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Characterization of ultra-fine grained aluminum produced by accumulative back extrusion (ABE)

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In the present work, the microstructural evolutions and microhardness of AA1050 subjected to one, two and three passes of accumulative back extrusion (ABE) were investigated. The microstructural evolutions were characterized using transmission electron microscopy. The results revealed that applying three passes of accumulative back extrusion led to significant grain refinement. The initial grain size of 47 μm was refined to the grains of 500 nm after three passes of ABE. Increasing the number of passes resulted in more decrease in grain size, better microstructure homogeneity and increase in the microhardness. The cross-section of ABEed specimen consisted of two different zones: (i) shear deformation zone, and (ii) normal deformation zone. The microhardness measurements indicated that the hardness increased from the initial value of 31 Hv to 67 Hv, verifying the significant microstructural refinement via accumulative back extrusion.

1. Introduction

Severe plastic deformation (SPD) is an effective approach to produce ultra-fine grain (UFG) and even nanograin (NG) materials. The UFG and NG materials exhibit superior mechanical properties comparing to their coarse grained counterparts, e.g. simultaneous enhancement of strength and ductility [1–3]. Recently, extensive studies have been carried out to develop various SPD techniques and to establish optimum processing parameters for fabricating UFG materials [4,5]. During the SPD process, the workpiece is subjected to intense plastic deformation resulting in the production of bulk UFG materials [6–8].

Among the SPD techniques, the ones based on extrusion process have attracted much more attention due to the capability of applying large deformations. This resulted in developing new SPD techniques based on extrusion process such as twist extrusion (TE) [9], cyclic extrusion and compression (CEC) [10], simple shear extrusion (SSE) [11] and torsion extrusion [12]. Recently, Alihosseini et al. [13] developed a new SPD technique so-called cyclic forward–backward extrusion (CFBE).

Although ABE was introduced as a novel extrusion technique for the first time in 2009 [14], there are not many studies in the literature regarding this method. ABE is a kind of SPD in which the back extrusion (BE) and compression are carried out cyclically. As the BE and compression are performed many times on a workpiece, the term accumulate is used to differentiate it from the conventional extrusion process. The applied cyclic extrusion and compression leads to extensive grain refining. That is because severe plastic deformation causes an accumulated strain introduced into the workpiece when the material undergoes several extrusion–compression cycles. One significant advantage of ABE over BE is the absence of cracks and porosity in the processed workpiece.

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Besides, it has been reported that ABE can be a very effective technique in producing the materials with ultrafine grains (UFGs) [14,15]. Faraji et al. [16] showed that the processing of AZ91 alloy by ABE led to an inhomogeneous microstructure. However, they showed that an increase in the inner punch diameter resulted in better microstructure homogeneity [4,17]. Despite the extensive use of aluminum alloys, there are only a few studies regarding the ABE processing of these alloys. Alihosseini et al. [18] indicated that after only one cycle of ABE process on AA6061 alloy, significant grain refinement was achieved.

The schematic of the ABE process is shown in Fig. 1. The inner punch with a given diameter is pressed into the workpiece. The movement of the inner punch causes the excess material to flow out through the gap between the die and the inner punch. The deformed material finally takes a cup-shape form at end of first-half pass. Then, the outer punch compresses back the cup-shaped specimen causing the inner punch move upwards to its initial state (end of second-half pass) [19]. At this stage (end of first pass), the shape of workpiece is similar to its initial shape.

In the present work, the microstructural evolutions and mechanical properties of AA1050 subjected to several passes of ABE are investigated.

2. Experimental Procedure

The material used in this study was AA1050 aluminum alloy. Cylindrical specimens of 20 mm in diameter and 10 mm in height were machined, along the extrusion direction, from the as-received extruded rods.

The ABE die with 15 mm inner-punch diameter and 20 mm outer-punch diameter was manufactured from the tool steel having a hardness of 55 HRC. The die stroke, i.e. the maximum distance that the inner punch penetrates into the material, was 7.5 mm. The workpiece was subjected to three ABE passes using a 30 ton INSTRON machine operating at a cross-head speed of 10 mm/min. The friction between the specimen and the die was reduced by applying MoS_2 as a lubricant [4]. Microstructural evolutions were characterized using TEM technique (Philips CM 200 operated at 200 kV). Thin foils were prepared from ABEed specimens by twin-jet electro-polishing using a 400 ml HNO3 and 800 ml CH3OH solution. Microhardness measurements were conducted in the mid-diameter of specimens in their radial direction using a load of 200 g for 15 s.

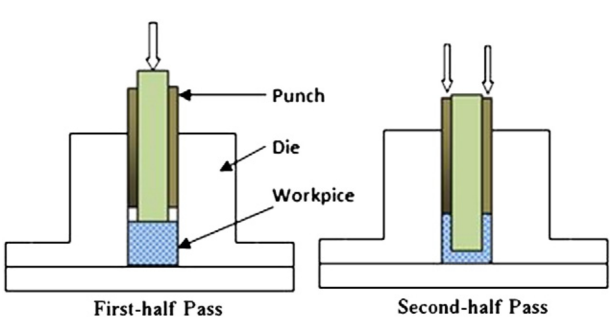

Fig. 1 – Schematic of the ABE process.

3. Results and Discussion

3.1. TEM Observations

The initial grain size of workpiece (about 47 μm) was refined to the grains of 500 nm after three ABE passes. Such a significant microstructural refinement can be attributed to severe shear deformation applied to the workpiece due to repeated back extrusion. In this regard, the cross-section of ABEed specimen was divided into two different zones: (i) shear deformation zone (region I in Fig. 2), and (ii) normal deformation zone subjected to normal strains (region II in Fig. 2). This is consistent with the findings of Faraji et al. [16,17] who indicated that there were two distinct areas: (i) a shear deformation zone, and (ii) a normal strain zone. They proved that the grains located in the shear deformation zone were much finer than the ones formed in the zones subjected to normal strains. Faraji et al. [17] reported that in the ABE processing with the same die geometries used here, in the region (I) the plastic strain was about 1.5, while in the region (II) it was about 5 after the first pass.

In this paper the terms "(sub)grain" and "(sub)grain size" were used when discussing the microstructure of the first two passes of ABE. Due to an absence of an experimental proof for the occurrence of a very large fraction of high angle boundaries in this work, the pioneers of SPD have defined that a structure consists of grains when at least 85% of the grain boundaries are high angle boundaries.

Figs. 3 to 5 show the TEM micrographs and the histograms regarding the size distribution of (sub)grains formed in the specimens subjected to different ABE passes.

According to Fig. 3, the microstructure after one ABE pass is inhomogeneous due to a difference in local accumulated plastic strain. After the first pass, the (sub)grain size in the shear and normal deformation zones is about 950 nm and 5 μm, respectively which corresponds to the strain level of 5 and 1.5 respectively, as reported in Ref. [17]. The microstructure consists of deformed and non-deformed grains containing some kind of dislocation tangles. This is in agreement with the past works [20–22] who attributed this phenomenon to the inherent inhomogeneous plastic deformation when the workpiece is subjected to only one ABE pass. The microstructure illustrated in Fig. 3 indicates a typical cell structure with its SAD pattern. This is in agreement with the results reported by Park et al. [20]. After the first pass of ABE, some original coarse grains are divided into (sub)grains. The structure in zone I consisted mainly of (sub)grains and dislocation cell structures [20,21]. In the region II (Fig. 3), the grain refinement is not noticeable because of lower accumulated strain which is about 1.5, as mentioned in Ref. [17]. In this region, the workpiece is likely affected by normal strain rather than by shear strain.

Fig. 4 shows the TEM micrographs taken from the regions I and II of the sample subjected to two ABE passes. From Fig. 4, it is clear that the region I contains the (sub)grains of 650 nm (which corresponds to a strain of ~10 [17]); while in the region II, the average size of (sub)grains is about 815 nm, which corresponds to the strain level of ~3 as already discussed in Ref. [17]. The (sub)grains are mostly equiaxed and the grain