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Dependencies of grain refinement on processing route and die angle in equal channel angular extrusion of bcc materials

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ABSTRACT

The efficiency of grain refinement in equal channel angular extrusion of body-centered cubic (bcc) materials is investigated based on slip activities from crystal plasticity simulations, which account for both the macroscopic and crystallographic features of deformation. It is shown that the characteristics of slip activities, especially the relative contributions of slip systems newly activated or reversed at the transitions between successive passes, vary significantly with the processing routes (A, B and C) and die angles ($\phi = 90^\circ$ and 120°). The simulations assuming $\{1\,1\,0\}\langle 111\rangle$ slip suggest that routes B and A lead to the most significant contributions of newly activated slip systems and hence are most efficient for grain refinement with $\phi = 90^\circ$ and 120°, respectively. Further incorporation of $\{1\,1\,2\}\langle 111\rangle$ slip systems leads to the highest efficiency by route B for both die angles. These predictions are in partial agreement with experimental observations in the literature. Comparison of these results with those of face-centered cubic materials reveals the relevance of crystal structure and deformation mechanism during grain refinement.

1. Introduction

Equal channel angular extrusion (ECAE) is a proven technique to produce bulk ultra fine-grained materials through severe plastic deformation [1,2]. The deformation of the workpiece during each ECAE pass can be reasonably approximated as simple shear on the intersection plane of the entry and the exit channels and hence depends mainly on the die angle (ϕ) between the two channels. In multi-pass ECAE strain path changes (SPCs) take place between successive passes, depending on the necessary rotation ($\pi-\phi$) for re-inserting the workpiece (see Fig. 1) and optional rotations. For a billet-like workpiece, the optional rotation (denoted as χ in Fig. 1) is usually carried out about its longitudinal axis and accordingly, three basic routes denoted symbolically as A ($\chi = 0^\circ$), B ($\chi = 90^\circ$)[1] and C ($\chi = 180^\circ$), are often considered [3]. It was already recognized in the earlier work by Segal [1] that the microstructures refined by ECAE vary considerably with the processing route. Since for a given die-set a certain level of grain refinement can be achieved at a lower number of passes by adopting a processing route with a higher efficiency, it is of practical interest to identify the optimum route for grain refinement.

For face-centered cubic (fcc) materials, a considerable number of experimental studies have demonstrated that the efficiency of grain refinement, mainly in terms of the generation of small grain/subgrains and high boundary misorientations, varies with both the processing route and the die angle; among the three basic routes, the optimum one for refinement is generally considered to be route B for $\phi = 90^\circ$, but route A for $\phi = 120^\circ$ (e.g. [3–6]). Comparatively, only a few studies on this topic were devoted to body-centered cubic (bcc) materials. With $\phi = 90^\circ$, Kim et al. [7] found a more rapid refinement in route A than route C in interstitial-free (IF) steel processed at room temperature for up to two, four and eight passes, respectively; a similar conclusion was also deduced from comparison of tensile strength in ECAE-processed low-carbon steel [8]. Conversely, Shin et al. [9] claimed a similar subgrain size in low-carbon steel after two passes of ECAE via routes A and C at an elevated temperature. Meanwhile, Li et al. [10,11] and Gazder et al. [12] examined the grain refinement in IF steel processed at room temperature with $\phi = 90^\circ$ and 120°, respectively; after four passes, a relatively finer substructure was obtained in route B than

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[1] Route B is sometimes designated as route B_C in order to distinguish it from the so-called route B_A, which involves alternatively +90° and −90° rotations about the longitudinal axis [3–6].

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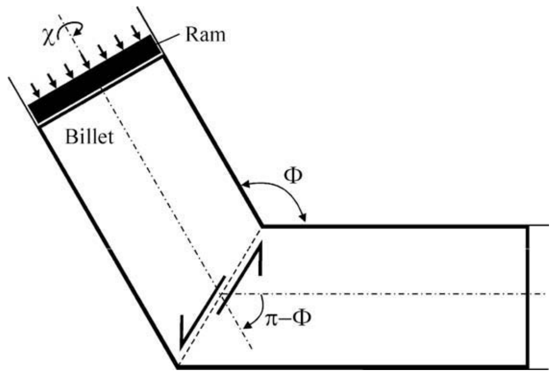

Fig. 1. Schematic of die geometry and billet rotations in multi-pass ECAE [18].

route A and then route C using the 90° die [10,12], whereas route A led to a relatively greater refinement than in route C followed by route B using the 120° die [11]. Overall, the dependencies of grain refinement efficiency on the processing route and the die angle are less conclusively demonstrated for bcc materials than for fcc ones.

Several theories have been proposed to interpret the dependencies of grain refinement on the processing route and the die angle, by considering the characteristics of macroscopic deformation, such as distortion of a cubic element [3], intersection of shear planes [4,5], redundant strain [6], or SPC [13]. They were utilized to elucidate, with reasonable success, the experimentally-identified optimum route for grain refinement in fcc metals processed with $\phi = 90°$ [3–5] or 120° [6], but none of these theories could interpret simultaneously the optimum routes for both die angles. Zhu and Lowe [14] pointed out that such dependencies on the die angle can be better explained if the crystal structure, especially the crystallographic texture and its relationship with the shear plane, is also considered. It was however assumed in their analysis that the {1 1 1} planes of grains are oriented between the shear direction and the grain elongation direction. This assumption is in contradiction with the general findings in fcc metals, i.e. the grain orientations after ECAE mainly align along two types of orientation fibers, one with the {1 1 1} planes *parallel* to the shear plane and the other with the ⟨110⟩ directions parallel to the shear direction (e.g. [15–17]).[2] Recently, a qualitative analysis on low-carbon steel by Mathis and Rauch [8] suggested that the grain refinement differences between routes A and C could be attributed to differences in the accumulated lattice rotations. It is evident from these investigations that the crystallographic nature of plastic deformation has to be taken into account in understanding the efficiency of grain refinement in ECAE.

Very recently, the author [18] proposed a new explanation for the optimum routes for grain refinement in ECAE with different die angles, based on crystal plasticity simulations accounting for both the macroscopic and crystallographic characteristics of plastic deformation. It was shown that the relative efficiencies of grain refinement can be well correlated to the significance of newly activated slip systems at the pass-to-pass transitions, at least for fcc materials. The present study extended the crystal plasticity simulations to bcc materials to evaluate the dependencies of grain refinement on the processing route and die angle. The results are further compared with those of fcc materials to assess the effect of crystal structure. The knowledge gained may contribute to the development of a comprehensive theory for the relative efficiencies of grain refinement, which will be helpful in identifying the optimum processing conditions in ECAE.

[2] A few degrees of deviation in the grain orientations from these ideal orientation fibers can be noted when a fan-shaped deformation zone develops in ECAE [15].

2. Crystal plasticity simulations

Crystal plasticity simulations of the deformation behavior during multi-pass ECAE with $\phi = 90°$ and 120°, respectively, were performed using the full constraints Taylor model [19]. This model assumes that each individual grain undergoes the same deformation, i.e. the one of the polycrystal, and can capture the main features of texture evolution in ECAE (e.g. [10]). The bcc material was assumed to have an initial random orientation distribution represented by 1200 grains. During each ECAE pass the macroscopic deformation of the billet was assumed to be simple shear on the die's intersection plane (see Eq. (3) in Ref. [20]) and was applied in 50 increments. For a reasonable account of the material behavior in multiple passes, a total of eight passes for each of the three basic routes was simulated *continuously*, with inter-pass billet rotations implemented in accordance with the corresponding route.

At the grain level the plastic deformation was assumed to be accommodated by dislocation glide on available slip systems, with the shear rate $\dot{\gamma}^s$ and resolved shear stress τ^s of the *s*-th slip system having a power–law relationship of the form [21]:

$$\dot{\gamma}^s = \dot{\gamma}_0^s \mathrm{sgn}(\tau^s)\left|\frac{\tau^s}{\tau_0^s}\right|^{1/m} \tag{1}$$

where m is the strain rate sensitivity index, and $\dot{\gamma}_0^s$ and τ^s are the reference shear rate and shear stress of the *s*th slip system. A very small value was assumed for m (= 0.02) to approach the rate-insensitive condition ($m \to 0$) and, meanwhile, to avoid the classical ambiguity problem associated with the Taylor model under the rate-insensitive condition. The reference shear stress and shear rate were taken to be the same for all slip systems in the same family and they did not change during the deformation (i.e. strain hardening was neglected). It is noted that, unlike fcc crystals, bcc crystals have more than one possible slip mode operating at room temperature. In most cases assuming slip on {1 1 0} and {1 1 2} planes along ⟨111⟩ directions is sufficient to interpret the plastic behavior in bcc materials (see e.g. [22,23]). This is also well confirmed in microstructure observations [10–12,24] and texture modeling [10,11] for ECAE-processed bcc metals. Therefore, the present simulations were carried out by assuming {1 1 0}⟨111⟩ slip (case-I), or mixed {1 1 0}⟨111⟩ and {1 1 2}⟨111⟩ slip (case-II). Case-I was designed mainly to compare with the previous simulations [18] conducted for fcc materials with {1 1 1}⟨110⟩ slip, which has a dual relation with the bcc {1 1 0}⟨111⟩ slip; in case-II, the ratio of the reference shear stresses, $\alpha = \tau_0^{s,\{1\,1\,2\}}/\tau_0^{s,\{1\,1\,0\}}$, was varied between 0.9 and 1.1 (a reasonable range to consider according to Refs. [22,23]), to inspect the influence of the relative contributions from the two slip modes. It is also of importance to note that these simulations were not meant to imitate directly the process of grain subdivision, which, as pointed out by Hansen and Juul Jensen [25], involves the deformation behavior at the microscale.

Since the subdivision of grains through orientation fragmentation is closely related to the accumulation of excess dislocations, information about the slip activities is believed to be helpful in understanding of the grain refinement efficiencies in the various cases. To quantify the slip activities, statistic data in terms of the average number of active slip systems[3] per grain was computed for each increment, *i*, by comparing the simulation results at that increment and those of the previous one, ($i-1$). This set of data includes: (1) N_{all}, average number of *all* active slip systems at incre-

[3] Under the present condition of rate-sensitive plasticity ($m = 0.02$), all slip systems have $\dot{\gamma}^s \neq 0$, but only the ones with $\dot{\gamma}^s$ larger than 10^{-5} of the total shear rate $\dot{\Gamma} (= \sum_{s=1}^{12}|\dot{\gamma}^s|)$ are considered to be active.