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A new method for grain refinement in magnesium alloy: High speed extrusion machining

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ABSTRACT

Magnesium alloys have received broad attentions in industry due to their competitive strength to density ratio, but the poor ductility and strength limit their wide range of applications as engineering materials. A novel severe plastic deformation (SPD) technique of high speed extrusion machining (HSEM) was used here. This method could improve the aforementioned disadvantages of magnesium alloys by one single processing step. In this work, systematic HSEM experiments with different chip thickness ratios were conducted for magnesium alloy AZ31B. The microstructure of the chips reveals that HSEM is an effective SPD method for attaining magnesium alloys with different grain sizes and textures. The magnesium alloy with bimodal grain size distribution has increased mechanical properties than initial sample. The electron backscatter diffraction (EBSD) analysis shows that the dynamic recrystallization (DRX) affects the grain refinement and resulting hardness in AZ31B. Based on the experimental observations, a new theoretical model is put forward to describe the effect of DRX on materials during HSEM. Compared with the experimental measurements, the theoretical model is effective to predict the mechanical property of materials after HSEM.

1. Introduction

Weight reduction of automobile is an attractive option for significant advances in both fuel efficiency and the resulting reduction in CO_2 emission [1,2]. Magnesium alloys are attractive metals for the aerospace and automotive field to take advantage of their high strength-to-weight ratio [3]. However, magnesium alloys show poor ductility at ambient temperature due to their hexagonal close-packed (HCP) crystal structure and an insufficient number of operative slips [4]. Compared with the competing materials, the strength of magnesium is lower than that of steel or aluminum [5–7]. Therefore, the poor ductility and strength of magnesium alloys limit their wide range of applications as engineering materials.

Severe plastic deformation (SPD) has emerged as an effective technique to produce ultrafine-grained microstructure for improved ductility and strength [8–11]. Conventional SPD techniques such as equal channel angular pressing (ECAP) [12], high pressure torsion (HPT) [13], accumulative roll bonding (ARB) [14] and accumulative back extrusion (ABE) [15,16] are able to vary the grain size and grain boundary distribution, thus conferring the microstructure significantly different properties. However, in these conventional SPD techniques, multiple passes of deformation process are needed to accumulate large strain in materials, and suitable route and temperature are also necessary in order to refine the microstructure down to ultrafine-grain [17–20].

Machining has been proved to be a particularly effective method to achieve SPD [21,22]. Compared with the conventional SPD techniques, the SPD method of machining needs one deformation step to produce large strain in the material. Chandrasekar and co-workers have used the machining SPD method to promote formation of ultra-fine grained (UFG) and nanocrystalline microstructures [23,24]. In order to control the deformation field, Chandrasekar further devised a large strain extrusion machining (LSEM) apparatus by introducing constraint into machining [25]. Dai and co-workers developed the dynamic LSEM and quasi-static LSEM devices to research the suppression of repeated adiabatic shear banding and deformation field [26,27].

As for the SPD process of magnesium alloy, the SPD speed plays an important role in the deformation behavior of magnesium alloy. Shear bands or crack could be produced at low SPD speed in magnesium alloy [28,29], which is harmful for its usage. As SPD speed increasing, dynamic recrystallization (DRX) behavior is dramatically enhanced by high temperature [28,30]. For low speed

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LSEM magnesium alloys, Efe et al. first suppressed the crack initiation in magnesium alloy sheet by high hydrostatic pressure [29]. However, high speed LSEM magnesium alloys is not explored in improving the properties of magnesium alloys. It is suggested that remarkable grain refinement could be obtained during high speed LSEM magnesium alloys, due to the contribution of DRX in high speed SPD. Grain refinement could potentially help to improve strength of magnesium alloys owing to Hall–Petch relationship [31,32]. Therefore, it is meaningful to research the grain refinement of magnesium alloys in high speed extrusion machining (HSEM).

In this paper, in order to enhance DRX behavior, a high speed LSEM device is designed to process magnesium alloys. A systematic HSEM experiments with different chip thickness ratios were conducted for magnesium alloy. The cutting speed is 10 m/s. The chip morphology reveals the variation of microstructure in magnesium alloy with decreasing chip thickness ratio. Compared with the microstructure in magnesium alloy before HSEM experiments, the grains after HSEM experiments are refined more greatly. There are multiple grain sizes for large chip thickness ratio in HSEM, where the large grains are surrounded by smaller grains. With the decreasing chip thickness ratio, the large grains are further refined and uniformly small grains are attained. To characterize the mechanical property of magnesium alloy for different chip thickness ratios in HSEM, Vickers hardness testing of magnesium alloy is conducted before and after HSEM. The Vickers hardness measurements show that the magnesium alloys of multiple grain sizes have a better mechanical property than that of the uniformly small grains.

The paper is organized as follows: in Section 2 we briefly narrate the experimental procedure of the HSEM magnesium alloy AZ31B. The microstructural observations and the mechanical properties of magnesium alloys for different chip thickness ratios are given in Section 3. Section 4 presents the theoretical model for HSEM magnesium alloys. Section 5 gives remarkable conclusions of our present investigation.

2. Experimental procedure

The initial sample used in the experiments is magnesium alloy plate AZ31B. Chemical composition is specified in Table 1. The annealing temperature of AZ31B is 345 °C. The microstructure of the initial sample and its grain size distribution are illustrated in Fig. 1. The average initial grain size is about 38.9 μm as shown in Fig. 1b.

The technique of HSEM has been elaborated in [27]. Fig. 2 shows a schematic of HSEM, where an orthogonal machining process is taken into consideration. The wedge-shaped tool with a rake angle α is static and the workpiece with a cutting layer depth t_0 is moving toward the tool. Finally, because of the process of shear in primary shear zone (PSZ) OA, the workpiece materials in the cutting layer flow out along the rake face of the tool in the form of a chip with a thickness t_c. The inclined angle φ of PSZ is named as shear angle. Based on the definition of chip thickness ratio $\lambda = t_c/t_0$ [33,34], the different chip thickness ratios can be obtained by changing the position of constraint during HSEM.

In order to explore the relationship between different chip thickness ratios and microstructure of magnesium alloy in HSEM, the different cutting conditions for HSEM AZ31B are listed in Table 2 by adjusting the position of constraint. After cutting, chips were collected and embedded into clean resin. The lateral process was mechanically polished and then the polished surfaces were etched in a 5 g picric acid + 10 ml water + 10 ml acetic acid + 100 ml ethanol solution for about 10 s to reveal the deformed microstructure of AZ31B.

Table 1
Chemical composition of the magnesium alloy AZ31B.

Elements	Mg	Al	Zn	Mn	Si	Cu	Ca	Others
Wt. (%)	97	2.5–3.5	0.6–1.4	0.2	0.1	0.05	0.04	≤0.01

These etched specimens were further observed with the optical microscope (Olympus BX51M) to examine the morphologies of chips. The grain sizes were measured by the planimetric procedure in the image analysis software Image Pro-Plus 6.0 according to ASTM E112-10 method by counting at least 500 grains [35,36].

The specimens for electron backscatter diffraction (EBSD) analysis were prepared by polishing with SiC (down to 2000 grit size) and further electropolishing using a solution of 90 ml ethanol and 10 ml perchloric acid (25 V at −30 °C). JOEL JSM-7800F was used to examine EBSD maps of AZ31B samples. The operating voltage was 15 KV and the observation surface was on the cross section perpendicular to normal direction (ND). The scanning step length was 2 μm and 0.4 μm for the initial sample and deformed samples respectively.

Vickers hardness testing of samples is further conducted on the hardness tester (Everone MH-5L) to reveal the relationship between the mechanical property and the microstructure of magnesium alloy. Vickers hardness measurements were carried out on the cross section perpendicular to ND at regular distance intervals, using a 100 g load for 15 s.

3. Experimental observations

3.1. Microstructure measurements

Fig. 3 shows the microstructure of chips for different chip thickness ratios in HSEM AZ31B under the cutting condition of Table 2. Compared Fig. 1 with Fig. 3, the originally coarse grains are refined more markedly by even a single pass of HSEM processing. The chip thickness ratio in HSEM has a great influence on grain refinement. The grains have a heterogeneous distribution in HSEM for large chip thickness ratio where the large grains are surrounded by smaller grains (Fig. 3a). With the decreasing chip thickness ratio, the large grains are further refined and the small grains have a homogeneous distribution in chips (Fig. 3b–d).

In order to reveal the relationship between grain size and chip thickness ratio, the grain sizes were measured by the statistical methods described in experimental procedure and the distribution of grain sizes is illustrated in Fig. 4. The grains of the AZ31B before HSEM have a Gaussian distribution with the average grain size of 38.9 μm (Fig. 1). Compared with the initial grain size, the average grain size of AZ31B after HSEM is much smaller.

The grains are refined by controlled chip thickness ratio in HSEM; however, the grain size distribution varies with chip thickness ratio. For the chip thickness ratio $\lambda = 0.93$ (Fig. 4a), the grains have a heterogeneous distribution with grain size ranging from 0.5 μm to 50 μm and a bimodal grain structure of coarse grains embedded in a fine matrix is produced. About 70% of the microstructure is composed of fine grains with a mean size of 2 μm, while the rest of the grains have sizes ranging from 8 μm up to 50 μm. When the chip thickness ratio is less than a certain value (Fig. 4b–d), the bimodal grain size distribution disappear and the refined grains have a Gaussian distribution. As shown in Fig. 4b–d, the average grain sizes for $\lambda = 0.57$, $\lambda = 0.43$ and $\lambda = 0.32$ are close to each other. The chip thickness ratio less than a certain value can not remarkably affect the grain refinement if the initial temperature and cutting speed are both fixed in HSEM.

It is noteworthy that the average grain size can be refined down to ~2 μm in HSEM at the ambient temperature of 293 K by a