Materials Science and Engineering A 527 (2010) 5557–5564

Contents lists available at ScienceDirect

Materials Science and Engineering A

journal homepage: www.elsevier.com/locate/msea

# Transformation matrix analysis on the shear characteristics in multi-pass ECAP processing and predictive design of new ECAP routes

Wei Liang*, Liping Bian, Guoyin Xie, Wenli Zhang, Hongxia Wang, Shunqi Wang

*College of Materials Science and Engineering, Taiyuan University of Technology, 79 Yingze West Street, Taiyuan 030024, PR China*

ARTICLE INFO

*Article history:*
Received 12 March 2010
Received in revised form 30 April 2010
Accepted 19 May 2010

*Keywords:*
ECAP
Grain refinement
Shearing
Orientation transformation

ABSTRACT

In this paper, transformation matrices are established to describe the orientation transformation of the planes and directions in a sample during multi-pass equal channel angular pressing (ECAP) processing. From this basis, the shearing characteristics associated with multi-pass ECAP processing in different processing routes are analyzed, and a new ECAP route expected to be more effective for grain refinement and particle redistribution is proposed. With the aid of transformation matrix analysis, it is demonstrated that route $B_C$ involves a redundant strain process and, hence, is not very effective for particle redistribution but is useful for grain refinement. The experimental results prove that the new proposed ECAP route, called route $B_{C\text{-}UD2}$, is more successful for both grain refinement and particle redistribution. The established transformation matrix analysis method is helpful both in analysis of the shear characteristics of multi-pass ECAP processing and in the design of new ECAP routes.



## 1. Introduction

Equal channel angular pressing (ECAP), developed by Segal and his co-workers in the 1970s and 1980s [1,2], has now emerged as a widely known procedure for the fabrication of ultrafine-grained metals and alloys [3].

ECAP is also known as equal channel angular extrusion (ECAE), in which severe plastic deformation (SPD) is induced by repetitive extrusions through two equal cross-section channels intersecting at an angle $\Phi$. Typically, the channels intersect at a right angle (i.e., $\Phi = 90^\circ$). In this case, the strain imposed in a single pass is approximately 1 for any value of $\Psi$ (the angle subtended by the arc of curvature at the point of intersection) [4]. The channels are normally squared or circular, and the samples or the billets with a square or circular cross-section, respectively, can be rotated by increments of 90° between each separate extrusion. According to the rotation around the longitudinal axis of the sample, different processing routes are developed. There are four basic routes, namely routes A, $B_A$, $B_C$ and C, as described in the literature [5].

It has been shown that the processing route has a significant influence on the efficiency of ECAP processing in microstructural refinement as well as in the fragmentation and the modification of the distribution of precipitates. In general, it is believed that route $B_C$ is the most effective for grain refinement when using a die with $\Phi = 90^\circ$ [6,7], although route A was identified as the optimal procedure with a channel angle of 120° [8]. Furukawa et al. [5] attributed the most rapid refinement of route $B_C$ compared to all of the routes examined by them to its high levels of recoverable shearing. Such a recoverable shearing corresponds to a so-called redundant process. It was believed that the shear occurred on the same plane but in the reverse direction in the first and third pass, and similarly in the second and fourth pass in route $B_C$. As a result, slip in the first pass was cancelled by slip in the third pass and slip in the second pass was cancelled by slip in the fourth pass in route $B_C$ [3,9]. As Zhu and Lowe stated in [9], however, such an explanation is superficial and does not address the fundamental mechanism. Moreover, some of the shear strain paths, especially in route $B_C$, are questionable and will be clarified in this paper.

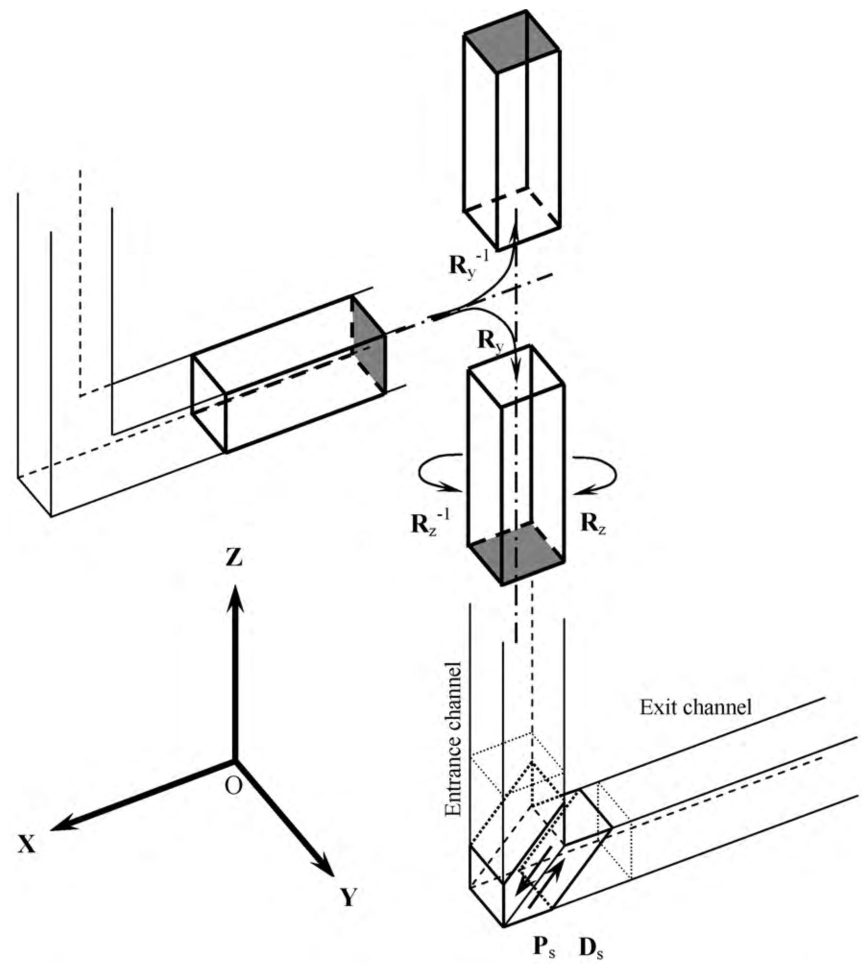
Many studies have also revealed the great potential of ECAP for precipitate fragmentation [10–12] and homogenization of the constituent particle distribution [13,14]. It is shown that processing up to eight passes by routes A and $B_A$ results in a pancake arrangement of the matrix and precipitates with little difference in orientation, whereas processing by routes $B_C$ and C results in the maintenance of the original structure configuration [13]. Such structure features in different routes can be reasonably explained using the shear patterns provided by Furukawa et al. [5]. Thus, it is evident that route $B_C$ is least effective for precipitate redistribution even though it is optimal for microstructural refinement. The more efficient processing routes for microstructural refinement and precipitate redistribution are still being determined. The shearing patterns provided by Furukawa et al. [5,15] are useful in understanding the microstructural features relating to the four basic ECAP routes and their combinations. However, until now, no

* Corresponding author. Tel.: +86 351 6018398; fax: +86 351 6018398.
*E-mail address:* liangwei@tyut.edu.cn (W. Liang).

0921-5093/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.msea.2010.05.058

general theoretical approach exists to assist in the design of a new desired route beyond the basic ones and their combinations [4] as well as to predict its effectiveness in microstructural refinement and precipitate redistribution.

Usually the deformation during ECAP is simplified as simple shearing on the intersecting plane of the two channels for analysis of the microstructural development and texture in samples subjected to ECA pressing [5]. Such a deformation model is referred to




Orientation transformation matrices for the operation of each pressing pass

| routes | 2*n*-th pass | (2*n*+1)th pass |
|---|---|---|
| A | $\mathbf{P}(A)=\mathbf{P}_s\mathbf{R}_y$ | |
| | $\mathbf{D}(A)=\mathbf{D}_s\mathbf{R}_y$ | |
| $B_A$ | $\mathbf{P}_e(B_A)=\mathbf{P}_s\mathbf{R}_z\mathbf{R}_y$ | $\mathbf{P}_o(B_A)=\mathbf{P}_s\mathbf{R}_z^{-1}\mathbf{R}_y$ |
| | $\mathbf{D}_e(B_A)=\mathbf{D}_s\mathbf{R}_z\mathbf{R}_y$ | $\mathbf{D}_o(B_A)=\mathbf{D}_s\mathbf{R}_z^{-1}\mathbf{R}_y$ |
| $B_C$ | $\mathbf{P}(B_C)=\mathbf{P}_s\mathbf{R}_z^{-1}\mathbf{R}_y$ | |
| | $\mathbf{D}(B_C)=\mathbf{D}_s\mathbf{R}_z^{-1}\mathbf{R}_y$ | |
| C | $\mathbf{P}(C)=\mathbf{P}_s\mathbf{R}_z^{2}\mathbf{R}_y$ | |
| | $\mathbf{D}(C)=\mathbf{D}_s\mathbf{R}_z^{2}\mathbf{R}_y$ | |
| $B_{C\text{-}UD2}$ | $\mathbf{P}_e(B_{C\text{-}UD2})=\mathbf{P}(B_C)$ | $\mathbf{P}_o(B_{C\text{-}UD2})=\mathbf{P}_s\mathbf{R}_z^{-1}\mathbf{R}_y^{-1}$ |
| | $\mathbf{D}_e(B_{C\text{-}UD2})=\mathbf{D}(B_C)$ | $\mathbf{D}_o(B_{C\text{-}UD2})=\mathbf{D}_s\mathbf{R}_z^{-1}\mathbf{R}_y^{-1}$ |

Notes: **P** and **D** are the orientation transformation matrices of plane and direction, respectively. The subscripts "e" and "o" denote the even-numbered and odd-numbered passes, respectively.

**Fig. 1.** Pressing routes and the corresponding orientation transformation matrices for each pass in the ideal model.