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# A crystal plasticity-based explanation for the dependencies of grain refinement on processing route and die angle in equal channel angular extrusion

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An explanation for the relative effectiveness of grain refinement in equal channel angular extrusion is proposed based on crystal plasticity simulations. It is shown that the processing route and die angle have significant influences on the characteristics of slip activities at pass-to-pass transitions. A higher efficiency of grain refinement by the experimentally recognized optimum route is attributed to a higher contribution from newly activated slip systems at the transitions.


*Keywords:* Equal channel angular extrusion; Grain refinement; Crystal plasticity; Severe plastic deformation; Strain path

Equal channel angular extrusion (ECAE) has been successfully applied to produce ultrafine-grained bulk materials by severe plastic deformation [1,2]. The billet deformation in each pass of ECAE depends mainly on the die angle $\Phi$ between the entry and exit channels. In multiple passes, unavoidable strain path changes (SPCs) take place between successive passes, due to the necessary rotation ($\pi$–$\Phi$) for re-inserting the billet in the entry channel and an optional rotation $\chi$ about the billet longitudinal axis (Fig. 1). The latter rotation defines the "processing route". Seeking for the optimum route for grain refinement has been a subject of intense research in the last decade [3–8]. For face-centered cubic (fcc) metals, a considerable number of experimental studies have demonstrated that the efficiency of grain refinement depends on both the processing route and die angle. Among the three basic routes, namely $A$ ($\chi = 0°$), $B$ ($\chi = 90°$)[1] and $C$ ($\chi = 180°$), the optimum route for grain refinement in fcc metals is generally found to be route $B$ for $\Phi = 90°$ or route $A$ for $\Phi = 120°$ (e.g. [2,4,6]).

To interpret such dependencies, several theories have been proposed based on the macroscopic deformation characteristics in ECAE. Furukawa et al. [3] analyzed the shearing characteristics of a cubic element in ECAE with $\Phi = 90°$. It was concluded that the efficiency of grain refinement decreases in the order of routes $B$, $C$ and $A$, in agreement with experimental observations on high purity aluminum [4]. A similar sequence of efficiency was also inferred from the intersection of macroscopic shear planes [4,5]. Nonetheless, these theories suggested that route $B$ is also optimum for $\Phi = 120°$, which is contradictory to the observations for aluminum alloys [6]. For $\Phi = 120°$, Gholinia et al. [6] proposed a redundant strain theory to explain the higher efficiency of route $A$ than route $B$ and then $C$; this theory, again, can not explain the higher efficiency of route $B$ for $\Phi = 90°$. In reviewing the above theories, Zhu and Lowe [8] pointed out that an explanation for the relative efficiency of grain refinement must consider also the crystal structure. By incorporating the interactions between the shear plane and crystallographic texture, they offered a more consistent explanation for these conflicting conclusions about the optimum routes. However, it was assumed in their analysis that the {1 1 1} planes of grains are aligned between the macroscopic shear direction and grain elongation direction. This assumption contradicts the general observations on texture evolution, which have shown that the grain orientations after ECAE mainly align along two types of orientation fibers, one with the {1 1 1} planes parallel to the shear

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[1] Route $B$ was sometimes also designated as route $B_C$ [3,5,6,8].

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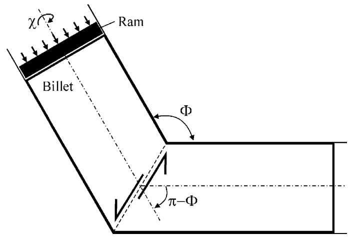


**Figure 1.** Schematic of the ECAE die geometry and rotations of billet in multiple passes.

plane and the other with the ⟨1 1 0⟩ directions parallel to the shear direction (see e.g. [9,10] for route *A* and [11] for routes *B* and *C*).

The objective of the present study was to evaluate the influences of processing route and die angle on the grain refinement efficiency in ECAE, by directly considering the crystallographic nature of grain deformation. For this purpose, crystal plasticity simulations of ECAE for a total of eight passes via the three basic routes, with $\Phi = 90°$ and 120°, respectively, were performed using the full constraints Taylor model. This model assumes individual grains have the same deformation as that of the polycrystal [12] and is able to capture the main features of texture evolution in ECAE (e.g. [7]). The macroscopic deformation of the billet during each pass was assumed to be simple shear on the die's intersection plane [1,13] and was applied in 50 increments. The material was assumed to have a fcc crystal structure, and have an initial random orientation distribution represented by 1200 grains. The plastic deformation of grains is accommodated by dislocation glides on the {1 1 1}⟨1 1 0⟩ slip systems. The shear rate $\dot{\gamma}^s$ and resolved shear stress $\tau^s$ of the *s*th slip system have a power–law relationship of the form [14]: $\dot{\gamma}^s = \dot{\gamma}_0^s \mathrm{sgn}(\tau^s)|\tau^s/\tau_0^s|^{1/m}$, where $m$ is the strain rate sensitivity index, and $\dot{\gamma}_0^s$ and $\tau_0^s$ are respectively the reference shear rate and shear stress of the *s*th slip system. In the present simulations, a very small value was assumed for $m$ (=0.02) to approach the Taylor rate-insensitive condition ($m \to 0$); for simplicity, $\tau_0^s$ and $\dot{\gamma}_0^s$ were assumed to be the same for all slip systems and not change during the deformation (i.e. strain hardening was neglected). It should be noted that these calculations were not meant to simulate directly the process of grain subdivision, which, as pointed out by Hansen and Juul Jensen [15], involves grain deformation behavior at the microscale.

Since the subdivision of grains is closely related to the accumulation of dislocations, examination of the slip activities is necessary for an integrated understanding of the grain refinement efficiencies in the different cases. The slip systems with $\dot{\gamma}^s$ larger than $10^{-8}$ of the total shear rate $\dot{\Gamma}\left(=\sum_{s=1}^{12}|\dot{\gamma}^s|\right)$ were considered to be active. Examination of the results reveals that with this criterion, either 6 or 8 slip systems are activated in each grain and the associated stress state corresponds to a vertex of the rate-insensitive ("Bishop–Hill") yield surface. Statistic data in terms of average number (per grain) of active slip systems 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) $N_{\mathrm{all}}$, average number of *all* active slip systems

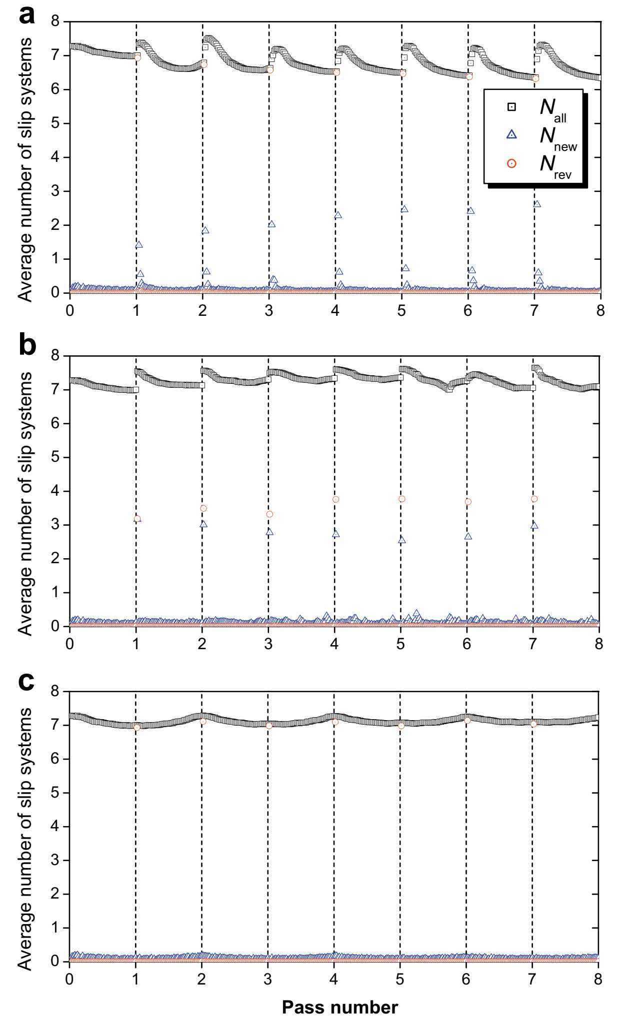


**Figure 2.** Variation of the average number of all active ($N_{\mathrm{all}}$), newly activated ($N_{\mathrm{new}}$) and reversed ($N_{\mathrm{rev}}$) slip systems in $\Phi = 90°$ ECAE with route (a) *A*, (b) *B*, and (c) *C*.

at increment $i$; (2) $N_{\mathrm{new}}$, average number of systems *newly* activated at increment $i$;[2] and (3) $N_{\mathrm{rev}}$, average number of systems that are active in both increments, but operate in opposite senses, i.e. the slip direction is *reversed*. The difference between $N_{\mathrm{all}}$ and ($N_{\mathrm{new}} + N_{\mathrm{rev}}$) is the average number of active systems operating in the *same* sense for both increments.

Figures 2 and 3 plot the $N_{\mathrm{all}}$, $N_{\mathrm{new}}$ and $N_{\mathrm{rev}}$ values as a function of pass number ($n$) for the three basic routes with $\Phi = 90°$ and 120°, respectively. These results reveal that the processing route and die angle have mild influences on the $N_{\mathrm{all}}$ values, but remarkable influences on the $N_{\mathrm{new}}$ and $N_{\mathrm{rev}}$ values. For all routes and both die angles, $N_{\mathrm{all}}$ evolves with the deformation in each pass, while its overall variation with the pass number is not significant. The variation of $N_{\mathrm{all}}$ in each pass is more complex in routes *A* (Figs. 2a and 3a) and *B* (Figs. 2b and 3b) than in route *C* (Figs. 2c and 3c). In the latter case, $N_{\mathrm{all}}$ simply decreases with the deformation in odd-numbered passes but increases in even-numbered

[2] The activation of new slip systems generally reflects abrupt changes of the local stress state from one vertex to another in the yield surface.