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Modeling of plastic localization in aluminum and Al–Cu alloys under shock loading

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ABSTRACT

This paper focuses on the modeling of plastic deformation localization in pure aluminum and aluminum–copper alloys during the propagation of a plane shock wave. Modeling is carried out with the use of continual dislocation plasticity model in 2-D geometry. It is shown that the formation of localization bands occurs at an angle of 45° to the direction of propagation of the shock front. Effective initiators for plastic localization in pure aluminum are the perturbations of the initial dislocation density, in the alloys – perturbations of the dislocation density and the concentration of copper atoms. Perturbations of temperature field in a range of tens of kelvins are not so effective for plastic localization. In the alloy plastic localization intensity decreases with an increase of strain rate due to the thermally activated nature of the dislocation motion.

1. Introduction

Plastic deformation of bulk samples in many situations tends to form bands of localized plastic deformation. The strain of the material in bands significantly exceeds its value in surrounding areas, and up to 90% of plastic deformation of substance concentrates there [1–4]. Practical interest in this phenomenon is stimulated by cases of deviations between elasto-plastic characteristics of the deforming body with shear bands from the one with homogeneous deformation. For example, the formation of localization bands causes decrease of shear strength of dispersion-hardened materials and represents the initial stage of shear fracture of samples subjected to a severe deformation.

Beginning from the pioneer work by Tresca [5] shear localization attracts the attention of many researchers [1,6–9]. One of the interesting cases of localization is realized in materials subjected to shock loading. Since aluminum and its alloys are widely used in technological applications, plastic localization in these materials under dynamic loading has been studied in a large number of works. Loading of aluminum samples by shock waves (SW) with amplitude up to 50 GPa in order leads to formation of typical deformation texture with various dislocation structures and shear bands, formation of twins is not observed under this conditions [10,11]. The dynamical deformation of aluminum alloys involves the deformation structures of similar type [10,12,13]. However, formation of shear bands in alloys, apparently, occurs at higher exposure level; so in the alloy AMg6 shear localization was observed at higher amplitude of the stress wave compared to the pure aluminum [10]. Huang and Gray III [12] showed that under identical loading the shear bands could be either present or absent in alloys of the same chemical composition but aged under different conditions. Bands of plastic localization formed during the shock loading can reach hundreds of micrometers in length [11]. Distance between the bands ranges from a few micrometers [11] to tens of micrometers [10]. The bands thickness ranges from 0.2 μm [12] to 5 μm [10] and can vary along a band due to the fact that neighboring slip planes can be activated simultaneously with the band propagation [13]. The localization bands can begin or abut on large solid precipitates, such as 150 nm inclusion of θ' phases in Al–4% Cu alloy [13]. According to [12] the small precipitations (25 nm Al_3Zr) are contained in slip bands. The orientation of the slip bands with the respect to the direction of stress wave propagation varies depending on the orientation of grain, however, the greatest number of bands are oriented at angles of 45–90° to the direction of wave propagation; bands oriented at lesser angles occur in a smaller amount, and bands parallel to the direction of the wave propagation are absent [13].

An important attempt to interpret the mechanisms of plastic localization was made by Zener and Hollomon [1], they assumed that temperature increasing in local areas during the deformation leads to thermal softening of material and then plastic flow tends to concentrate in these areas. Asaro and Rice [9], considering the point of view by Price and Kelly [14] that localization starts from

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dislocation cross slip, suggested that a plastic flow instability develops in materials with initial heterogeneous distribution of properties. The homogeneous plastic deformation provokes unessential temperature increase in many materials, which tend to accumulate the shear strain in bands [15,16]. Moreover, the high-speed infrared photography showed that the temperature growth does not exceed 10 K in iron [17] and 100 K in titanium [18] even in the areas of localized plastic flow. The growth of shear strength occurs in pure metals at high strain rate due to increasing of the phonon drag for dislocation motion [19,20], therefore, the thermoplastic mechanism of flow localization development seems unlikely in this case. In case with alloys situation is more complex, authors of work [21] demonstrated that at high strain rate the shear strength of alloy increases with a growth of temperature, while decreasing of strain rate leads to thermal softening of material. This nonmonotonic dependence of shear strength on temperature can lead to various degree of localization during deformation with various rates.

Theoretical approach to the analysis of plastic localization based on kinetic equations for dislocation ensemble with the diffusion term was proposed by Aifantis [22] and Estrin and Kubin [23]. Further development of this approach revealed that the initial perturbations of the material properties lead to the formation of various ordered dislocation structures [24]. Kok et al. [25] modeled the Portevin–Le Chatelier effect; it showed that regions of plastic localization are formed during the deformation and that a nonhomogeneous field of plastic strain is expressed in jerky stress–strain relation. The physically based model without gradient constitutive formulation was used in this simulation, in which formation of localization of plastic deformation was related only to consideration of the polycrystalline structure in the model. Bronkhorst et al. [26] numerically studied formation of the localized plastic strain region in deforming "hat-shaped samples". The thermo-mechanically coupled elasto-viscoplastic single crystal formulation based on Busso [27] and Acharya and Beaudoin [28] models was implemented to describe plastic relaxation. The geometric loading conditions used in the simulation led to the formation of the localization zone, stretching from top to bottom edge of samples contact. Becker [29] investigated formation of the localization bands under dynamic loading with characteristic deformation rate of about $10^7\,s^{-1}$. It was demonstrated that formation of zones with higher or lower accumulated plastic strain occurs only due to the grain structure because all thermal effects in the plasticity models are neglected. Shehadeh and co-authors [30,31] studied the dislocation behavior during shock loading with the dislocation dynamic implemented in finite element method. Discrete dislocation dynamic simulation [30] showed that propagation of the shock wave is accompanied by the formation of dislocation walls confined in slip systems, which have maximally effective orientation providing the shear stress relaxation. Formation of dislocation walls was attributed to interaction of randomly distributed dislocation sources with shock wave. These dislocations walls form the plastic localization bands with the thickness of micrometers order [31]. Lee and Zikry [32] analyzed the stability of plastic deformation in material with dispersed second phase of greater hardness. Solid inclusions act as initiators of plastic localization, development of which leads to the formation of deformation bands. The interesting result obtained in this work is that plastic localization in numerical simulation with finite element method can occur due to initial form of cells, the so called hourglassing instability.

Borodin and Mayer [33] performed a numerical study of plastic strain localization during dynamic channel angular pressing. It was shown that the propagation of the SW initiated by the initial collision of sample with a guiding wall causes generation of localization bands with orientation of 45° to the direction of SW propagation. The cause for their generation is heterogeneity of the initial distribution of dislocations in the target volume. Localization behind the shock front also was studied in [34]. Mayer et al. [35] performed a more detailed analysis of the plastic localization causes. Authors showed that the initial perturbations of the dislocation density and temperature provide a linear increase in the localization degree during a simple shear of rectangular area, while the development of the instability should demonstrate the exponential growth of the initial perturbations, at the same time, main role in the formation of plastic localization belongs to stress concentrators. The role of temperature effects in plastic flow instability is not clear and requires further study. The modeling of localization bands formation in pure aluminum and Al–Cu alloy during the propagation of plane SW is presented in this paper. The influence of perturbations of dislocation density and temperature in pure aluminum and Al–Cu alloys, as well precipitations concentration in alloy on the formation of shear localization bands is analyzed.

2. Model and calculations set

Simulation of SW propagation and related plasticity effects is carried out with the dislocation plasticity model formulated in [35,36]. The model consists of the typical system of continuum mechanics equations and the plasticity core based on the equations of dislocation dynamics and kinetics. Dynamics equations in plasticity core describe the motion of dislocations in their own slip planes and take into account the following factors: 1) the interaction of dislocations with lattice vibrations by temperature-dependent coefficient of phonon friction obtained by molecular-dynamic calculations [37,38], 2) the resistance to dislocation motion from the forest dislocations and the Peierls barrier [39], 3) thermally activated overcoming of obstacles by dislocations in case of alloy [21]. Kinetic equation is constructed on the basis of empirical source of dislocations [36]; dislocation annihilation with opposite signs is considered in accordance with work [40].

The continuum mechanics equations represent three conservation laws: the continuity equation, the equation of substance motion and the energy conservation law. First two equations have typical form, the third one is modified in order to present a more detailed description of change of internal energy in elasto-plastic processes.

The continuity equation

$$\frac{1}{\rho}\frac{d\rho}{dt} = -\frac{\partial v_k}{\partial x_k}, \tag{1}$$

and the equation of substance motion

$$\rho\frac{dv_i}{dt} = \frac{\partial}{\partial x_k}(-P \cdot \delta_{ik} + S_{ik}), \tag{2}$$

have the typical form used in continuum modeling [41].

Here indexes i, k, l correspond to the space directions and run from 1 to 3; the summation rule is actual for dummy indexes; δ_{ik} is the bivalent mixed tensor. In Eqs. (1), (2): ρ is the mass density of substance; $v_i = \{v_x, v_y, 0\}$ is velocity vector and $x_i = \{x, y, 0\}$ are the Cartesian coordinates of substance points; P is the pressure; S_{ik} is the tensor of stress deviators, which characterizes the shear stress. The energy conservation law is stated below after accounting of plastic strain in stress deviators.

We use the generalized Hooke law [42] describing plastic deformation through plastic strain tensor w_{ik} in order to determine the stress deviators

$$S_{ik} = 2G\left[u_{ik} - \frac{1}{3}u_{ll} \cdot \delta_{ik} - w_{ik}\right], \tag{3}$$