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Grain refined and basal textured surface produced by burnishing for improved corrosion performance of AZ31B Mg alloy

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ABSTRACT

Grain refinement and strong basal texture were produced on AZ31B Mg alloy surface concomitantly by a newly developed severe plastic deformation (SPD) process, severe plasticity burnishing (SPB). The remarkably improved corrosion resistance of AZ31 in NaCl solution after SPB was attributed mainly to dramatically reduced grain size and strongly basal-textured grain orientation. The residual stresses introduced by SPB were also found to influence the corrosion resistance to some extent. Compared with other SPD processes, SPB is fast, cost-effective, does not change material bulk properties and requires little changes to the industrial production process.

1. Introduction

Mg alloys are potential lightweight materials for automotive applications. Their use can notably improve vehicle fuel economy. According to the increasingly stringent fuel economy standards recently established by US governments [1], the fuel efficiency of the passenger cars sold in the US will have to average at least 37.8 miles per gallon by year 2016. More automotive applications of magnesium alloys are expected in the near future after their corrosion issues are properly addressed. In addition, magnesium alloys are also emerging as promising candidate materials for biodegradable metallic implants in cardiovascular and musculoskeletal applications [2]. Currently, the poor corrosion resistance of Mg alloys is one of the hurdles limiting these applications [3–5]. Therefore, the improvement of corrosion performance is an important topic in Mg alloy science and engineering.

It has been reported that grain size of magnesium alloys has a remarkable influence on their corrosion resistance [6]. Grain refinement from 25.7 to 4.5 μm induced by equal channel angular pressing (ECAP) led to better corrosion performance for AZ31 Mg alloy in simulated body fluid (SBF) [7]. It was also reported on pure magnesium that grain refinement from 125 to 2.6 μm by ECAP enhanced its corrosion resistance in 0.1 M NaCl solution [8]. The grain boundary of AZ31B Mg alloy was claimed as physical corrosion barriers and smaller grain size led to better corrosion resistance in 3.5 wt.% NaCl solution [9]. The critical influence of grain size on corrosion resistance was also reported on other materials and claimed to be analogous to the classical Hall–Petch relationship [10]. However, contradictory findings have been reported. Both pure magnesium [11] and AZ91D [12] samples after ECAP with finer grains were reported to be less corrosion resistant than as-cast one in 3.5 wt.% NaCl solution. It was also reported that no evidence could be found to support the claim that changes in grain size and twin density by heat-treatment were the principal causes of the reduced corrosion resistance in AZ31 Mg alloys [13].

While the relationship between grain size and corrosion resistance is intensely focused in published studies, the importance of crystallographic orientation cannot be overlooked. In addition to the grain orientation effect on corrosion behavior for pure Mg [14], a recent study further experimentally and theoretically demonstrates that the basal plane of AZ31 Mg alloy is more corrosion resistant than the other planes due to its higher atomic coordination and thus lower surface energy [15]. This finding has also been further confirmed by another study in which the corrosion rates of AZ31 Mg dramatically increased with decreased basal texture intensity [16]. The effect of texture on corrosion resistance was reported to even outweigh that of grain size for pure titanium after ECAP [17].

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Residual stress after mechanical processing is another important factor that may influence the corrosion resistance. The high residual compressive stress generated in the subsurface via a deep rolling process was claimed to reduce the corrosion rate of a biphasic magnesium-calcium alloy by a factor of approximately 100 [18]. The corrosion performance of 7475-T7351 aluminum alloy was significantly improved by inducing large compressive residual stresses near the surface through low plasticity burnishing [19]. The pitting resistance of AISI 316L stainless steel was improved after inducing near-surface compressive residual stresses [20]. It was also reported that large residual stresses would reduce the corrosion resistance of magnesium alloys, although the grain size of the alloys became smaller [21]. The influence of different machining and grinding procedures on stress corrosion cracking of AISI 304 stainless steel was recently investigated and high tensile stresses induced by grinding were also found to cause more severe pitting corrosion [22].

The above literature shows that grain size is not the only factor determining the corrosion resistance of an alloy. It is important to understand the overall effect of grain size, texture and residual stresses after processing on corrosion resistance.

In previous investigation on the effect of grain size on mechanical and corrosion properties, ECAP has been most commonly used to control the grain size of a material. In that process, the material has to be heated and maintained above 200 °C [6,11], which limits the grain refinement. Also, the multiple passes during ECAP are time consuming. Moreover, ECAP can only be used for raw materials. Subsequent processes, such as machining, are needed to achieve the desired geometry of products, which may significantly change the microstructures near the surface [23] and weaken the benefits gained from ECAP. In fact, corrosion resistance is determined by the surface layer. Surface engineering may improve the corrosion performance through only modifying the surface microstructure without affecting the material bulk properties. For example, surface mechanical attrition treatment (SMAT) has been proved to be an effective way to fabricate nanostructured surface layers on various metallic materials [24] and its beneficial influence on the corrosion resistance of 316L stainless steel has been reported [25]. However, the disadvantages of SMAT are also obvious. First, repetitive impacts on workpieces during SMAT may increase the surface roughness and induce micro cracks. Both increase and decrease of corrosion resistance by this method have been reported [26]. Second, conducting the process in vacuum or a protective gas is inefficient and thus impractical for most industrial applications.

Compared with ECAP and SMAT, burnishing has stood out as one of the most practical SPD techniques that can effectively modify the surface microstructure of an alloy. In this study, a newly developed and cost-effective SPD process, severe plasticity burnishing (SPB), which can significantly refine grains and form strong basal texture in one pass in only 20 s, was applied on AZ31 Mg alloy. The corrosion performance of AZ31B Mg alloy before and after SPB was evaluated by means of immersion and electrochemical measurements. It is expected that the measured dependence of corrosion resistance on grain size, texture and residual stress will help further reveal the corrosion mechanism of AZ31B Mg alloy.

2. Materials and methods

The work material studied was commercially available AZ31B magnesium alloy which was received in the form of a 3.22 mm thick sheet. Disk specimens having 130 mm diameter were cut from the sheet by vertical milling.

2.1. Burnished sample preparation

Roller burnishing is a manufacturing process used in industry to reduce surface roughness, increase hardness and/or introduce beneficial compressive residual stresses. In this study, the roller used is fixed, different from traditional roller burnishing where the roller is allowed to rotate to reduce plastic work on the surface. The burnishing experiments were conducted on a Mazak Quick Turn-10 Turning Center equipped with an Air Products and Chemicals ICEFLY® liquid nitrogen delivery system. For dry burnishing, no cooling method was used; for cryogenic burnishing, liquid nitrogen was sprayed to the tool-workpiece interface at 0.6 kg/min. The experiment setup is shown in Fig. 1. The AZ31B Mg disk was fixed in the lathe chuck and rotated during processing. A machining clearance cut using an uncoated carbide insert was conducted to reduce the diameter from 130 to 128 mm at a feed rate of 0.1 mm/rev and a cutting speed of 100 m/min in order to standardize initial burnishing conditions. Then a fixed roller (no rotation) made of high speed tool steel was pushed against the disks at a constant feed rate of 0.01 mm/rev. The radial force (F_r) and tangential force (F_t) during burnishing were measured using a KISTLER 3-Component Tool Dynamometer. The diameter of the roller is 14.3 mm. The burnishing speed, i.e., the linear speed at the contact point between the fixed roller and the disk, was set to 100 m/min. The burnishing process was stopped when the final diameter was reduced to 126 mm.

2.2. Microstructure and texture analysis

After burnishing, metallurgical samples were cut from the burnished disks. After cold mounting, grinding and polishing, acetic picric solution was used as an etchant to reveal the grain structure. Optical microscopy was used to record the cross-sectional microstructures before and after burnishing. A Zeiss EVO 50 scanning electron microscope (SEM) was used to record the microstructure near the topmost surface after cryogenic burnishing. The crystallographic orientations on the surfaces before and after burnishing were analyzed by using a Bruker D8 Discover X-ray diffractometer.

2.3. Residual stress measurement

The residual stress state in burnished AZ31 Mg samples was analyzed by X-ray diffraction technique using the $\sin^2\psi$ method [27]. The parameters used in the X-ray analysis are shown in Table 1. It is noted that the penetration depth of the X-ray beam in the Mg alloy is about 25 μm for the diffraction parameters used in this study.

2.4. Corrosion tests

To investigate the influence of grain refinement induced by SPB on corrosion resistance of AZ31B Mg alloy, four different methods

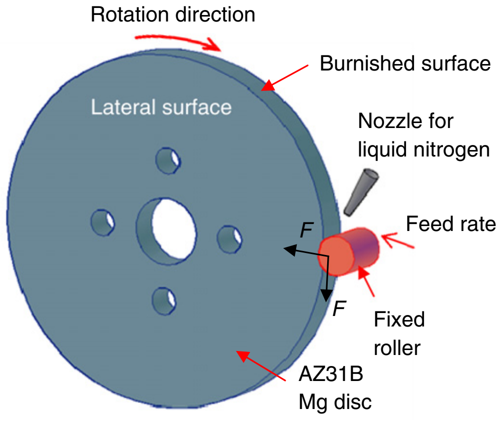

Fig. 1. Schematic of the severe plasticity burnishing (SPB) process.