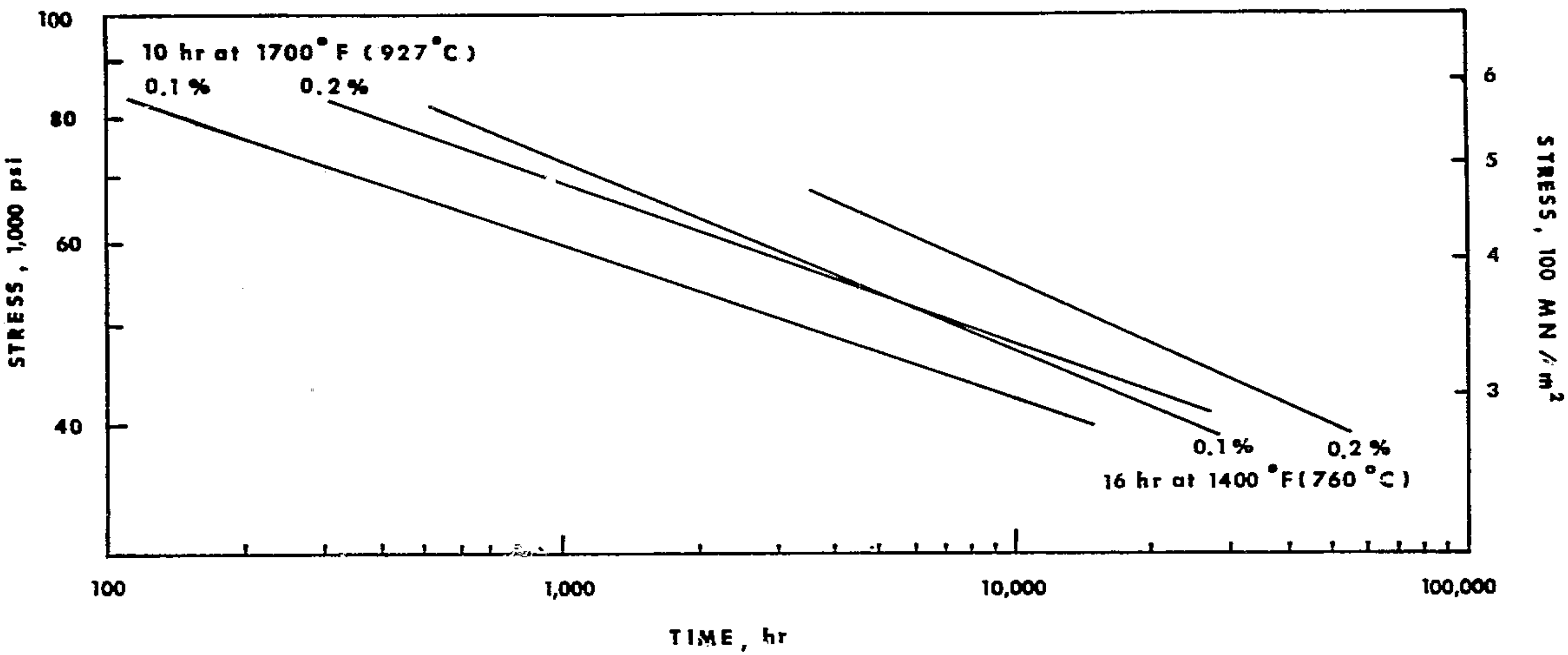

Figure 8. Iso-creep strain curves at 1200°F(649°C) for two heat treatments of Waspaloy. A longer time was required for 0.1 and 0.2 percent creep for the material aged at 1400°F (760°C) (dislocation mechanism of shearing) than for that aged at 1700°F (927°C) (dislocation mechanism of by-passing).

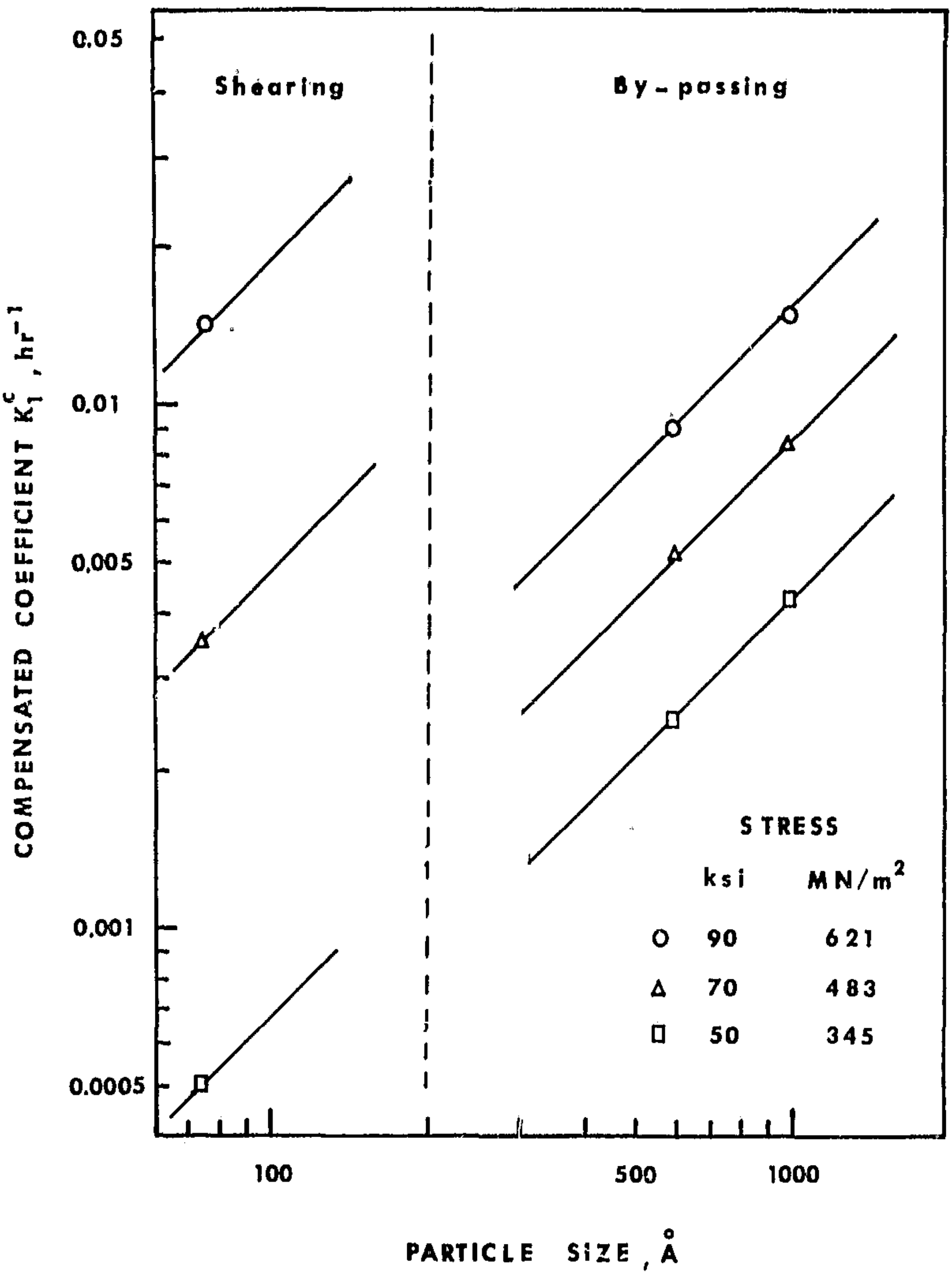

Figure 9. The dependence of the rate coefficient K_1 on γ' particle size for Waspaloy at 1200°F (649°C). The linear relationships shown are in accordance with the theory presented.