



Influence of preliminary ultrasonic treatment upon the steady-state creep of metals of different stacking fault energies



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ABSTRACT

This paper addresses the issue of the ultrasound effects upon the creep deformation of metals with different levels of stacking fault energy. The influence of preliminary ultrasound irradiation time upon the steady state creep rate is considered. Synthetic theory of irrecoverable deformation is taken as a mathematical apparatus. The analytical results show good agreement with experimental data.

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1. Introduction

The procedure of an alternating loading of ultrasonic frequency applied together with intermediate annealing is an efficient tool for the improvement of high-temperature strength of metals and alloys. In what follows, the indicated combined procedure is called the ultrasonic treatment (UT). The application of UT to materials used in machine building, chemical industry, and other branches of engineering would guarantee a significant increase in the service life of workpieces caused by the realization of latent reserves of strength and a decrease in the weight of structures [29,30,8].

The aim of the present work is to construct a suitable mathematical model for getting an analytic dependence of the rate of stationary creep of materials ($\dot{\epsilon}$) on the level of sonication time (τ) for constant parameters of intermediate annealing. The factor complicating the problem is that three different processes – alternating loading, annealing in a load-free state, and straining due to a constant in time loading (creep) – and their interplay must be modeled. Furthermore, the stacking fault energy of a metal strongly affects the behavior of $\dot{\epsilon} - \tau$ dependency. In Rusinko's early work [27], the model, constructed on the base of the synthetic theory of irrecoverable deformation, describing the influence of UT upon the creep of the metals of low stacking fault energy (e.g., cooper), is presented. This paper will discuss the modeling of $\dot{\epsilon} - \tau$ curve for the metals of both low and high stacking fault energy.

It is clear that the classical theories of creep (the theory of hardening and aging and the hypothesis of equation of state), see, e.g., Rabotnov [21], Bethen [5], are incapable of modeling the dependence of $\dot{\epsilon}$ on τ , because they study the rate of stationary creep as a function of the acting stress and neglect the prehistory of loading.

2. Experimental data and their analysis

The procedure of ultrasound treatment (UT) includes the sonication of a specimen with subsequent annealing in the prerecrystallization temperature range. The experiments are carried out as follows:

- (i) sonication of a batch of specimens in longitudinal vibrations of frequency f at room temperature for certain time periods, τ , at a given stress amplitude, σ_m , (the values of σ_m and f are identical for the entire batch);
- (ii) annealing of the specimens in the unloaded state at a temperature T_a for a time t_a (the values of T_a and t_a are identical for the entire batch);
- (iii) uniaxial creep testing in tension; the values of tensile stress, σ_x , and temperature, T_c , are identical for the entire batch.

The first two stages constitute the procedure of ultrasound treatment (Fig. 1). Experimental data show that the steady-state creep rate of the pre-sonicated specimens strongly depends on the duration of ultrasound action τ if the other parameters (σ_m , T_a , t_a , T_c and σ_x) are constant. As follows from Figs. 2 and 3, the

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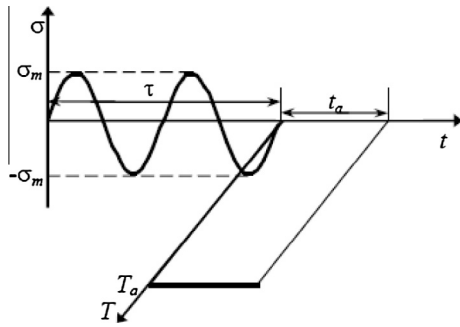


Fig. 1. The scheme of UT.

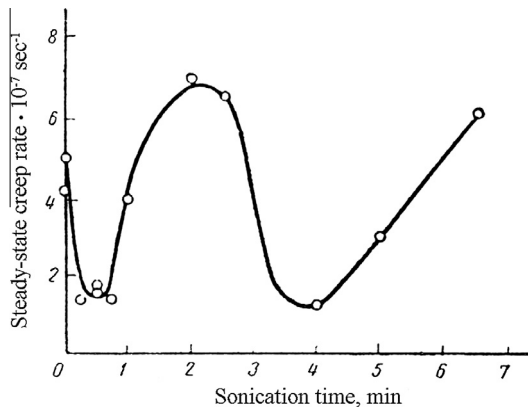


Fig. 2. Steady-state creep of aluminum in tension (260 °C, $\sigma = 9.6$ MPa) as a function of sonication time in the course of preliminary UT (oscillation frequency and amplitude: $f = 20$ kHz and $A = 15$ μm , the temperature and duration of annealing: $T_a = 260$ °C and $t_a = 1$ h); [3].

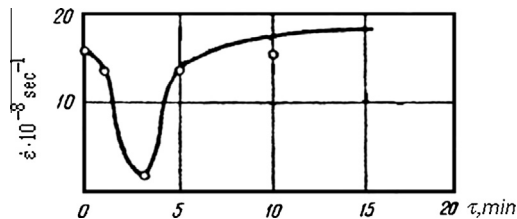


Fig. 3. Steady-state creep rate of copper in tension (500 °C, $\sigma = 15$ MPa) as a function of sonication time in the course of preliminary UT (oscillation frequency and amplitude: $f = 20$ kHz and $A = 25$ μm , the temperature and duration of annealing $T_a = 500$ °C and $t_a = 1$ h); [2].

dependences of the rate of steady-state creep on the sonication time τ for aluminum and copper are different and not monotonic [2,3]. The variations of the rate of steady-state creep after UT were observed also for, nickel and its alloys [4,9,10,15], molybdenum [16], and stainless steel [13].

The hardening caused by preliminary ultrasonic treatment can be attributed to the changes in the crystal structure of the specimens subjected to ultrasonic irradiation and stabilizing annealing. In the process of ultrasonic irradiation, the number of dislocations, dislocation loops and dipoles, and point defects grows dramatically and original relatively perfect crystals split into fragments whose sizes and orientations depend of the level of microplastic strains, i.e. the duration of sonification [31,18,14,6,11]. The boundaries of the fragments form a three-dimensional network of subboundaries and play the role of sites of dislocation pileups. The number of dislocations – the carriers of microplastic strains – grows in the course of sonication so that starting from a certain sonication time,

τ^* , saturation dislocation pattern is observed [14]. Further increase in τ ($\tau > \tau^*$) leads to the nucleation of fatigue microcracks.

Using transmission electron microscopy and X-ray investigations, Bazelyuk et al. [2,3] Demchenko et al. [10], Belostockij et al. [4] and Novikov [17] report that the stabilization annealing of sonicated metal leads to the formation of thermally stable dislocation substructure by means of the annihilation of dislocations resulting in the reduction of internal stresses, and by the interaction of point defects with dislocations: point-defect atmospheres pin the network of subboundaries formed in the course of sonication. According to Bazelyuk et al. [2,3] the sonication time needed to induce the sufficient number of point defects for a considerable pinning of subgrain boundaries in aluminum is about 2 min at the amplitude of oscillation 15 μm ($f = 20$ kHz).

The dislocation substructure formed in the course of preliminary UT impedes the development the subsequent creep by restricting the free path of dislocations (i.e. both coarse and fine sliding decreases), and by blocking the dislocation sources [2,3,13,14]. As a result, the steady-state creep of the material subjected to preliminary UT decreases. However, this hardening phenomenon has a non-monotonous character. As seen from Figs. 2 and 3, the $\dot{\epsilon} = \dot{\epsilon}(\tau)$ function decreases only for a certain time-period, $\tau \in [0, \tau_{opt}]$, where τ_{opt} is an optimal sonication time, $\tau_{opt} \approx 0.5$ min and $\tau_{opt} \approx 3$ min for aluminum and copper, respectively. For $\tau > \tau_{opt}$ the creep rate tends to its initial value. Bazelyuk et al. [2,3], Kulemin [14], and Bazelyuk et al. [13] suggest that beginning with a certain value of τ , the defect-substructure formed in the course of UT loses its thermomechanical stability. This means that the defects energy stored in material during the UT, which is above the optimal value, induces softening processes (an active recrystallization starts, subgrain walls falls apart, etc.) dominating over the hardening ones, which results in the increasing portion of $\dot{\epsilon} = \dot{\epsilon}(\tau)$ curve (from 0.5 to 2 min for aluminum and above 3 min for copper).

On passing the minimum, $\dot{\epsilon} = \dot{\epsilon}(\tau)$ curves for copper and aluminum from Figs. 2 and 3 exhibit different types of behavior. The major two reasons for this phenomenon can be explained by the interplay between (i) the number of the point defects nucleated in preliminary sonication, and (ii) different mechanisms of the recovery in the course of secondary creep for materials with different stacking-fault energies, γ , ($\gamma_{Al} = 0.2$ J/m², $\gamma_{Cu} = 0.04$ J/m², i.e., $\gamma_{Al}/\gamma_{Cu} \approx 5$). As well-known, steady-state creep develops through a thermally activated recovery (softening), which can be of two types: polygonization and recrystallization. The recovery mechanism depends on the level of the stacking fault energy of metal (SFE): polygonization dominates in the metals with a high SFE, and recrystallization does in the metals with a low SFE [7,21].

As stated above, the number of point defects grows with an increase in τ and beginning with a certain sonication time they start to play a considerable role in the common hardening of material caused by ultrasound. As stated above, to obtain a tangible hardening effect from the point defects in aluminum at least 2 min sonication is needed. That is why the $\dot{\epsilon} = \dot{\epsilon}(\tau)$ curve for aluminum shows the second decreasing portion for the sonication time above 2 min. At the same time, in copper, the creep rate for τ greater than 3 min remains unchanged, on the level corresponding to the absence of preliminary treatment (while the number of ultrasound induced point defects monotonically grows as a function of τ).

Bazelyuk et al. [2,3,13] and Kulemin [14] explain this by the difference in the softening processes, which are in equilibrium with hardening ones and determine the secondary creep rate. Copper, as a metal with low stacking-fault energy, softens mainly as a result of recrystallization, which nucleates preferentially in the regions with the highest defect densities [20,19]. Therefore, if the number of defects from preliminary UT exceeds a critical value, the subgrains boundaries containing them become centers of

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