Materials and Design 35 (2012) 251–258

Contents lists available at SciVerse ScienceDirect

Materials and Design

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

Numerical and experimental investigation of the deformation behavior during the accumulative back extrusion of an AZ91 magnesium alloy

G. Faraji [a], H. Jafarzadeh [a], H.J. Jeong [b], M.M. Mashhadi [a], H.S. Kim [b,*]

[a] Department of Mechanical Engineering, University of Tehran, Tehran, Iran
[b] Department of Materials Science and Engineering, POSTECH, Pohang 790-784, Republic of Korea

ARTICLE INFO

Article history:
Received 5 August 2011
Accepted 26 September 2011
Available online 10 October 2011

Keywords:
A. Nanomaterials
F. Plastic behavior
G. Optical microscopy

ABSTRACT

In the present study, the finite element method (FEM) and an experimental investigation were performed during the accumulative back extrusion (ABE) processing of an AZ91 magnesium alloy in order to investigate the effects of the deformation ratio (= inner punch diameter/outer punch diameter) and die stroke (DS) on the plastic deformation behavior. The results showed that increasing the deformation ratio and DS led to better deformation homogeneity and more plastic strains. There are two distinct regions in the ABE processed samples containing low and high plastic strain areas and the metallurgical investigations showed that more grain refinement with a mean grain size of 1.5 μm takes place in high strain regions while the grain sizes are larger in other regions. A comparison between the FEM and experimental results of the required loads and developed microstructures showed good agreement.

1. Introduction

Magnesium alloys have been received much attention as important materials in aerospace, automobile and construction industries due to their low density, high specific strength and stiffness and good machinability [1]. The mechanical properties of magnesium and its alloys depend strongly on the grain size; for example, fine grained magnesium alloys exhibit a good combination of strength and ductility at room temperature and also superplasticity at elevated temperatures. Thus, the mechanical properties of magnesium alloys can be significantly improved through deformation processing in a solid state [2–5].

Severe plastic deformation (SPD) techniques have been widely used to fabricate bulk ultrafine grained (UFG) materials with simultaneous enhancement in the strength and ductility though grain refinement to UFG scale [6–10]. Since the development of the SPD technique in the 1970s, many new SPD processes have been proposed [10–21]. In particular, accumulative back extrusion (ABE) processing was introduced as a novel bulk deformation method by Fatemi-Varzaneh and Zarei-Hanzaki for producing UFGed and nanostructured bulk cylindrical materials [22]. Fatemi-Varzaneh et al. investigated the deformation homogeneity in the ABE processing of an AZ31 magnesium alloy using FE modeling and experimental verifications [23]. Faraji et al. investigated the microstructure inhomogeneity of the ABE processed AZ91 alloy demonstrating that the final microstructure was not homogenous after one pass ABE [24]. A study on shear bands in ABE processing of AZ31 was done by Fatemi-Varzaneh et al. [25]. Yoon et al. [26] also analyzed nonuniform deformation in ABE using the finite element method (FEM) and concluded that the deformation nonuniformity and folding defects cannot be relieved by multiple ABE passes.

Fig. 1 shows a schematic of the ABE process: first, a cylindrical workpiece is placed on the bottom die. A twin punch setup, where the punches are designed to slide through each other, is the key feature of this method. The inner punch with a predetermined diameter is forced into the workpiece, which causes the excess material to flow through the gap between the die and the inner punch (Stage I). The deformed material forms a cup-shaped specimen. The cup-specimen is then flattened using the outer punch under geometrical constraints to form a shape close to the original (Stage II). The whole process can be repeated many times and can introduce high plastic strains because the deformed shape of the workpiece after the AEB process is the same as the initial shape. Although the AEB process is a novel process that introduces a large strain and UFG structure in the workpiece, a systematic theoretical report has not yet been published. There are several parameters that control the deformation behavior of the workpiece in the AEB process. Among various control parameters, the deformation ratio (= inner punch diameter/outer punch diameter) and die stroke (DS) are important geometric ones.

In this paper, the FEM and an experimental investigation were performed on the ABE processing of an AZ91 magnesium alloy to investigate the effects of the deformation ratio, DS, and friction coefficient on the plastic deformation behavior of the ABE processed samples.

* Corresponding author.
E-mail address: hskim@postech.ac.kr (H.S. Kim).

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doi:10.1016/j.matdes.2011.09.057

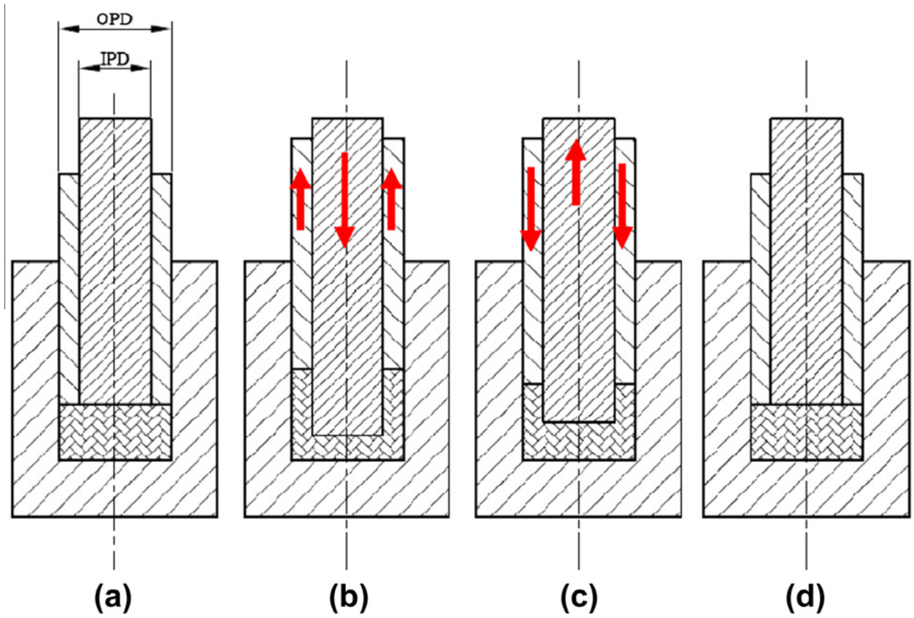

Fig. 1. Schematics of the ABE process: (a) initial state, (b) the inner punch penetrating the workpiece, (c) the outer punch pushing the workpiece back to the initial state and (d) the final state.

2. Experimental procedure

The material used in this study is an AZ91 magnesium alloy with a composition of Al (9.1 wt.%), Zn (0.68 wt.%), Mn (0.21 wt.%), Si (0.085 wt.%), Cu (0.0097 wt.%), Ni (0.001 wt.%), Fe (0.0029 wt.%), and Mg (the remaining wt.%). The specimens with Ø 20 mm and a height of 10 mm were machined from cast ingots. In order to investigate the deformation ratio effect, two ABE dies with 15 mm and 12 mm in the inner punch diameter (IPD) and 20 mm in the outer punch diameter (OPD) were manufactured from hot worked tool steel and hardened to 55 HRC. The ABE experiments were performed with a 30 ton INSTRON press using a pressing speed of 10 mm/min at 300 °C. The friction between the specimen and the dies was reduced by applying MoS_2 as a lubricant [24]. The pressing loads generated in the inner and outer punches were recorded during the process.

The ABE processed specimens were cut into parallel-with-axis workpieces and the surfaces were prepared using standard metallographic techniques in order to study their microstructural features. Optical micrographs (OM) were employed to examine the microstructure produced by the ABE process. Fig. 2 shows the ABE experimental setup with the initial and ABE processed samples.

3. FEM procedure

A commercial FEM code (Abaqus/Explicit; Simulia) was used to perform all deformation simulations. The simulations were performed using an axisymmetric model in which the geometrical dimensions and mechanical properties of the specimens in the simulation were identical to those of the experiment, allowing the direct comparison of the simulation results with those obtained experimentally. Axisymmetric four node elements (CAX4R) were employed to model the workpiece sections. The arbitrary Lagrangian–Eulerian (ALE) adaptive meshing maintained a high quality mesh system under SPD by allowing the mesh to move independently with respect to the underlying material. To accommodate the predetermined large strains during the simulations, an adaptive

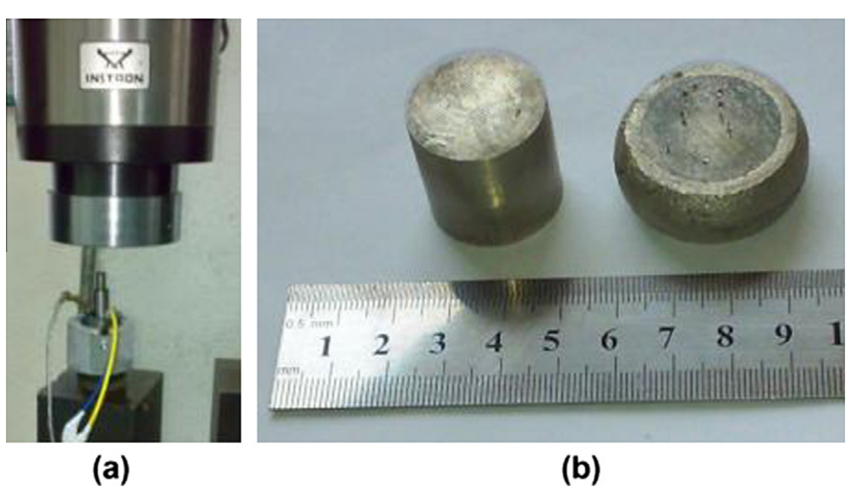

Fig. 2. Pictures of (a) the ABE experimental setup and (b) the initial and compressed billets at 300 °C.