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Towards bulk nanostructured materials in pure shear

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ABSTRACT

Pure shear extrusion (PSE) is introduced as a new technique for severe plastic deformation of metals and alloys. In PSE, a sample with square cross section deforms to a rhombic alongside the diagonals and then, reversed back to its initial shape. The efficiency of pure shear for grain refinement is demonstrated by investigating the microstructure of two aluminum alloys, i.e., AA1050 and AA6063, after PSE. Formation of nanosized cell structures is resolved in both alloys. The percentage of high angle boundaries is found to be greater for the case of AA6063 alloy when compared to AA1050.

1. Introduction

Severe plastic deformation (SPD) has shown remarkable capacities for processing different metals and alloys towards production of bulk nanostructured materials (BNM) with unique mechanical properties. Despite of having different technological characteristics in the existing SPD techniques, e.g., equal channel angular pressing (ECAP) [1], high pressure torsion (HPT) [2,3], twist extrusion (TE) [4] and simple shear extrusion (SSE) [5], these processes are normally based on simple shear. It has been claimed by Segal [6] that a more efficient grain refinement occurs in simple shear vs. pure; however, to the knowledge of the author, there is no SPD technique purely based on pure shear to verify this claim. In fact, among the existing SPD techniques claimed to be based on pure shear, e.g., accumulative roll bonding (ARB) [7] and repetitive corrugation and straightening (RCS) [8], the material is deformed in a combined mode, not pure shear, and significant effects of inhomogeneous deformation and redundant work are involved. In fact, lack of the presence of a SPD process providing the possibility of applying homogeneous pure shear has made it quite difficult to investigate the effect of deformation mode on microstructural evolution. In this article, the effect of pure shear on grain refinement of AA1050 and AA6063 aluminum alloys is investigated using a new SPD technique, i.e., pure shear extrusion (PSE).

2. Theory

The principles of PSE are schematically shown in Fig. 1(a), where two sections of upper (zone II) and lower (zone III) deformation zones are joined at a conjunction plane, denoted by $P-P'$ in the figure. The sample has to be inserted in the entry channel (zone I) and pressed using a ram. The sample will have to leave the die from the exit channel (Zone IV).

In the upper deformation zone, the square cross section of a sample gradually changes into a rhombic while keeping a constant cross sectional area at every instant of deformation. Since the cross section of the sample is constant in the course of deformation, it may be assumed that there is no velocity change and consequently no strain in longitudinal cross section of the sample. This implies that the strain is totally determined by the lengthening of the lines in x direction and shortening in y direction and therefore, strain may be considered homogeneous in the cross section of the sample.

The top view of PSE deformation from the upper surface to the conjunction plane of the upper and lower deformation zones is shown in Fig. 1(b). The ratio of the long diagonal of the rhombic (L) to the diagonal of the initial square (D) determines the amount of strain imposed on the material in each deformation pass which may be calculated as [9]

$$\varepsilon_{eq} = \frac{4}{\sqrt{3}} \ln\left(\frac{L}{D}\right) \tag{1}$$

No permanent change in the geometry of the deformed sample provides the possibility of repeating the process for more than one pass and therefore, may stand as a new technique for sever plastic deformation of metals and alloys.

3. Experimental procedure

A PSE die with a 20 mm square entry channel was used. The deformation zone was composed of two sections of 25 mm in

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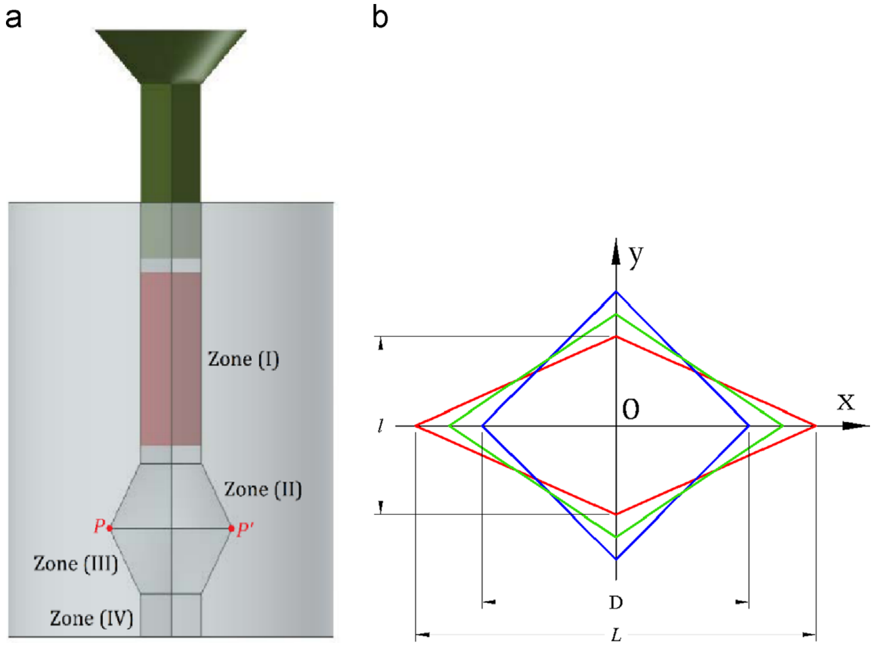

Fig. 1. (a) Schematic illustration of pure shear extrusion, showing the ram in green color, the sample in red in zone I (the entry channel), the upper (zone III) and lower (zone IV) deformation zones and the exit channel (zone V) and (b) Top view of PSE deformation illustrating the changes of the cross section of the sample at the half course of PSE deformation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

height. The diagonal ratio, i.e., (*L*/*D*), of the die was 2. According to Eq. (1), by using a die with this specification, an equivalent value of strain of 1.6 would be imposed on the sample. The height of the exit channel was 20 mm. A split die was used to avoid stress concentration at the corners and to facilitate easy removal of the specimens. Extrusions were conducted at a constant ram speed of 1 mm/s using a hydraulic press of 400 t capacity.

AA1050 and AA6063 aluminum alloys with the chemical composition shown in Table 1 are used in order to verify the application of PSE for SPD processing and grain refinement. Rectangular samples of $19.8 \times 19.8 \times 100.0\ \mathrm{mm}^3$ were machined from rolled plates. In order to dispose the effects of previous deformation on the results, the samples were fully annealed for 1 h at 350 (for AA1050) and 550 °C (for AA6063).

The nanostructures of the samples after PSE were investigated using electron backscatter diffraction (EBSD). Samples were prepared from longitudinal cross section of the specimen across the long diagonal of the rhombic through the conventional procedure, starting from mechanical grinding and ending with electrolytic polishing (17 V; 80 s; flow rate: 15; electrolyte: 7.8% perchloric acid, 9% water, 73.1% ethanol and 10% butylcellulose; temperature: 0 °C). EBSD was performed using a JEOL 6500 scanning electron microscope (accelerating voltage: 25 kV; tilt angle: 70°; working distance: 25 mm; step sizes: 0.5 lm). Orientation contrast data were analyzed with the HKL analyzing software. Subgrains were detected by setting a critical value of 15° as the minimum misorientation value of high angle grain boundaries (HAGBs). The minimum misorientation value of low angle grain boundaries (LAGBs) was set to 2°.

4. Results and discussion

Fig. 2 illustrates EBSD maps of the AA1050 alloy after one pass PSE at room temperature. The low angle grain boundaries (with misorientation angles between 2 and 15°) are shown by the red lines and the high angle grain boundaries (with misorientation larger than 15 °) by the black lines. Formation of a cell structure at a size range of less than 1 μm is observed. Grain refinement in commercial purity aluminum alloys has been previously investigated by application of other SPD techniques, e.g., ECAP [10] and ARB [11]. It is found that the application of these processes may yield grain refinement in the alloy down to a size range of less than 1 μm which is in line with the findings in this investigation. However, it should be noted that the aim of the current study was not to compare the efficiency of the PSE process, but to demonstrate the capability of the process and the mode of deformation (pure shear) for grain refinement. Comparison between the results obtained by other researchers indicated that efficient grain refinement may occur in pure shear which provides the possibility for investigating the effect of the mode of deformation on grain refinement in future research.

Table 1
Chemical composition of the AA1050 alloy used in this study.

Element	Cu	Mg	Si	Fe	Mn	Zn	Ti	Al
AA1050 (wt%)	0.03	0.03	0.25	0.3	0.05	0.06	0.04	Balance
AA6063 (wt%)	0.9	0.9	1.4	0.4	0.1	0.07	0.04	Balance

EBSD maps showing the grain structure of the PSE processed AA6063 alloy are shown in Fig. 3. Similar to the results observed in the case of AA1050 alloy, the formation of nanosized cell structure is observed. Shear bands are clearly seen at the diagonal direction of the image which compose high angle grain boundaries with the matrix. Formation of a nanosized cell structure after one pass PSE indicates that the process may be efficiently used as a new SPD technique for grain refinement.

The fraction of low and high angle boundaries is presented at the right hand side of the EBSD images in Figs. 2 and 3. It is clear that after one pass of PSE 23% of boundaries are at high angle in the case of AA1050. This ratio increases to 30% when AA6063 alloy is considered. This may be understood when the mechanism of grain refinement in SPD processing and the effect of precipitates on microstructural evolution are considered. Grain refinement by severe plastic deformation may be explained as the occurrence of