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INFLUENCE OF MG AND CU ON THE DYNAMIC YIELD STRESS OF ALUMINIUM ALLOYS

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Abstract. Based on the temperature relaxation model of plasticity, the effects of the irreversible deformation of metals that appear under conditions of various temperature and strain rate regimes are studied. The appearance of the yield drop on the dynamic deformation dependence for 2519A aluminium alloys at a temperature of -45°C in the range of strain rates 1000–4000 s^{-1} is predicted. Dynamic dependencies for Al-13Mg aluminium alloys at temperatures 325°C and 425°C are constructed. The temperature relaxation model of plasticity applied is able to predict various types of deformation curves for on one material in a wide range of strain rates and temperatures.

Keywords: relaxation model of plasticity, aluminium alloys, yield drop

1. Introduction

Yield drop effect on stress-strain diagrams of aluminium alloys Al-Mg and Al-Cu arising from changes in temperature and strain rate loading conditions demonstrates the temporary nature of plastic deformation. The duration and temperature of heat treatment [1,2], the compositions of magnesium [3,4,5] and copper, the strain rate, and changes in the chemical composition (e.g., Mg) regulate the material's response to the load. In this paper, we discuss the combined influence of temperature and strain rate on dynamic deformation dependencies.

The principle of temperature-time correspondence is actively discussed on various aluminum alloys. Dynamic deformation curves for Al-Sc alloys without a yield dop effect, presented in [6], showed the sensitivity of the yield stress to the temperature and strain rate at -150°C, 25°C and 300°C and 800–2800 s^{-1}. The yield stress changes for 7075 aluminium alloy on the dynamic deformation curves without a yield drop from -150°C to room temperature, discussed in [7,8,9], were observed. Dynamic stress-strain curves for 2024-T351 aluminum alloy [10] at temperatures from 20°C to 270°C showed negative strain rate dependence in a wide range of strain rates from 1000 to 2000 s^{-1}. Comparison of dynamic stress-strain relations (at strain rates of 500 – 4500 s^{-1}) of ultrafine-grained 2219 aluminium alloy at cryogenic and room temperatures is studied in [11]. Al-Mg and Al-Cu aluminum alloys differ from those listed above in that under certain conditions of temperature-rate modes of deformation, the effect of a yield drop appears on the stress-strain diagrams [3,12-14]. In all the works listed above, the effect of temperature-time correspondence is qualitatively observed. Models capable of quantitatively predicting and explaining this effect are not presented in these works.

Dynamic plasticity models [15-18] are not designed to predict the yield drop effect or pronounced peak stress on the stress-strain curves [19]. Models based on the dislocation theory take into account the extent of the upper yield stress and the stage of drop stress before establishing uniform yielding but do not evaluate the strain rate dependence of the material [20]. Non-monotonicity of deformation dependencies is explained by the dominant role of

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temporal processes before the beginning of plastic deformation. The dynamic deformation dependences of steel [21-23] with the observed effect of pronounced peak stress are often used to verification of models, which makes it possible to predict the appearance of a yield drop on the deformation dependences with an increase in the strain rate at a fixed temperature. By virtue of the principle of temperature-time correspondence, there are high strain rate and temperature regimes, wherein a similar effect of the yield drop is observed as well as the corresponding increase in peak stress.

In this work, the use of the temperature relaxation model of plasticity [24,25] is proposed to predict the deformation dependence of aluminium alloys at low temperatures using an Al-Cu alloy [12] and temperatures close to the melting temperature of Al-Mg alloys [3].

2. Temperature relaxation model of plasticity

The relaxation model of plasticity [25] as a continuation of the structural-temporal approach to plasticity [12] is based on the concept of material incubation time [26]. With the structural-temporal approach, the dynamic yield strength of materials for a wide variety of tasks can be predicted. The beginning of the plastic yielding for an arbitrary loading pulse is determined with the structural-temporal approach [12]:

$$\frac{1}{\tau}\int_{t-\tau}^{t}\left(\frac{\Sigma(s)}{\sigma_y}\right)^{\alpha} ds \leq 1. \tag{1}$$

Here, $\Sigma(t)$ is the stress function of time, τ is the characteristic time of stress relaxation or the incubation time of yielding, σ_y is the static yield strength, and α is the coefficient of the material's amplitude sensitivity. The time of the beginning of the macroscopic yield t_* is defined as the moment at which the equality sign in Eq. (1) is attained. The time parameter τ is a constant value for the whole range of the strain rates and is independent of the details of plastic deformation.

We consider the relaxation model of plasticity [27,28]. Let the linear strain-growth law $\varepsilon(t)=\varphi(t)H(t)$ be applied to the sample; here, $H(t)$ is the Heaviside function, and $\varphi(t)$ is the strain function of time. We introduce the dimensionless relaxation function $0<\gamma(t)\leq 1$:

$$\gamma(t) = \begin{cases} 1, & \frac{1}{\tau}\int_{t-\tau}^{t}\left(\frac{\Sigma(s)}{\sigma_y}\right)^{\alpha} ds \leq 1, \\ \left(\frac{1}{\tau}\int_{t-\tau}^{t}\left(\frac{\Sigma(s)}{\sigma_y}\right)^{\alpha} ds\right)^{-1/\alpha}, & \frac{1}{\tau}\int_{t-\tau}^{t}\left(\frac{\Sigma(s)}{\sigma_y}\right)^{\alpha} ds > 1. \end{cases} \tag{2}$$

The equality $\gamma(t)=1$ in Eq. (2) corresponds to the case of accumulating elastic deformation before the onset of the macroscopic yield t_*. A decrease in the relaxation function in the range of $0<\gamma(t)<1$ corresponds to the material's transition to the plastic deformation stage. During the plastic deformation stage $t\geq t_*$, the following condition is satisfied for $\gamma(t)$:

$$\frac{1}{\tau}\int_{t-\tau}^{t}\left(\frac{\gamma(t)\Sigma(s)}{\sigma_y}\right)^{\alpha} ds = 1. \tag{3}$$

Equality (3) is retained because the state is fixed at yield moment $t=t_*$ (a detailed calculation scheme for t_* is given [24]), and the accumulated elastic stresses are subsequently relaxed in the material ($0<\gamma(t)<1$). We determine the true stresses in the sample under deformation at $t\geq t_*$ in the following form:

$$\sigma(t) = E(t)\varepsilon(t), \tag{4}$$

where $E(t)=E\gamma^{1-\beta}(t)$ is the coefficient related to the behaviour of stresses, E is Young's modulus, and β is the scalar parameter ($0\leq\beta<1$), which describes the degree of hardening of the material. The case of $\beta=0$ corresponds to the absence of hardening. Considering the stages of elastic and plastic deformations separately, we can obtain the general stress-strain dependence from Eq. (4):

$$\sigma(t) = \begin{cases} E\varepsilon(t), & t < t_*, \\ E\varepsilon(t)\gamma(t)^{1-\beta}, & t \geq t_*. \end{cases} \tag{5}$$

Let us consider the temperature dependencies of the characteristic relaxation time and static yield strength, introduced by [24,25]. The incubation time physically characterizes the duration of the process of restructuring the material structure. Examples of such processes during plastic deformation are the movement of dislocations and grain boundary sliding [27]. Under the influence of temperature, the processes of structural transformations are accelerated, and the incubation time is decreased. Thus, the incubation time is inversely proportional to the dislocation movement rate. In the literature, to predict the effect of temperature on the static yield strength of a material, we consider the empirical Johnson-Cook model (1), written for the case of the static loading and zero plastic strain:

$$\sigma_y = \sigma_0 \left(1 - \left(\frac{T - T_m}{T_m - T_{RT}}\right)^{\kappa_\sigma}\right), \tag{6}$$

where σ_0 and κ_σ are material constants, T_m is the temperature of melting, and T_{RT} is the reference temperature. Temperature dependence of the incubation time is similarly introduced:

$$\tau_y = \tau_0 \left(1 - \left(\frac{T - T_m}{T_m - T_{RT}^\tau}\right)^{\kappa_\tau}\right), \tag{7}$$

where τ_0, κ_τ and T_{RT}^τ are material constants, obtained from the analysis of the dependencies of yield strength on strain rate for different temperatures. To calculate the temperature-deformation dependencies, we introduce the temperature dependence for the parameter β:

$$\beta = \beta_0 \exp\left(-\frac{T}{T_\beta}\right), \tag{8}$$

where β_0 and T_β are material constants. Using temperature dependencies (6)-(8), deformation dependencies are predicted in different temperature-rate regimes of loading.

3. Cu-Al alloys

In the example of monotonic dynamic deformation dependencies of Cu-Al alloys, we discuss the principle of temperature-time correspondence. The experimental deformation dependencies of the 2519A aluminium alloy [12] in various strain rates and temperatures below room temperature (Fig. 1-Fig. 3) were verified based on the temperature relaxation model of plasticity. Figure 1 shows the predict-ed dynamic deformation dependencies of the 2519A aluminium alloy at temperatures -45°C [12] and strain rates 1400, 2500, and 4200 s^{-1}. Figures 2 and 3 show the predicted dynamic deformation dependencies of 2519A aluminium alloy at temperatures -45°C, 0°C and 20°C and strain rates of 1400 and 4200 s^{-1}, respectively. To calculate the theoretical dependencies in Fig. 1-Fig. 3, we evaluated the parameters of the temperature relaxation model of plasticity; β_0=0.095, T_β=680°C, τ_0=0.2 μs, κ_τ=5 and T_{RT}^τ=142°C.

Theoretical dependencies in Fig. 1-Fig. 3 correspond well with the experimental data of the 2519A aluminium alloy. Increasing the strain rate from 1400 s^{-1} to 4200 s^{-1}, as observed in Fig. 1, resulted in a change of the monotonic deformation dependence at strain rate 1400 s^{-1} on non-monotonic deformation dependencies (2500, 4200 s^{-1}) with an increase in yield stress accompanied by a yield drop effect. A similar change in deformation dependencies with the appearance of a yield drop when decreasing the temperature from -45°C to 20°C is observed in Fig. 2 and Fig. 3.

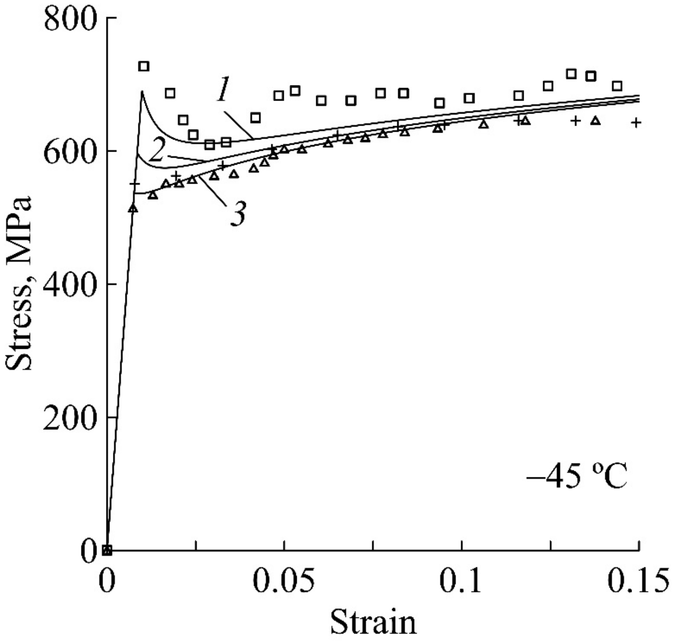

Fig. 1. Dynamic stress-strain curves diagrams plotted by the temperature relaxation model of plasticity (solid lines: (1) 4200 s^{-1}; (2) 2500 s^{-1}; (3) 1400 s^{-1}) and experimental data [12] (Δ 1400 s^{-1}; + 2500 s^{-1}; □ 4200 s^{-1})

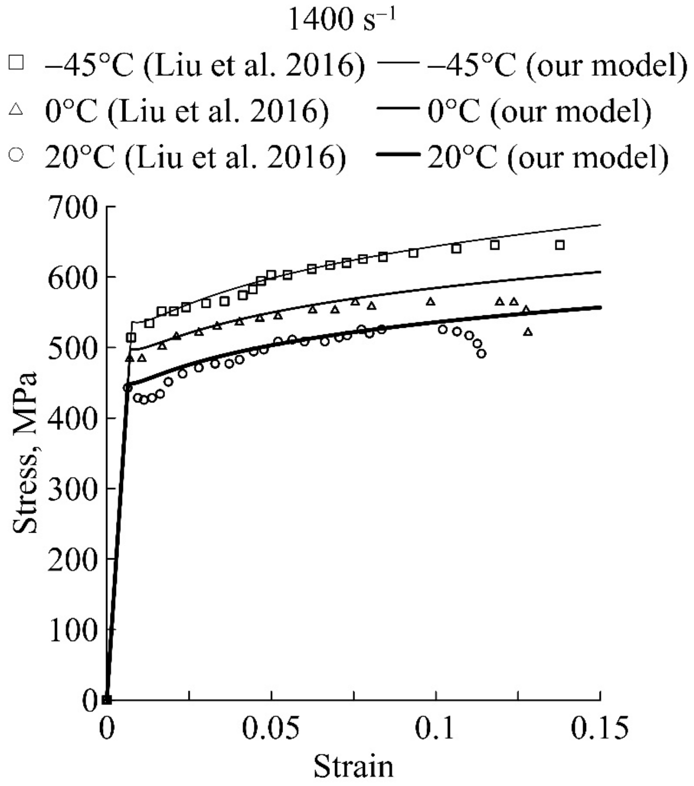

Fig. 2. Dynamic stress-strain curves plotted by the temperature relaxation model of plasticity (RP model) at a strain rate of 1400 s^{-1} and temperatures of -45°C, 0°C and 20°C based on experimental data [12]

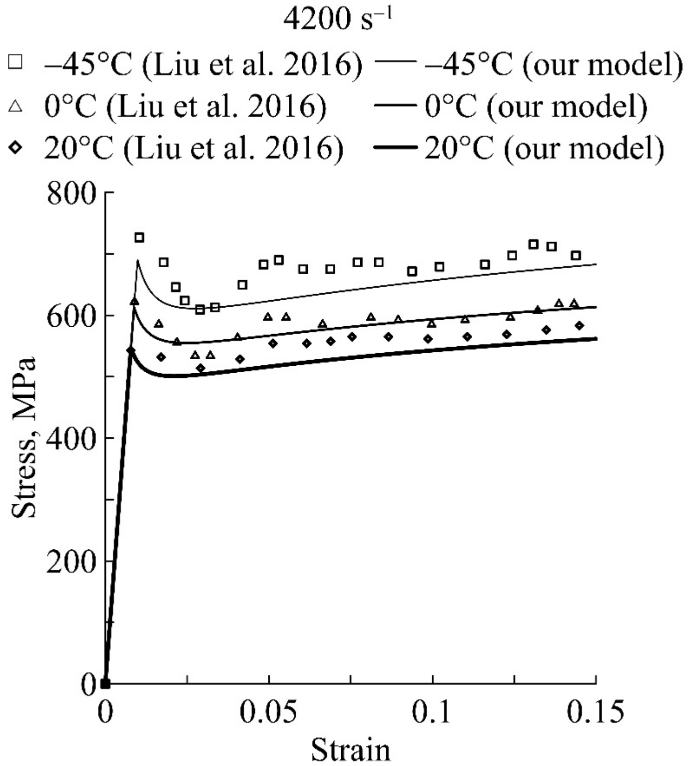

Fig. 3. Dynamic stress-strain curves plotted by the temperature relaxation model of plasticity (RP model) at a strain rate of 4200 s^{-1} and temperatures of -45°C, 0°C and 20°C based on experimental data [12]

Theoretical dependencies in Fig. 3 are good at predicting an increase in peak stress with decreasing temperature. The physical mechanisms of plastic relaxation leading to the yield drop effect when the strain rate increases are fairly well-understood and based on a dislocation theory. A sharp increase in the density of mobile dislocations causing yield drop effect is also observed with a decrease in temperature close to room temperature [9]. The set of structural-temporal parameters of the temperature relaxation model of plasticity does not depend on temperatures or strain rate. This makes it possible to simultaneously predict the deformation of an aluminium alloy in varying temperature and strain rate conditions and to observe the temperature-time correspondence with the deformation dependencies.

4. Mg-Al alloys

In this section, we consider the dynamic deformation dependencies of aluminium magnesium alloys, in which the yield drop effect is observed in the deformation dependences with a higher strain rate. Experimental deformation dependencies of Al-13Mg [3] in various strain rates (0.1 and 1 s^{-1}) and temperatures (325°C and 425°C) (Fig. 4 and Fig. 5) were verified on the basis of the temperature relaxation model of plasticity. Dynamic deformation dependencies in Fig. 5 have an almost monotonic dependence in contrast to the dependencies in Fig. 4. The yield drop phenomenon in Fig. 4 is explained by the solute drag creep still dominating plastic flow after yielding [3]. Thus, the temperature relaxation model of plasticity is able to predict non-monotonic dependences with an emerging yield drop when the temperature changes from 325°C to 425°C.

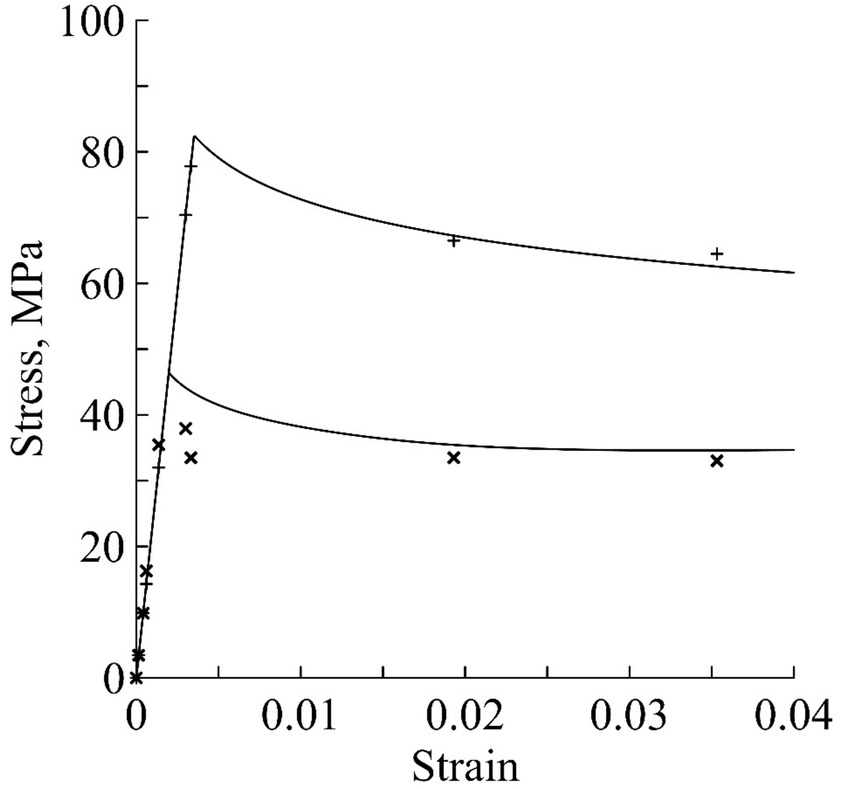

Fig. 4. Stress-strain dependencies of Al-13Mg [3] at strain rates 0.1 and 1 s^{-1} and 425°C

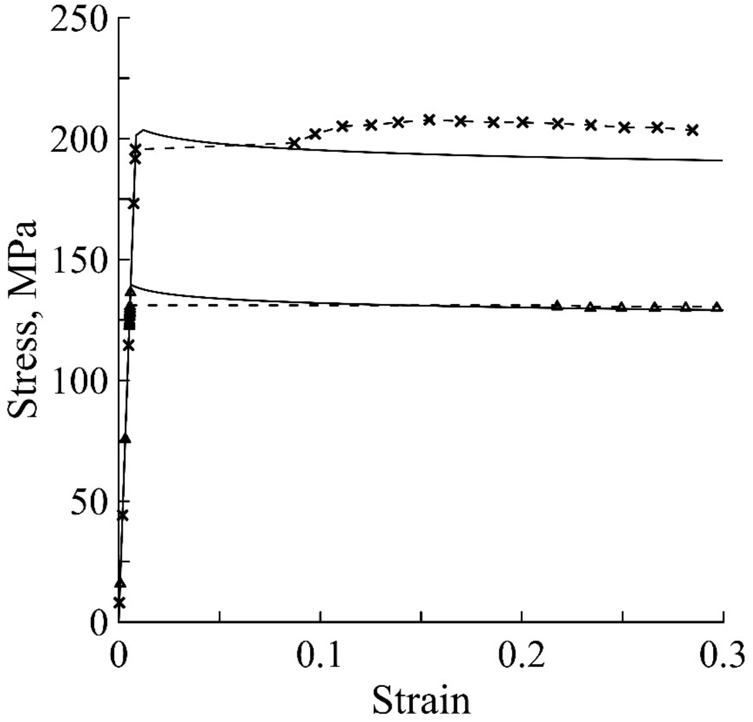

Fig. 5. Stress-strain dependencies of Al-13Mg [3] at strain rates 0.1 and 1 s^{-1} and 325°C

6. Conclusions

The dynamic deformation dependencies of Al-Cu and Al-Mg alloys in a wide range of temperatures and strain rates were predicted based on the temperature relaxation model of plasticity. The occurrence of a yield drop at the initial stage of plastic deformation with an increase in the strain rate and a decrease in temperature was predicted with the unique model.

Analysis of theoretical dependencies shows that the principle of the temperature-time correspondence in the proposed model is performed.

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