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Intergranular mechanical equilibrium during the rolling deformation of polycrystalline metals based on Taylor principles

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ABSTRACT

Taylor principles indicate that the Taylor strain tensor is identical to the macroscopic strain tensor during plastic deformation and prevails everywhere inside polycrystalline aggregates, in which real grain behaviors generally differ. These principles have been modified in many deformation models while considering strain and stress equilibria in local areas, e.g., grains, grain pairs or grain clusters. However, the Taylor strain tensor is still valid in the surrounding matrix of local areas. In this paper, a reaction stress model based on intergranular mechanical interactions is proposed for rolling deformation caused by penetrating slips and additional local slips while keeping reaction shear stresses below certain top limits. Both stress and strain equilibria are reached in entire rolling sheets in the model, and the same Taylor texture is predicted without the Taylor strain tensor anywhere inside the polycrystalline matrix, regardless if the isotropic matrix is rigid or elastic. Rolling-texture formation in experimental polycrystalline metals could be simulated based on the model if the relaxation effects of additional slips on reducing the top limits of reaction shear stresses are included.

1. Introduction

Cold rolling is a very important segment for texture formation and evolution during sheet processing in metal industries. The consequent recrystallization texture of sheet products after rolling directly connects engineering properties with related anisotropy. Therefore, corresponding theories for rolling-texture formation are required to understand the law of rolling-texture evolution. Most current crystallographic models simulating rolling textures induced by homogeneous dislocation slips are mainly based on Taylor principles [1], including different modifications [2–6]. The original Taylor model assumes that the strain tensor describing the plastic deformation of any given grain is homogenous inside that grain and equal to the strain tensor of its surrounding matrix, as well as to the macroscopic plastic strain tensor that can be identified as the Taylor strain tensor (TST). Evidently, no stress equilibrium exists, except strain equilibrium among deformed grains and their surrounding matrix in Taylor model, as well as in its relaxed constraint modification [2,7].

One of the widely used modifications of Taylor model is the viscoplastic self-consistent (VPSC) model with many different variants [3]. In this model, each grain is treated as an ellipsoidal viscoplastic inclusion embedded in a homogeneous effective matrix, whose strain tensor is equal to TST. A number of slip systems in each grain are activated differently, and the incompatible stress tensor is managed to be reduced. The advanced lamel (ALAMEL) model is another modification of Taylor theory, in which a large number of neighboring grain pairs are embedded in the matrix [4]. Both stress and strain equilibria are established in the boundary area between two grains of each grain pair [5]. In a similar way, the grain-interaction (GIA) model treats a large number of grain clusters embedded in the matrix [6]. Each cluster consists of eight grains, between which both stress and strain tensors around the boundary area inside clusters manage to reach a certain equilibrium during deformation. VPSC, ALAMEL, and GIA enable satisfactory rolling-texture predictions that agree with those of experimental observations [5,8,9], whereas the strain tensor of matrix around any deformed grain, grain pair, or grain cluster is basically considered to be equal to TST.

The plastic strain tensors of grains in real polycrystalline aggregate generally deviate differently from the macroscopic plastic strain tensor while keeping stress and strain equilibria everywhere. Therefore, the strain prescription of matrix around deformed grains based on TST is not completely appropriate. Meanwhile, stress equilibria between matrix and grain pairs or grain clusters have not yet been achieved satisfactorily [4,6]. Modified Taylor models demand certain computation time that

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needs to be reduced for industry applications, especially some very complicated and time-consuming models [10–12], although solutions for stress equilibrium at grain boundaries are found.

Slip systems during deformation are known to be activated in multiple ways with different slip rates. The above-mentioned models attempt to identify appropriate combinations of multiple slips integrally while also considering stress and strain equilibria, which highly complicates the simulation calculations. However, these calculations could be largely simplified if a combination of multiple slips is disassembled into many fine slip steps, in which different step fractions of different slip systems represent their slip rates. This consideration was successfully applied to simulate simple tensile deformations based on intergranular reaction stresses [13]. Accordingly, this work attempts to establish a simple and time-saving model of rolling deformation based on more rational intergranular interactions, as well as stress and strain equilibria, between deformed grains and their surrounding matrix without TST prescription.

2. Stress tensor inducing grain deformation in rigid matrix during rolling

The external stress tensor $[\sigma_{ij}]$ in the case of rolling deformation is generally approximated by a biaxial plane stress state, whereas hydrostatic pressure is subtracted. The tensor is expressed in a simplified way as follows:

$$\left[\sigma_{ij}\right]=\begin{bmatrix}\sigma_{11} & \sigma_{12} & \sigma_{13}\\ \sigma_{21} & \sigma_{22} & \sigma_{23}\\ \sigma_{31} & \sigma_{32} & \sigma_{33}\end{bmatrix}=\sigma_y\begin{bmatrix}0.5 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & -0.5\end{bmatrix} \tag{1}$$

where 1, 2, and 3 are the rolling direction (RD), transverse direction (TD), and normal direction (ND) of rolling sheet, respectively, and σ_y is the yield stress of an entire rolling sheet or a grain concerned. Obviously, the normal stress σ_{22} in TD and all shear-stress components $\sigma_{ij}\big|_{i\neq j}$ are roughly zero.

Supposing that deformation of a free single crystal is conducted using a slip system identified by a unit vector $\boldsymbol{b}=(b_1, b_2, b_3)$ in the direction of Burgers vector and normal direction $\boldsymbol{n}=(n_1, n_2, n_3)$ of the slip plane, then the plastic strain tensor $[\varepsilon_{ij}]$ induced by a slip penetrating nonrigid grains is expressed in the rolling sample coordinate, cf. Eq. (1), as follows:

$$\left[\varepsilon_{ij}\right]=\begin{bmatrix}\varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13}\\ \varepsilon_{21} & \varepsilon_{22} & \varepsilon_{23}\\ \varepsilon_{31} & \varepsilon_{32} & \varepsilon_{33}\end{bmatrix}=\delta\begin{bmatrix}b_1n_1 & \frac{1}{2}(b_1n_2+b_2n_1) & \frac{1}{2}(b_1n_3+b_3n_1)\\ \frac{1}{2}(b_2n_1+b_1n_2) & b_2n_2 & \frac{1}{2}(b_2n_3+b_3n_2)\\ \frac{1}{2}(b_3n_1+b_1n_3) & \frac{1}{2}(b_3n_2+b_2n_3) & b_3n_3\end{bmatrix} \tag{2}$$

where δ is the relative displacement of the penetrating slip. The normal strain component $\varepsilon_{11}>0$ and $\varepsilon_{33}<0$ are valid under the external stress tensor indicated by Eq. (1), whereas the absolute value of ε_{22} is commonly very low.

The strain component values $\varepsilon_{11}>0$ and $\varepsilon_{33}<0$ become true after a tiny step of plastic rolling. However, the components of plastic shear strain (Eq. (2)) in any deformed grain of a polycrystal instead of in a free single crystal are commonly blocked by neighboring grains and cannot be achieved freely. The block effect can be expressed as a reaction stress (RS) tensor $[\sigma'_{ij}]$ according to Hooke's law [13]:

$$\left[\sigma'_{ij}\right]=\frac{E}{1+\nu}\times\begin{bmatrix}\varepsilon_{11}+\frac{\nu\theta}{1-2\nu} & \varepsilon_{12} & \varepsilon_{13}\\ \varepsilon_{21} & \varepsilon_{22}+\frac{\nu\theta}{1-2\nu} & \varepsilon_{23}\\ \varepsilon_{31} & \varepsilon_{32} & \varepsilon_{33}+\frac{\nu\theta}{1-2\nu}\end{bmatrix} \tag{3}$$

where all neighboring grains are regarded as an absolute rigid matrix ($\theta=\varepsilon_{11}+\varepsilon_{22}+\varepsilon_{33}$), E is Young's modulus, and ν is the Poisson's ratio of deformed grains. This equation indicates that the possible plastic shear strain components (Eq. (2)) are completely suppressed. Such suppression induces elastic shear strains inside the grain inversely as the slip penetrates while compensating for strain incompatibility between the nonrigid grain and its rigid surrounding matrix.

The plastic deformation of a grain in polycrystals proceeds under both external stress tensor (Eq. (1)) and RS tensor (Eq. (3)) in the subsequent rolling step. The external normal stress components σ_{ii} (Eq. (1)) undergone by a grain prevail; the normal RS components σ'_{ii} in Eq. (3) merges approximately into these stress components while the grain maintains its yield state during rolling. Therefore, the stress combination $[\sigma_{ij}]$ acting on the deformed grain according to Eq. (1)–(3) becomes

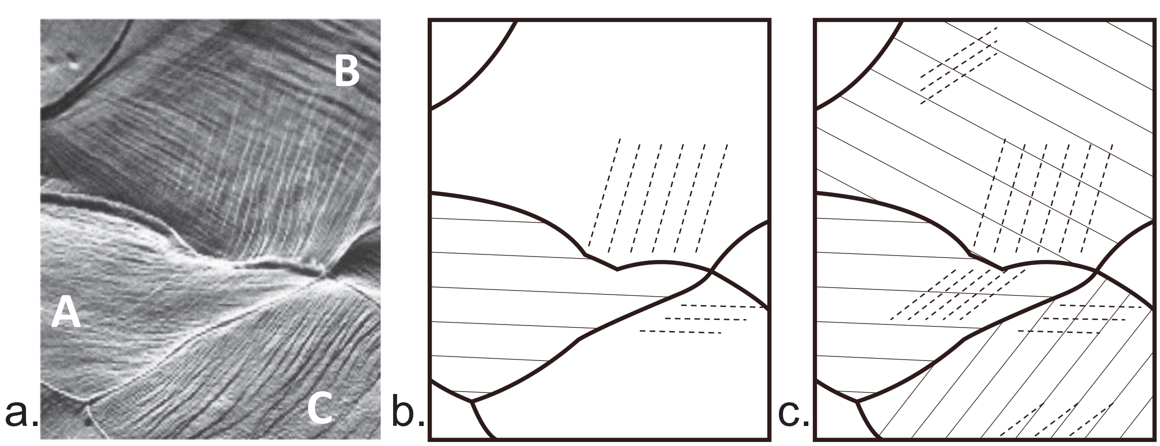

Fig. 1. Deformed interstitial-free steel and corresponding analysis of slips observed in different grains (a. microstructure; b. penetrating slips in grain A induce additional slips in grains B and C; and c. interaction of different slips in neighboring grains). Fine lines: penetrating slip traces; dashed lines: non-penetrating slip traces.