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IMPROVEMENT IN THE FORMABILITY OF AZ31 MAGNESIUM ALLOY BY ELECTROPULSING-DIFFERENTIAL SPEED ROLLING[1]

Electropulsing-differential speed rolling (EDSR), a facile technique that combines electropulsing technology with differential speed rolling (DSR), was used to manufacture AZ31 Mg alloy strips in the present study. For comparison, the effects of both EDSR and the conventional electropulsing rolling (CER) process on the microstructure, texture and mechanical properties of AZ31 Mg alloy were studied. The relevant results indicate that the resistance to deformation drops significantly and that the annealing process can be completely canceled by introducing electropulsing into the rolling process. Compared with a CER-processed sample, an EDSR-processed one has a more homogeneous grain size and higher fracture elongation, possibly because of the reduction of the basal texture intensity during EDSR. Hence, EDSR may expand the advantages of DSR with the assistance of the thermal and athermal effects of electropulsing technology.

Keywords: *electropulsing, differential speed rolling, microstructure, texture, mechanical properties.*

Introduction

Magnesium wrought alloys are very attractive because of their excellent properties and versatile applications [1]. However, their hexagonal close-packed structure leads to poor ductility and workability at room temperature, especially in the case of rolling thin strips. The formability of Mg alloys is strongly affected by texture and deformation temperature. Although activating the non-basal slip systems by elevating the rolling temperature could enhance the deformation capability of magnesium alloys [2], the high temperature leads to more complex systems, restricts the selection of lubricants and leads to other drawbacks when processing strips. Moreover, normal, symmetrically rolled Mg alloys often exhibit very limited formability at ambient temperatures due to their strong basal texture [3]. It is therefore important to roll Mg alloy strips at low temperature and weaken the basal texture to enhance their formability.

Electropulsing has been used to improve the plasticity of metallic materials and accelerate phase transformation [4, 5]. The effects of electropulsing on the plastic deformation of Mg alloys have been studied widely in recent years. Some results have indicated that thermal and athermal effects play an important role in the deformation of Mg alloys because they offer an additional driving force for recrystallization [6]. However, studies on multiple-pass electropulsing rolling for Mg alloy strips have been rarely reported. In addition, the existing study has reported that DSR, in which the upper and lower rollers operate at different circumferential speeds, can introduce intense shear deformation throughout the sheet thickness of specimens [7]. Therefore, this technique results in the modification of the textural evolution and reduces the grain size of Mg alloy strips.

1. Experimental

Commercial hot-rolled samples of AZ31Mg alloy (3 wt. % Al, 1 wt. % Zn, 0.2 wt. % Mn, balance Mg) with a thickness of 1.55 mm were selected for this investigation. The EDSR process was conducted at a rotation speed ratio of 1:1.33 without lubrication and by heating the rolls' surfaces. The samples were rolled from 1.55 to 0.61 mm in thickness by 11 passes; each pass reduction was 8 % without annealing throughout the entire rolling process. The surface temperatures of the samples were 500 K at the entrance and 350 K at the exit of the rollers**.** For comparison, the CER process was conducted under the same rolling conditions.

A schematic view of the DSRE process is shown as Fig. 1. Multiple current pulses were applied to the AZ31 magnesium alloy strip directly between the anodes and the cathodes at a distance of 225 mm on-line and continuously when the strip moved. At the same time, two rollers were held at room

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temperature. The surface temperature of the sample near the entrance of the rollers was detected by infrared thermo scope A and that of the sample near the exit of the rollers was detected by infrared thermo scope B. By adjusting the electrical parameters, multiple positive-direction pulses with various frequencies and a pulse duration of 60 μs could be generated by an electropulsing generator, as depicted in Fig. 1. The current parameters, such as the amplitude, root-mean-square (RMS) density, and frequency, could be monitored by an oscilloscope with a Hall effect component, and the corresponding values of the amplitude, the RMS, and the frequency were set to be 160 A/mm^2, 280 A, and 450 Hz, respectively, throughout the entire process. Meanwhile, the effect of electropulsing on the rolling separating forces was traced continuously using a sensor, with an automatic data acquisition system established between the mill and a computer.

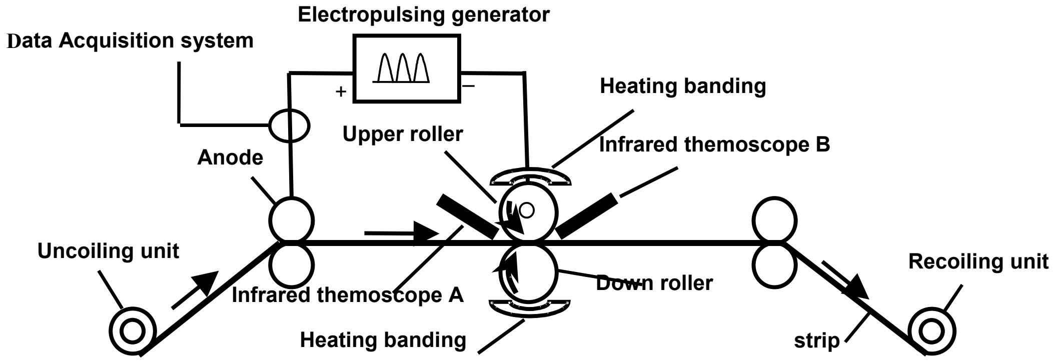

Fig. 1. Schematic view of EDSR process.

Uniaxial tensile tests were performed on strip specimens with a gauge length of 22 mm at room temperature and a rate of 0.5 mm/min, with the tensile axis parallel to the rolling direction. The metallurgical microstructures of the specimens were observed using an Olympus GX51 microscope. The grain size was measured by the linear intercept method from five random images. The (0002) incomplete pole figures were measured at the center of the samples, along their thickness, by the Schulz reflection method at α-angles ranging from 20 to 90°.

2. Results and discussion

2.1. Effects of CER and EDSR on the rolling separating force

All of the data regarding the rolling separating forces measured during the experiments, with or without the aid of electropulsing, CER or EDSR, were listed in Table 1 and shown in Fig. 2. Clearly, the forces shift under different rolling conditions. It was discovered that (1) compared with cold rolling the introduction of electropulsing leads to an approximately 20 % drop in the rolling separating force; (2) it seems that the effects of the rolling methods on the rolling separating force are independent of each other and can be superimposed. The sharp decrease in the separating force may be due to the following: First, the friction forces on the two work roll surfaces are asymmetrical because of the different line speeds between the upper and lower work rolls; thus, the deformation zone is asymmetrically rolled, which ultimately reduces the mean rolling pressure below the symmetrical rolling pressure. Second, the athermal effect of electropulsing assists the movement of dislocations [8], and the resistance to deformation decreases when the dislocation density decreases.

Table 1

Rolling conditions of samples and rolling separating force during rolling

Rolling method	Rolling reduction, %	Electric pulse	Average force, N
Conventional rolling (1:1)	10	Off	4041
		On	3232
	15	Off	4689
		On	3697
Differential speed rolling (1:1.33)	10	Off	2791
		On	2313
	15	Off	3251
		On	2586

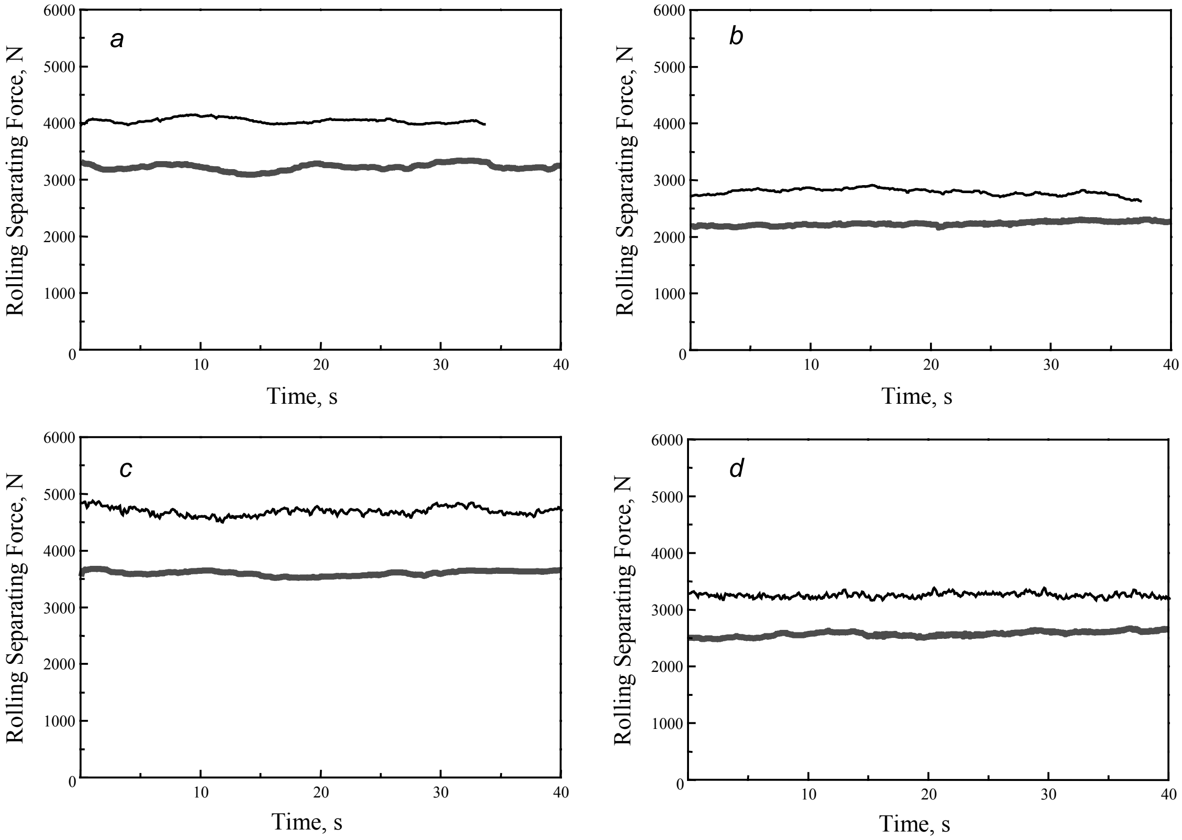

Fig. 2. Rolling separating force of samples under different rolling conditions. CER processing with 10 % (*a*) and 15 % reduction (*c*); EDSR processing with 10 % reduction (*b*) and 15 % reduction (*d*). The black lines represent room-temperature rolling, and the red lines represent rolling with the aid of electropulsing.

2.2. Effects of CER and EDSR on the microstructure of the AZ31 strip

Optical images of the microstructure of the (*a*) as-received material, (*b*) the sample processed by CER and (*c*) the sample processed by EDSR are shown in Fig. 3. The average grain sizes of the as-received material, the CER-processed sample and the EDSR sample are 20, 9 and 7 μm, respectively. The grains of the samples processed by CER and EDSR were refined compared with those of the as-received material. This refinement implies that recrystallization occurred during rolling. However, the rolling

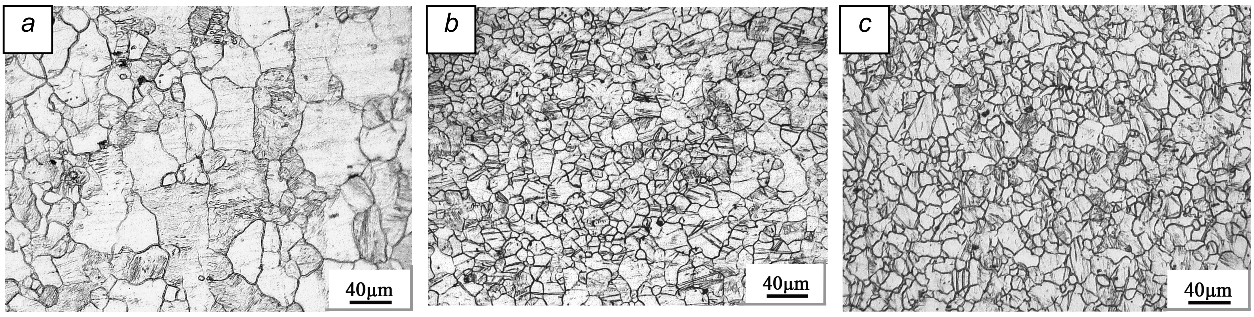

Fig. 3. Optical images of the microstructure of the as-received material (*a*), the CER-processed sample (*b*) and the EDSR-processed sample (*c*).

temperature was relatively lower than that of traditional warm rolling [9, 10]. Previous studies indicate that electropulsing could effectively activate the $\{11\bar{2}2\}$ $<11\bar{2}3>$ slip system and assist the climb of non-basal dislocations due to the coupling of thermal and athermal effects [11]. Therefore, the introduction of electropulsing into the rolling process can simultaneously reduce the rolling temperature and eliminate the annealing process. It should also be noted that the EDSR-processed sample showed more homogeneously distributed grains than the CER-processed one. This difference can be attributed to the larger strain rate and equivalent strain caused by DSR [12]. Fine grains can be induced by recrystallization at a high strain rate and low temperature [13]. These two conditions were met simultaneously in the EDSR process. This result indicates that the combination of electropulsing and DSR causes recrystallization to develop at a relatively low temperature, leading to fine microstructure.

2.3. Effects of CER and EDSR on the texture of the AZ31 strip

The (0002) pole figures of (*a*) the as-received material, (*b*) the sample processed by CER and (*c*) the sample processed by EDSR are shown in Fig. 4. The as-received material showed the majority of its basal plane oriented parallel to the extrusion direction. The CER-processed sample showed a pronounced basal texture with a circular orientation distribution. By contrast, the sample processed by EDSR showed a spread of orientations in the rolling direction. Additionally, the {0002} texture of the sample processed by EDSR exhibited a weaker basal texture intensity (8.0) than that of the sample processed by CER (11.0). The spread in the orientation distribution and the weakening of the basal texture intensity may be related to the different modes of loading between the two samples. The position of the neutral point is identical on both the upper and lower surface during CER, while it is altered in EDSR: that of the surface in contact with the larger roll moves toward the exit, and that of the other surface in contact with the smaller roll moves toward the entrance [9]. Therefore, the surface of the Mg alloy sample undergoes a certain amount of shear deformation, which may weaken the {0002} texture.

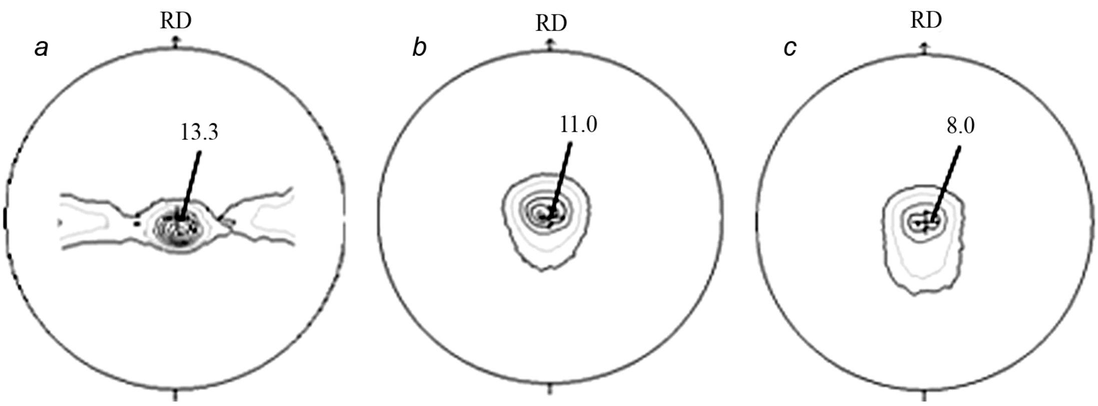

Fig. 4. (0002) pole figures of the as-received material (*a*), the CER-processed sample (*b*) and the EDSR-processed sample (*c*).

2.4. Effects of CER and EDSR on the mechanical properties of the AZ31 strip

The mechanical properties of the EDSR- and CER-processed samples are listed in Table 2 and Fig. 5. All materials exhibited a similar tensile stress of ~ 290 MPa. However, the fracture elongation depended on the rolling method: the sample processed by CER exhibited a relatively limited ductility below 15 %, whereas the sample processed by EDSR exhibited a ductility of 23.1 %. The enhancement in the ductility of the sample processed by EDSR may be attributed to its weaker basal texture intensity, as shown in Fig. 2. A previous study showed that twinning effectively serves as a complementary deformation mechanism in Mg alloy, and it readily occurs by tensile stress parallel to the c-axis direction [14]. As result, a weak basal texture allows twinning to occur easily; thus, twinning was the deformation mechanism of the sample processed by EDSR. Moreover, the EDSR-processed sample has a lower 0.2 % proof stress and greater elongation than the CER-processed one.

Table 2

Room-temperature tensile properties of samples processed by CER and EDSR

	0.2 % Proof stress, MPa	Tensile stress, MPa	Fracture elongation, %
As-received	166	244	20.2
CER	252	287	14.7
EDSR	244	285	23.1

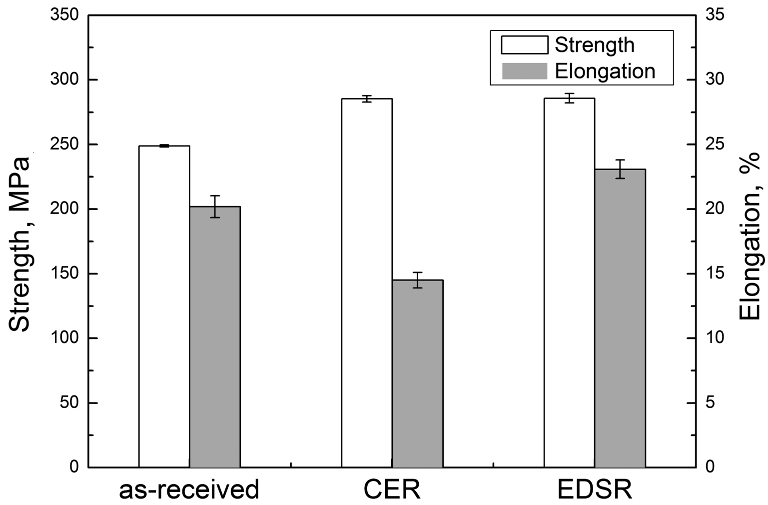

Fig. 5. Room-temperature tensile properties of AZ31 as-received sample and samples processed by ENR and EDSR.

Conclusions

The EDSR process makes full use of the advantages of electropulsing and differential speed rolling and is suggested to be effective in enhancing the ductility of AZ31 Mg alloy at low temperature. In this study, an EDSR-processed sheet exhibited lower yield stress, larger elongation to failure and finer grain size compared with those of an CER-processed sheet, and the grain sizes of both were significantly refined relative to the grain size of the as-received material. The EDSR technique can be used to manufacture thin strips of AZ31 Mg alloy without annealing due to the improvement in ductility it offers.

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