Materials & Design 83 (2015) 144–153

Contents lists available at ScienceDirect

Materials & Design

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

Effect of die design parameters on the deformation behavior in pure shear extrusion

F. Rahimi [a], A.R. Eivani [a,*], M. Kiani [b]

[a] School of Metallurgy and Materials Engineering, Iran University of Science and Technology (IUST), Tehran, Iran
[b] Department of Materials Engineering, Science and Research Branch, Islamic Azad University, Kermanshah, Iran

ARTICLE INFO

Article history:
Received 9 February 2015
Revised 31 May 2015
Accepted 4 June 2015
Available online 19 June 2015

Keywords:
Finite element method
Pure shear extrusion
Strain distribution
Filling fraction
Pressing load

ABSTRACT

Influences of die design parameters in terms of diameter ratio and length of the deformation zone on the distribution of effective strain, filling fraction of the die exit channel and pressing load in pure shear extrusion (PSE) are studied using finite element method (FEM). Dimensional stability, pressing load and hardness measurements are used to validate the predictions of the simulation. Acceptable agreements between the predictions of simulation and experimental results are observed. It is found that strain is inhomogeneously distributed which increases from the center to the corners. Effective strain, inhomogeneity of strain, filling fraction of the die exit channel and pressing load are increased with increasing diameter ratio. In addition, the work-piece is deformed more homogeneously at lower pressing load by increasing the length of deformation zone. However, filling fraction of the die exit channel initially increases by the length of the deformation zone up to 60 mm after which it reduces. The optimum die design parameters covering a range of acceptable effective strain and strain homogeneity, filling fraction of the die exit channel and pressing load are proposed as being 60 mm and 2 for length of the deformation zone and diameter ratio, respectively.

1. Introduction

The grain structure of an engineering material is an important factor which can significantly influence its physical and mechanical properties [1–3]. In this regard, it is demonstrated that materials with submicron or nanoscale grain structures indicate superior properties [4]. Therefore, it is necessary to use an appropriate technique to acquire the highest possible level of grain refinement [5]. In recent years, severe plastic deformation (SPD) has been used as an appropriate technique for grain refinement in bulk materials and consequently enhancement of the material properties [6–8].

So far, the most widely used methods for SPD processing are accumulative roll bonding (ARB) [9], high pressure torsion (HPT) [10,11], equal channel angular pressing (ECAP) [12–15], twist extrusion (TE) [16] and constrained groove pressing (CGP) [17]. Some of these laboratory scale techniques have been recently developed for industrial applications [18]. In addition, simple shear extrusion (SSE) has been recently introduced by Pardis and Ebrahimi [19], which serves as a new SPD technique for gradual deformation of the samples in simple shear mode [19].

A new SPD technique based on pure shear, i.e., pure shear extrusion (PSE), has been recently introduced by the present authors [20,21]. Pure shear is the dominant deformation mode of the material in this method. Application of a different mode of deformation may significantly affect the evolution of microstructure as claimed by Segal [22]. In fact, pure shear deformation in PSE is considered as a new achievement in PSE vs. simple shear which is the main deformation mode in most of the known SPD techniques, e.g., ECAP, TE and SSE.

Homogeneity of deformation is another key factor determining the effectiveness of a SPD process. In fact, a SPD process may be considered efficient if the deformation and consequently the improvement in mechanical properties are uniform. According to previous studies, it is well understood that some SPD techniques such as HPT and TE are inherently involved with inhomogeneous deformation [23,24]. However, the level of inhomogeneity changes with process parameters. For example, it is observed that by increasing the number of rotations in HPT, the homogeneity in hardness is improved [25]. Akbari Mousavi et al. [26] reported that with employing direct extrusion in TE, the sample is deformed more homogenously. Moreover, by repeating the TE for further cycles, the hardness of the processed sample is distributed more uniformly [27]. It is worth mentioning that the proper amount of back pressure and modified frictional condition have significant effects on

* Corresponding author.
E-mail address: aeivani@iust.ac.ir (A.R. Eivani).

http://dx.doi.org/10.1016/j.matdes.2015.06.007
0264-1275/

the distribution of strain in TE [16]. Regarding the ECAP process, it is observed that enhancement of the intersecting angle of the two channels increases the uniformity of deformation [28]. Wang et al. [29] reported that by employing the modified die design, samples may be deformed for more cycles without formation of major imperfections such as cracks and higher level of grain refinement with the optimum uniformity may be achieved. In addition, Djavanroodi et al. [30] used copper tube casing (CTC) method to increase the uniformity of the deformation across the sample in ECAP. It is observed that the strain inhomogeneity decreases as the cover tube thickness increases. Moreover, it is found that friction and back pressure may affect the homogeneity of deformation. In fact, Yoon et al. [31] observed that lower friction leads to the most uniform deformation while back pressure is applied during processing in ECAP. It should be added that the outer corner radius of the intersecting channel in ECAP has a noteworthy effect on the material flow and the strain inhomogeneity after deformation [32]. Kazeminezhad et al. [33] investigated the effect of die design in CGP on the deformation behavior of the processed sheet and reported that by processing for more cycles, the uniformity of deformation improves. According to this introduction, one may understand the significance of process parameters, e.g., die design factors, on the homogeneity of deformation in all SPD techniques including the one introduced recently, i.e., PSE [20,21].

This paper is focused on investigating the effect of die design parameters toward acquiring homogeneous deformation throughout the cross section of the product. This is in addition to the fact that the process must be designed to impose the largest strain on the sample. This may provide the opportunity of producing nanostructured materials with homogeneous distribution of nano-sized grains. For this purpose, finite element method (FEM) simulation is used to investigate the effective die design parameters on strain distribution and homogeneity of deformation in the work-piece during PSE. In order to verify the accuracy of the predictions of FEM simulations, experimental investigation was carried out.

2. Principles of pure shear extrusion

Principles of PSE are extensively discussed in earlier works of the authors [20,21]. In brief, the work-piece is squeezed through a channel consisting of five zones as demonstrated in Fig. 1. In the entry channel (zone I), the work-piece experiences no deformation and is directed to move toward the deformation zone. In the upper deformation zone (UDZ) (zone II), the work-piece deforms gradually while its square cross section changes to a rhombic. A diameter ratio of D_R is defined as the ratio between the largest diameter of the rhombic to that of square, as shown in Fig. 1. One may note that during the deformation, the cross sectional area of the work-piece remains unchanged. The use of relaxation zone (RZ) (zone III) at which no deformation is imposed on the work-piece is optional, but it may be effective on the filling fraction of the die and homogeneity of deformation. In Zone IV, the lower deformation zone (LDZ), shear deformation is imposed but in an opposite direction to that at zone II. This causes the work-piece to return back to its initial square cross sectional shape, i.e., from rhombic to square. In the exit channel (zone V), precisely similar to zone I, the work-piece experiences no deformation and finds the way out of the die.

The gradual changes in the cross sectional shape of the work-piece is schematically illustrated in Fig. 1. Since there is no change in the cross sectional area of the work-piece, there would be no enlargement of the work-piece. Consequently, by reversing the imposed deformation on the work-piece in zone IV, it is possible to return the sample back into its initial geometry. This method allows repetition of the process for several times and achieve higher strain which is the major key condition for a SPD technique.

3. Experimental procedure

Billets, 120 mm in length with square cross section of $20 \times 20\ mm^2$ were cut out from rolled sheets of aluminum AA1050. Chemical composition of the alloy is presented in Table 1. The samples were annealed at 550 °C for 30 min and cooled to room temperature in furnace. PSE experiments were performed at room temperature using a hydraulic press with ram speed of $1\ mm\ s^{-1}$ and pressing load was recorded. In order to reduce friction between the work-piece and the die walls, molybdenum disulfide (MoS_2) was used as lubricant. The experiments were stopped when the work-piece was totally extruded. In order to investigate the uniformity of the strain distribution and the

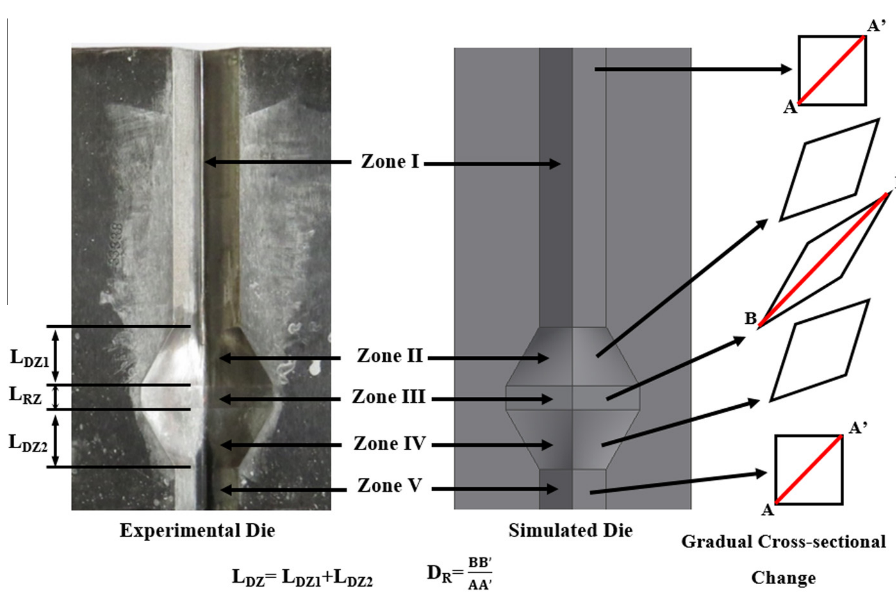

Fig. 1. Schematic illustration of pure shear extrusion (PSE), depicting the die consisting of five zones; gradual changes in the cross-sectional shape throughout the die, diameter ratio (D_R) and lengths of deformation zone (L_{DZ}) and relaxation zone (L_{RZ}).