

# PLASTIC SHEAR DEFORMATION UNDER CREEP CONDITIONS IN HETEROPHASE MATERIALS WITH NONCOHERENT PARTICLES OF THE SECOND PHASE

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**Abstract.** This paper presents results from mathematical modeling of plastic deformation of heterophase alloys with noncoherent particles under creep flow conditions. Creep curves are plotted for a range of moderate temperatures. Influence of scale characteristics of the strengthening phase on the creep curves has been studied. It has been shown that larger deformation is attained when the volume ratio is lower and the particle size is larger. Dependencies of deformation defect subsystems corresponding to the creep curves have been calculated.

## 1. Introduction

Mechanisms of plastic deformation and objective laws of its development have always been front and center for scientists that create materials with various properties. Knowledge obtained in this field opens possibilities for targeted formulation of alloys with predefined mechanical properties by searching through their composition and thermal treatment method. Due to the complex nature of studying defect movements during the deformation itself, mathematical modeling plays an important role; it is based upon theoretic and experimental data on crystalline lattice defects and their behavior under various modes of thermal and mechanical stress.

## 2. Materials and methods

In this paper, we are going to consider application of mathematical modeling to studies of mechanisms and processes taking place during the plastic deformation under creep flow conditions. Creep flow is a deformation under constant load ( $\tau = \text{const}$ ) [1, 2]. We will consider only the case of deformation under conditions of constant application of relatively low stress.

## 3. Results and discussion

Mathematical model used in this paper amounts to a system of differential equations for balancing deformation subsystem that consists of displacement-inducing dislocations (density  $\rho_m$ ), prismatic loops of vacancy (density  $\rho_p^v$ ) and interstitial (density  $\rho_p^i$ ) type, dipole dislocation structures of vacancy and interstitial type (density  $\rho_d^v, \rho_d^i$ ), interstitial atoms (density  $c_i$ ), monovacancies (density  $c_v$ ) and bivacancies (density  $c_{2v}$ ) [3]:



$$\begin{aligned}
\frac{d\rho_m}{da} &= (1-\omega_s P_{as}) \frac{F}{Db} - \frac{2}{a} (1-\omega_s) \rho_m^2 b \min(r_a, \rho_m^{-1/2}) (c_{2v} Q_{2v} + c_{1v} Q_{1v} + c_i Q_i) + \\
&+ \frac{2\alpha}{a} b \sqrt{\rho} (\rho_p^v (c_{1v} Q_{1v} + c_{2v} Q_{2v}) + \rho_p^i c_i Q_i) + \frac{2b}{ar_a} (\rho_d^i c_i Q_i + \rho_d^v (c_{1v} Q_{1v} + c_{2v} Q_{2v})), \\
\frac{d\rho_p^i}{da} &= \frac{\langle \chi \rangle \delta}{2\Lambda_p^2 b} - \frac{2\alpha}{a} \sqrt{\rho} \rho_p^i b (2c_{2v} Q_{2v} + c_i Q_i + 2c_{1v} Q_{1v}), \\
\frac{d\rho_p^v}{da} &= \frac{\langle \chi \rangle \delta}{2\Lambda_p^2 b} - \frac{2\alpha}{a} \sqrt{\rho} \rho_p^v b (c_{2v} Q_{2v} + 2c_i Q_i + c_{1v} Q_{1v}), \\
\frac{d\rho_d^v}{da} &= \frac{1}{\Lambda_p b} - \frac{2b}{ar_a} \rho_d^v (c_{2v} Q_{2v} + c_i Q_i + c_{1v} Q_{1v}), \\
\frac{d\rho_d^i}{da} &= \frac{1}{\Lambda_p b} - \frac{2b}{ar_a} \rho_d^i (c_{2v} Q_{2v} + c_i Q_i + c_{1v} Q_{1v}), \\
\frac{dc_i}{da} &= q \frac{\tau_{dyn}}{G} - \frac{c_i}{a} [((1-\omega_s) \rho_m + \rho_p + \rho_d) b^2 Q_i + Q_{1v} c_{1v} + Q_{2v} c_{2v} + Q_i (c_{1v} + c_{2v})], \\
\frac{dc_{1v}}{da} &= \frac{q\tau_{dyn}}{6G} - \frac{1}{a} [(((1-\omega_s) \rho_m + \rho_p + \rho_d) b^2 + c_i + c_{1v}) Q_{1v} c_{1v} + Q_i c_i c_{1v} - (Q_{2v} + Q_i) c_i c_{2v}], \\
\frac{dc_{2v}}{da} &= \frac{5q\tau_{dyn}}{6G} - \frac{1}{a} [(((1-\omega_s) \rho_m + \rho_p + \rho_d) b^2 + c_i) Q_{2v} c_{2v} + Q_i c_i c_{2v} - Q_{1v} c_{1v}^2],
\end{aligned}$$

where  $a$  is the amount of deformation,  $\delta$  is a particle size,  $\Lambda_p$  is a distance between the particles,  $c_i$  is a concentration of interstitial atoms,  $c_v$  is a concentration of vacancies,  $c_{2v}$  is a concentration of bivacancies,  $D$  is a diameter of displacement zone;  $F$  is a parameter determined by the form of dislocation loops and their distribution through the displacement zone;  $\tau_{dyn}$  is the stress value over the static resistance to dislocation movement;  $Q_j = Z_j \nu_D \exp(-U_j^{(m)}/kT)$  is the kinetic coefficient;  $U_j^{(m)}$  is the activation energy for migration of  $j$ th type point defects;  $Z_j$  is a number of locations open for  $j$ th type defect jump ( $j=i, v$ );  $\nu_D$  is the Debye frequency;  $k$  is Boltzmann's constant;  $T$  is a deformation temperature;  $\omega_s$  is a ratio of helical dislocations;  $\langle \chi \rangle$  is the average value of the parameter that characterizes the geometry of dislocation on the particles;  $q$  is the parameter that determines intensity of point defect generation;  $G$  is the shear modulus,  $b$  is the modulus of Burgers vector,  $\rho$  is dislocation density,  $\rho_p = \rho_p^i + \rho_p^v$  is density of prismatic dislocation rings,  $\rho_d = \rho_d^i + \rho_d^v$  is the density of dislocations in dipole configurations;  $\alpha$  is the parameter of interdislocation interactions;  $\tau_f$  is friction stress];

$$P_{as} = \begin{cases} V_{as}, & \text{if } V_{as} < 1, \\ 1, & \text{if } V_{as} \geq 1, \end{cases} \quad V_{as} = \left( \frac{Gb}{\pi} \right)^2 \frac{\rho_m \omega_s}{12\tau_f (\tau - \tau_f)}, \quad r_a = \frac{Gb}{4\pi\tau_f} \frac{(2-\nu)}{(1-\nu)}.$$

Here  $\nu$  is Poisson's ratio.

The system of equations of the model is supplemented with an equation that links the rate of deformation  $\dot{a}$  with the applied stress  $\tau$  and the density of dislocations in the material being deformed [4]:

$$\dot{a} = \frac{8\beta_r^{1/2} \rho_m^{1/2} \nu \left( ((1-\beta_r) \rho_m + \rho_p + \rho_d) (\tau - \tau_a) \right)^{1/3}}{\pi \xi^{1/6} (1-\beta_r) G^{1/3} b^{1/3} G(\rho)} \exp \left[ -\frac{U - (\tau - \tau_a) \Lambda b^2}{kT} \right]$$

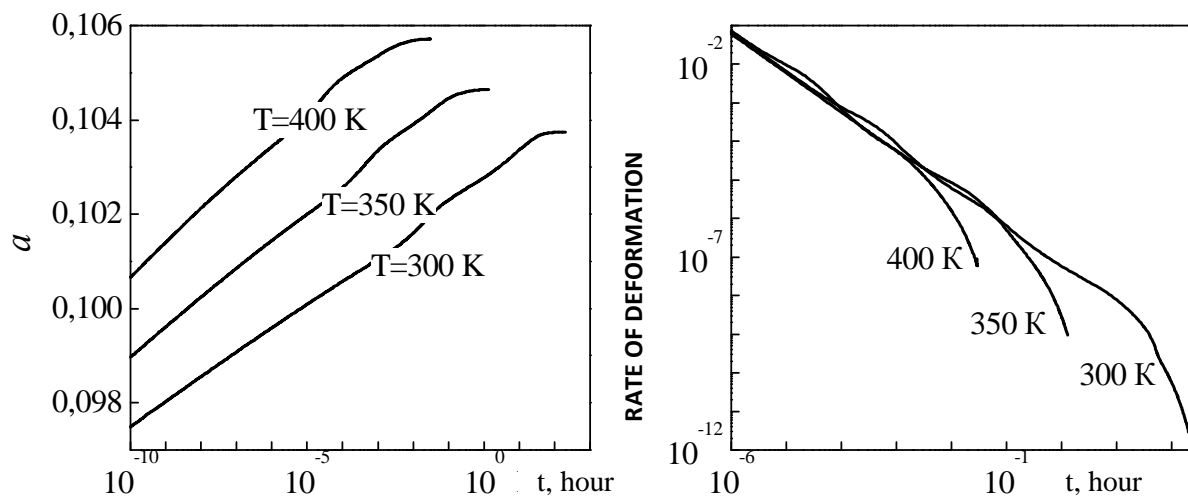
Here  $\xi$  is the ratio of immobile dislocations;  $\beta_r$  is the ratio of reacting dislocations;  $\Lambda$  is the average length of free dislocation segment.

To study the dislocation process under creep flow conditions, let us perform calculations with the parameters characteristic of monocrystals of particulate reinforced copper alloys ( $b=2.5 \cdot 10^{-10} \text{ m}^2$ ,  $F=4$ ,  $\nu_D=10^{13} \text{ s}^{-1}$ ,  $\alpha=0.5$ ,  $\alpha_a=0.45$ ,  $\alpha_i=0.5$ ,  $\alpha_r=0.3$ ,  $\beta_r=0.14$ ,  $\xi=0.5$ ,  $\tau_f=10 \text{ MPa}$ ,  $\nu=1/3$ ,  $Z_i=12$ ,  $Z_{iv}=12$ ,  $Z_{2v}=24$ ,  $\alpha_{dyn}=0.33$ ,  $k=1.38 \cdot 10^{-23} \text{ J/K}$ ,  $p_f=0.5$ ,  $\omega_s=0.3$  [5,6],  $U_i^f=3.28 \text{ eV}$ ,  $U_v^f=1.27 \text{ eV}$ ,  $U_i^m=0.117 \text{ eV}$ ,  $U_v^m=0.88 \text{ eV}$  [5, 6]). Initial density of shear-inducing dislocations is equal to  $10^{12} \text{ m}^{-2}$ ; the initial density of interstitial and vacancy dipoles and initial concentration of deformation defects are both zero.

A typical creep curve obtained at a constant stress may be divided into momentary deformation and the following three sequential stages [1, 2]. At the first stage of creep, the rate continuously decreases (stage I); this stage is usually called transitional creep stage. At low temperatures, creep curve of many metals and alloys may be sufficiently well described with a logarithmic law [1, 2]. At higher temperatures, the dependency of deformation on time at the first stage is  $a \cdot t^{1/3}$  [1, 2]. E. Andrade discovered this regularity and it is known as Andrade creep.

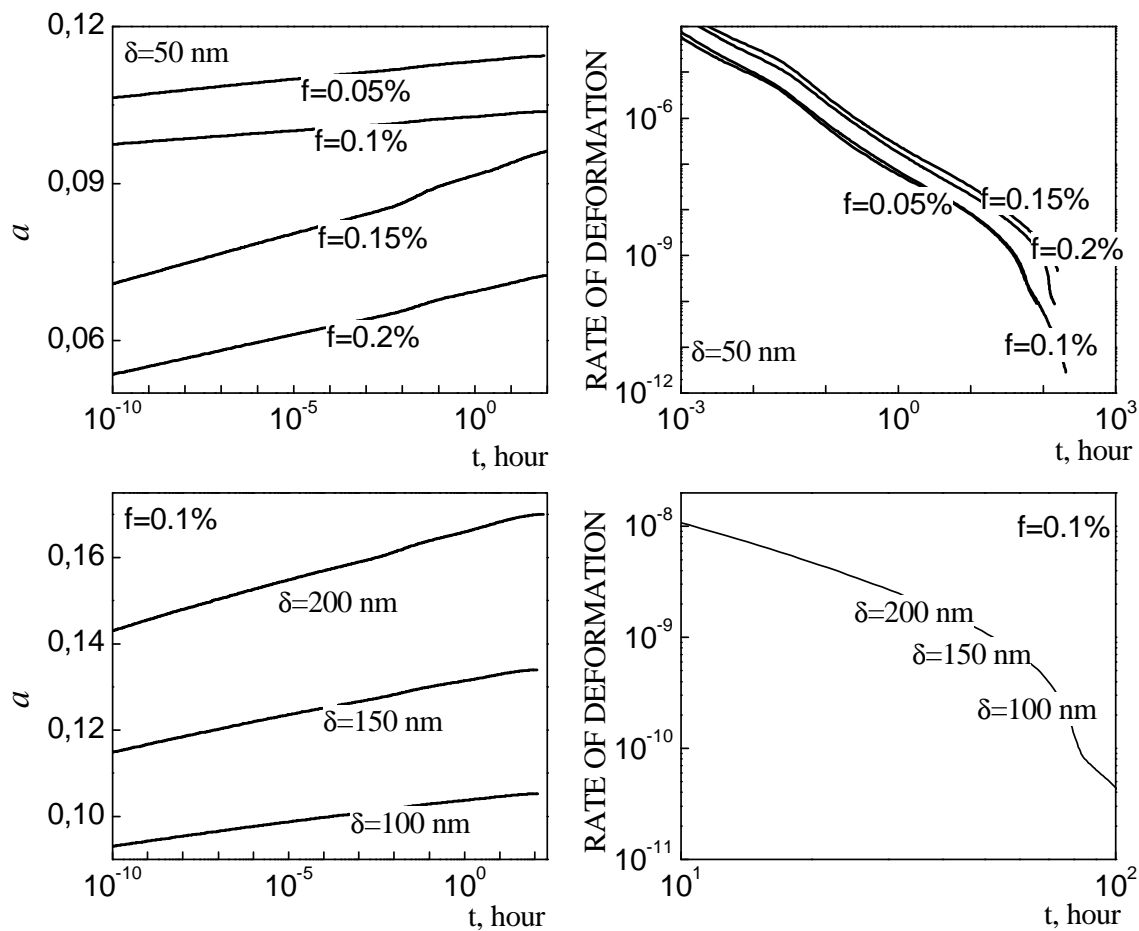
If the testing is prolonged enough (and takes place under high enough temperatures), the first stage of creep gives place to the second stage, where deformation continues at approximately constant rate. This stage is called settled creep [1, 2].

In the end, before the specimen is destroyed, the settled creep stage changes into the accelerated creep stage, stage III, that ends with the destruction of the specimen. At this stage, the creep continuously increases. However, in constant stress creep this stage is usually absent.



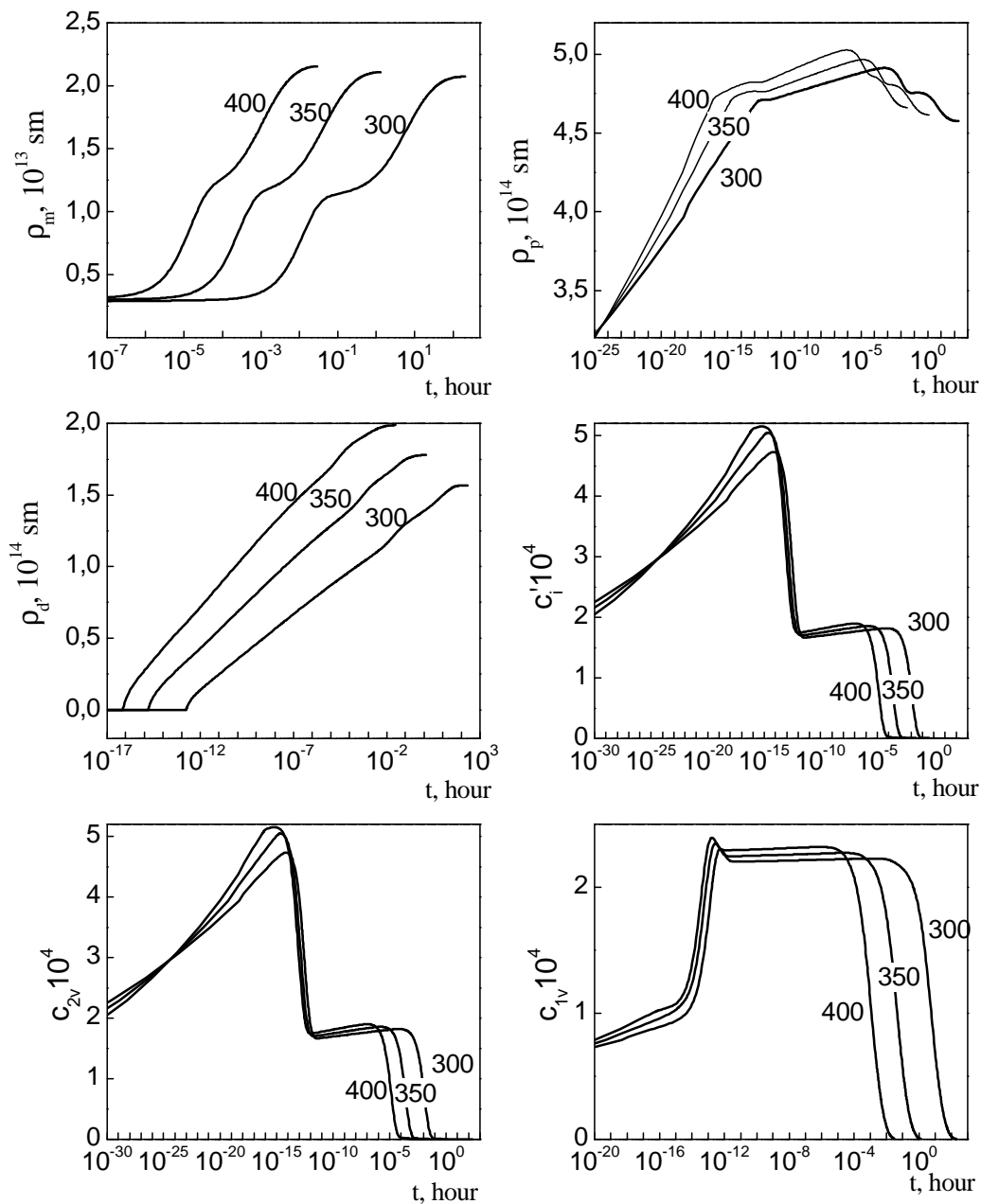
**Figure 1.** Creep curves in semilogarithmic coordinates for particle-reinforced copper-based materials at  $\tau=200 \text{ MPa}$ ,  $f=0.1\%$ ,  $\delta=50 \text{ nm}$ .

Figure 1 shows creep curves for various low temperatures. Creep curves are qualitatively similar; however, with increased temperature ( $T=400\text{K}$ ) the attainable deformation values are higher. The given curves correspond to the first stage of creep, that is, transitional creep. Significant segments of the curves are almost linear in semi-logarithmic coordinates, corresponding to logarithmic creep. Logarithmic creep is usually observed at low temperatures.



**Figure 2.** Creep curves in semilogarithmic coordinates for particle-reinforced copper-based materials at  $\tau=200$  MPa,  $T=300$  K,  $f$  is the volume fraction of the reinforcing phase.

The influence of volume fraction of the reinforcing phase and particle size on creep curves has been considered (Fig.2). It is evident, that the characteristics of the reinforcing phase have a significant influence on the deformation value, which is attained at the transitional creep stage: larger deformation values are attained when the volume ratio is lower and the particle size is larger. Figure 3 shows components of the deformation defect subsystem corresponding to the curves in Fig. 2.



**Figure 3.** Creep curves in semilogarithmic coordinates for particle-reinforced copper-based materials at  $\tau=200$  MPa,  $f=0.1\%$ ,  $\delta=50$  nm. Numbers at the curves are temperature in K

#### 4. Conclusion

Creep curves are plotted for a range of moderate temperatures. The curves correspond to the transitional creep stage. Significant segments of the curves are almost linear in semi-logarithmic coordinates, which corresponds to logarithmic creep. It has been demonstrated, that the characteristics of the reinforcing phase have a significant influence on the deformation value, which is attained at the transitional creep stage: the lower is the volume fraction and the larger is the particle size, the higher is the deformation value attained. Dependencies of deformation defect subsystems corresponding to the creep curves have been calculated. It may be noted, that the dominant elements of the deformation defect subsystem are prismatic loops and dipole configurations.

**References**

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