Grain Refinement and Damage of Polycrystalline Materials during Large Plastic Deformations: From the Viewpoint of Continuum Mechanics

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1 Introduction

Grain refinement under severe plastic deformations is currently being studied by a large number of laboratories throughout the world, due to the fact that ultra-fine grained structures have very appealing physical and mechanical properties. This surge of interest led to a number of publications investigating the fragmentation of particular metals and alloys under various conditions. (See, for example, [VIA00].)

Our goal here is to present a general approach to the problem, as seen from the viewpoint of continuum mechanics. We show that the interesting information about metals undergoing severe plastic deformation can be obtained only under the hypotheses of self-similarity of fragmentation and micro-damage, and the complementarity of the two processes. Based on these hypotheses (and some other natural physical assumptions), we obtain a system of kinetic equations which gives some new insight into the investigated phenomena and suggests formulations of new problems for experimental and theoretical investigations in particular materials.

2 Self-Similarity of Grain Refinement

By *self-similarity* we understand the following: if we consider high-angle boundaries under two arbitrary stages of deformation ϵ_1 and ϵ_2, then statistically they would differ only by their scale. Figure 1 shows the structures of iron published in [LC69], showing this point.

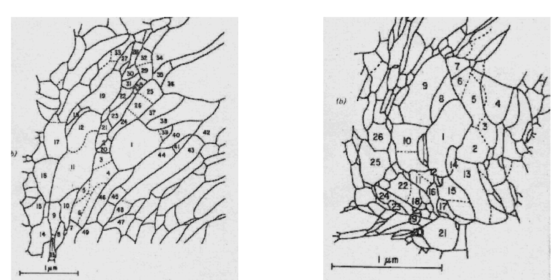

Figure 1: Substructure of an iron wire in two stages of deformation ([LC69]).

Here we provide experimental results supporting the hypothesis that fragmentation is self-similar, and show the following implications. The set of high-angle boundaries is characterized by a single scalar parameter – boundary length S per unit of cross-section area. Fragmentation process itself is also characterized by a single scalar parameter κ that appears in the normalized fragment distribution function. The value of S has a power dependence on the value of accumulated deformation. High-angle boundaries (in cross-section) are fractals with dimension D, $1 < D < 2$. Strain resistance has a power dependence on the value of accumulated strain and is related to the average fragment size by the Hall-Petch relationship with exponent $\mu = D - 1$. If the grain refinement mechanism remains unchanged, then so does μ.

3 Grain Refinement and Damage

Motivated by the desire to incorporate the structure of polycrystal into a continuum model of plasticity, we introduce two scalar parameters: the total volume of microvoids, denoted Θ, and the total area of high angle boundaries per unit volume of the material, denoted S. In order to obtain kinetic equations for Θ and S, we consider the following notions: (i) **accumulative zone (AZ)** defined as the region where dislocation charges accumulate in crystals during plastic deformation; such zones (with diameter about 100nm) emerge due to the inhomogeneities of shear along the sliding plane; (ii) **embryo of the high-angle boundary**; (iii) **microvoid** with diameter about 100nm. We assume that the relaxation of AZ is possible through the emergence of either embryos or microvoids. This is captured by the principle of complementarity of the processes of fragmentation and damage. Based on this principle and the hypothesis of self-similarity of the changes in metal structure during quasimonotone loading, we obtain a system of kinetic equations for Θ, S, N (the number of AZs), and N_b (the number of embryos per unit of the cross-section area). To define the equations, we view the high-angle boundaries caused by deformation first as stoppers for microshifts, and then as zones of relaxation for the bends of the crystalline lattice. The resulting system of kinetic equations represents the evolution of the structure of the representative volume of polycrystal during quasimonotone loading. In order to describe non-monotone loadings, we divide the evolution path on quasi-monotone segments and to join only the values of Θ, S, and N_b when going from one segment to the next. The number of AZs N is set to 0 in the beginning of every segment. This models the relaxation of AZ under a change of the loading direction. The analysis of the model shows the following: Under quasi-monotone loading, when describing metal damage, the model gives the same results as an earlier model previously proposed by the author in [BEV+94]. Non-monotone loading is characterized by smaller damage and less intensive fragmentation compared to the monotone loading.

Every metal (under given thermo-speed conditions of deformation and a given value of hydrostatic pressure) possesses a certain stationary microstructure (called extreme), which is attained at sufficiently large quasi-monotone deformations; if the deformation continues to increase, the microstructure is retained via continuous regeneration. Such microstructure is characterized by a certain size of fragments, and it guarantees for the metal its ideal plasticity under pressure in the sense that the deformation is fracture- and hardening- free. All metal forming processes form such a structure if they are used to accumulate a sufficiently large monotone deformation (whose value depends on the process). Unlike the extreme microstructure, the speed of converging to this microstructure (i.e., the intensity of the grain refinement process) for each metal depends not only on thermo-speed conditions of deformation and the value of hydrostatic pressure, but also on the value of strain, load path (e.g., quasimonotone, nonmonotone, sign-alternating, amplitude of deformation under sign-alternating loading, etc.), and also on the gradients of deformation speed tensors and rotations. The extreme structure of a given metal is formed faster by those processes that lead to a larger decrease of plasticity of this metal (under the same level of hydrostatic pressure in the center of deformation). In order to obtain submicro- and nanostructures, it is necessary to carry out these processes under high hydrostatic pressure in the center of deformation. In this case, the relaxation in internal stress happens along the direction of crystalline fragmentation, not the direction of the formation of microvoids.

Constitutive Equations The constitutive equations of the model correspond to those of the structurally inhomogeneous porous body model of [BEV+94]. The above relations contain two material parameters, one characterizing metal damage under deformation, and the other characterizing metal strain resistance. The work [BEV+94] assumes that these parameters are either constant or satisfy certain conditions that hold only for quasi-monotone loading; thus, the model in [BEV+94] can describe only such loadings. The kinetic equations obtained here allow one to compute the above parameters under arbitrary loadings. Using the obtained kinetic equations, we consider various plastic deformation problems. In particular, we investigate metal stability during simple shift under pressure.

References

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