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Structure and properties of hot-rolled and annealed AZ61 magnesium alloy

Struktura i własności stopu AZ61 po walcowaniu na gorąco i wyżarzaniu

Abstract

Magnesium alloy AZ61 was processed by hot rolling up to a large thickness reduction (~89%) in several routes with intermediate annealing. The hot rolling process was conducted at 450°C and at a 1.5 s^{-1} strain rate. The structure and texture evolution as well as the mechanical properties during processing were investigated. The structure studies showed that, during the hot-rolling process, a large number of twins formed, which had an impact on the mechanical properties of the hot-rolled samples. After annealing for 15 minutes, the twins were no longer observed in the annealed samples, causing a significant decrease in hardness. Moreover, an investigation of the hardness showed that annealing for 15 minutes did not remove all of the hardening effects nor did the hardness of the annealed samples decrease to the value before hot rolling. The texture investigations showed that the texture of the hot-rolled samples was a typical basal-type texture. However, the basal pick was split into two tilted towards the rolling direction (RD). The texture changed during annealing while the new strong texture components evolved. The annealing led to an increased intensity of $<10\bar{1}0>\{11\bar{2}0\}$ texture component and enhanced ductility. It was concluded that the texture changes observed in the present investigations may lead to the enhanced ductility of magnesium alloys and, therefore, help us design a deformation scheme for magnesium alloys consisting of several thermomechanical routes.

Keywords: magnesium alloys, texture, hot rolling, annealing

Streszczenie

Stop magnezu AZ61 został odkształcony przez walcowanie na gorąco do sumarycznego zgniotu 89%, w kilku przepustach z wyżarzaniem międzyoperacyjnym. Walcowanie odbywało się w temperaturze 450°C, a prędkość odkształcenia wynosiła 1,5 s^{-1}. W pracy badano wpływ struktury oraz tekstury na własności mechaniczne stopu AZ61. Badania strukturalne pokazały występowanie

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dużej liczby bliźniaków po walcowaniu na gorąco, co miało wpływ na własności mechaniczne. Po wyżarzaniu przez 15 minut struktura nie zawierała bliźniaków oraz zaobserwowano spadek własności mechanicznych badanych próbek, ale nie do wartości sprzed walcowania. Z kolei badania teksturowe wykazały, że po walcowaniu na gorąco powstaje tekstura typu bazalnego, z dwoma pikami odchylonymi od [0001] w kierunku walcowania. Po wyżarzaniu zaobserwowano dodatkowy komponent tekstury, $\langle 10\bar{1}0\rangle\{11\bar{2}0\}$, co spowodowało poprawę własności plastycznych badanego materiału. Zaobserwowane zmiany strukturalne i teksturowe wpływają silnie na własności plastyczne stopu AZ61, dzięki czemu możliwe jest odpowiednie zaprojektowanie procesu walcowania tego materiału.

Słowa kluczowe: AZ61, stopy magnezu, tekstura, walcowanie na gorąco, wyżarzanie

1. Introduction

Magnesium and its alloys are widely used as structural materials because of their low density and high specific strength [1, 2]. The main fields of use of magnesium alloys are industries such as automotive, aerospace, and electronics. However, the plastic deformation of magnesium alloys is rather problematic due to the strong anisotropy of the hexagonal structure [3]. One of the effects of anisotropy on the hcp structures is the formation of a strong basal texture during rolling, for example [4–6]. These strong textures cause great mechanical anisotropy in many magnesium alloys. Much effort has been done by several researchers to reduce the effect of the strong textures and mechanical anisotropy of the magnesium alloys by means of weakening the basal texture. Thus, very interesting processing methods have been developed. Valle et al. processed AZ61 by hot rolling in several thermomechanical routes at strain rates ranging from 10^{-4} to $10^{-2}\ s^{-1}$ and observed that a decrease of basal texture intensity together with dynamic recrystallization (DRX) led to the enhancement of AZ61 ductility manifested a capacity for large deformations in one pass [6]. Ma et al. processed magnesium alloy AM30 at high strain rates and found that, at strain rates $> 0.8\ s^{-1}$, profuse twinning is activated [7]. On the one hand, twinning has an impact on hardness, but on the other, the twins may accelerate the DRX processes, enhancing the ductility of the material [7]. Zhang et al. processed magnesium alloy AZ31B in a repeated unidirectional bending process (RUB) followed by annealing [8]. It was found that AZ31B after RUB and annealing exhibits better formability due to the grain coarsening and weakening of the basal texture as compared to as-received sheets. Zhu et al. has shown that massive twinning occurring during high-strain-rate rolling (HSRR, $\dot{\varepsilon} > = 2.9\ s^{-1}$) of AM60 at ambient temperatures leads to the weakening of the basal texture due to the DRX process nucleating on the twins [9, 10]. The common factor in the methods described above is the high temperature of the process, which reduces the formation of a strong basal texture and activates non-basal slip systems, twinning, and the DRX process. On the other hand, the high temperature of metal processing consumes the hardening effects and leads to an increase in grain size [10]. The ductility of magnesium and its alloys is sensitive to grain size [5]. Cepede-Jimenez processed pure magnesium with different grain sizes (36 μm and 19 μm) and showed that grain size has great impact on the ductility, mechanical properties, and final structure of the deformed pure magnesium [5]. The impact was the result of a grain-boundary configuration on the activation of different slip systems during plastic deformation. Sulkowski and Palka have processed the AZ61 magnesium alloy by hot rolling followed by annealing and observed that the texture changes during annealing after hot rolling enhanced its ductility [4].

In the present study, magnesium alloy AZ61 was processed by hot rolling with intermediate annealing. The aim of this paper was to examine the effects of annealing on the texture evolution and hardness of the given magnesium alloy after the hot-rolling process.

2. Experiments

In this study, magnesium alloy AZ61 with the nominal addition of Al 6% and Zn 1% was investigated. "As-received" ingot bars of 10 mm × 10 mm × 100 mm in dimension were prepared and pre-heated at 450°C for 1 hour followed by hot-rolling processes. During hot rolling, several thermomechanical routes were conducted. Each route consisted of rolling at a strain rate of 1.5 s^{-1} followed by annealing at 450°C for 15 minutes. There were three routes in total, and the final thickness reduction was 89% for a given AZ61. The structure and hardness investigations were performed on samples cut from the rolled material after rolling. After the rolling process, two types of samples were cut (named A and B and subjected to tensile tests. Sample A was oriented in such a way that the tensile direction (TD) was parallel to the rolling direction (RD), and in Sample B, the TD was perpendicular to the RD, as shown in Figure 1. Half of each A and B sample was annealed at 450°C for 1 hour. Structural investigations, including observations with an Olympus GX51 light microscope, were performed on the polished and etched samples. Each sample for structural investigations was sanded with sandpaper with gradations between 800 and 2400 followed by polishing with a woolen cloth. The final polishing was performed using diamond paste with a final particle size of 0.3 μm. After the final polishing, the samples were etched in an etching solution composed of 3 g of picric acid, 100 ml of ethanol, 10 ml of acetic acid, and 10 ml of water. The average grain size was estimated based on the Average Grain Intercept (AGI) Method. The hardness investigations (including Vickers hardness measurements) were performed with the use of a WallPert Testor 2000 instrument with 0.005 kgf. There were ten indents done for each sample subjected for hardness measurements, and the average value was calculated. Texture investigations (including X-ray measurements) were performed with the use of a Bruker D8 Advance device with Cu-Kα radiation operating at 30 kVe. The textures were measured along the normal direction (ND), as shown in Figure 1.

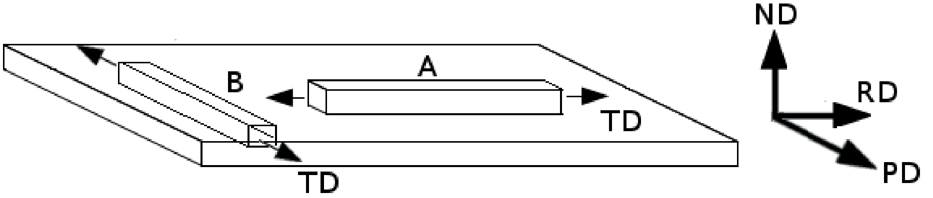

Fig. 1. A sketch showing the orientation of the rolling direction (RD), transverse direction (TD), and normal direction (ND) as well as the orientation of Sample types A and B

For each sample subjected to texture investigations, four pole figures (0002), $\{10\bar{1}0\}$, $\{10\bar{1}0\}$, and $\{11\bar{2}0\}$ were measured with the step size 5×5. The data obtained from X-ray measurements was processed by MTEX software and corrected by defocusation data.

3. Results and discussions

Figures 2 presents the structures of AZ61 after hot rolling and annealing.

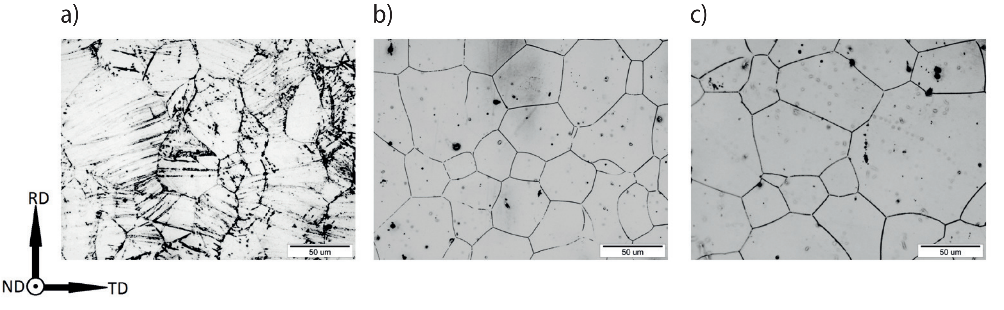

Fig. 2. The structures of AZ61 after hot rolling and annealing

In the case after hot rolling, a large number of twins formed inside the grains (Fig. 1a). The twins are not observed in the samples annealed for 15 minutes at 450°C (which can be seen in a comparison of Figures 1a and 1b). After annealing, a mixture of large and small grains is observed (Figs. 2b and 2c). Such a structure was observed by Valle et al. in magnesium alloy AZ31 after hot rolling at 450°C and at strain rate of 10^{-3} s^{-1} [6]. Valle concluded that the small grains around big grains resulted from a dynamic recrystallization process. However, in the present study, such a structure resulted from recrystallization after rolling. During annealing for 1 hour (Fig. 2c) mostly large grains are observed (with an average size of 35 μm).

In Figure 3, the average grain size of the hot-rolled and annealed samples is presented with its relation to annealing time. The average grain size after hot rolling is 35 μm for AZ61. During annealing for 15 minutes, the average grain size increased to 38 μm, and after 1 hour, to 42 μm. However, taking into account Figure 2c, a complex structure is observed where a mixture of large and small grains is visible.

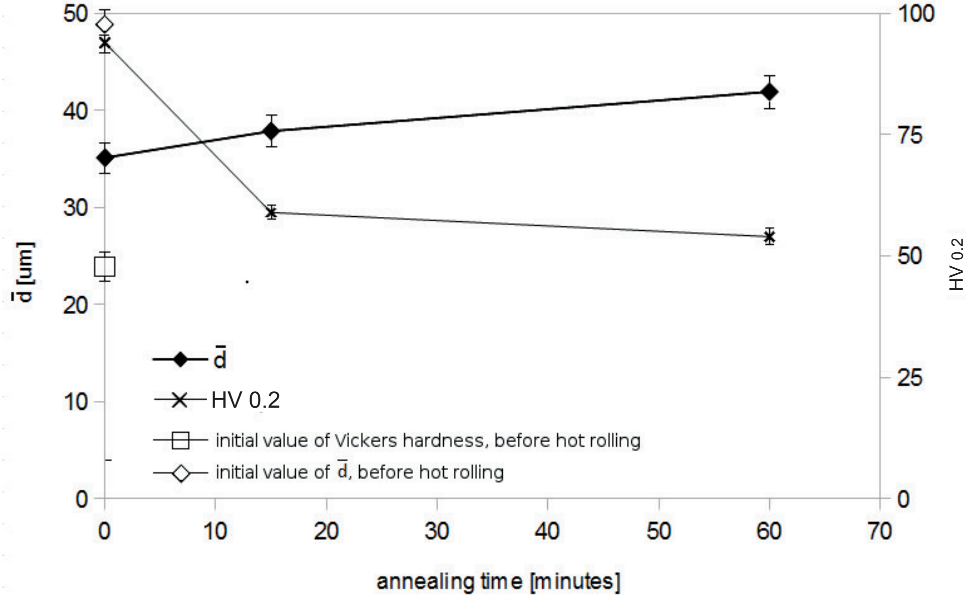

Fig. 3. Average grain size and Vickers hardness in relation to annealing time of hot-rolled and annealed AZ61

In addition, the average Vickers hardness is presented for hot-rolled and annealed samples of AZ61 in Figure 4. It can be seen that, after hot rolling, the hardness of AZ61 is 94 HV, which can be the result of the large number of twins. A strong decrease in hardness may be seen for AZ61 after annealing for 15 minutes. This may have resulted from the absence of twins rather than the increase of grain size. It is worth nothing that, after annealing for 15 minutes, the average hardness (56HV) does not decrease to the value of the initial fully-annealed sample (which was 50 HV). It may be concluded that the effects of the strengthening of plastic deformation are not completely removed from the material despite annealing for 15 minutes. After 1 hour of annealing, the average Vickers hardness of the AZ61 samples decreased to a value comparable to the initial value.

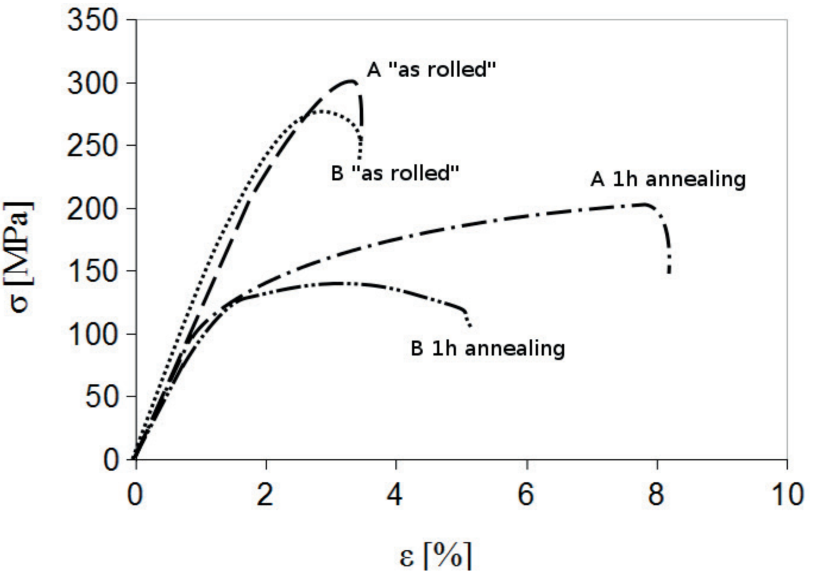

Fig. 4. Work-hardening curves for "as-rolled" and AZ61 samples annealed for 1 hour (for the meaning of A and B, see Fig. 1)

In Figure 4, the work-hardening curves are presented for "as-rolled" samples (which was material after hot rolling) and for samples annealed for 1 hour. The data from Figure 4 are summarized in Table 1, where R_{p02}, UTS, and A_5 are shown. The best mechanical properties, such as unlimited tensile strength (UTS) equal to 298 MPa and yield point (R_{p02}) equal to 271 MPa, has sample B "as-rolled", where TD is parallel to RD. The B "as-rolled" sample where TD is perpendicular to RD is very similar to Sample A "as-rolled." In this case, no strong anisotropy of mechanical properties was reported (as opposed to AZ91 after hot rolling, for example) [11]. Partially, the reason for this is the formation of a different texture in the case of the present study, which will be discussed later in this paper. However, after annealing for 1 hour, the anisotropy of mechanical properties increased while much-stronger differences in R_{p02}, UTS, and elongation (A_5) are observed (compare the curves in Figure 4 and data in Table 1).

Table 1. The values of R_{p02}, UTS, and A_5 for samples of AZ61 subjected to tensile tests

Property	A "as-rolled"	A annealed	B "as-rolled"	B annealed
R_{p02} [MPa]	271	106	249	122
UTS [MPa]	298	194	275	140
A_5 [%]	1.3	6	1.2	4.3

Figure 5 presents Orientation Distribution Functions (ODF) of section $\varphi_2 = 0°$ of texture after hot rolling and annealing of AZ61 samples.

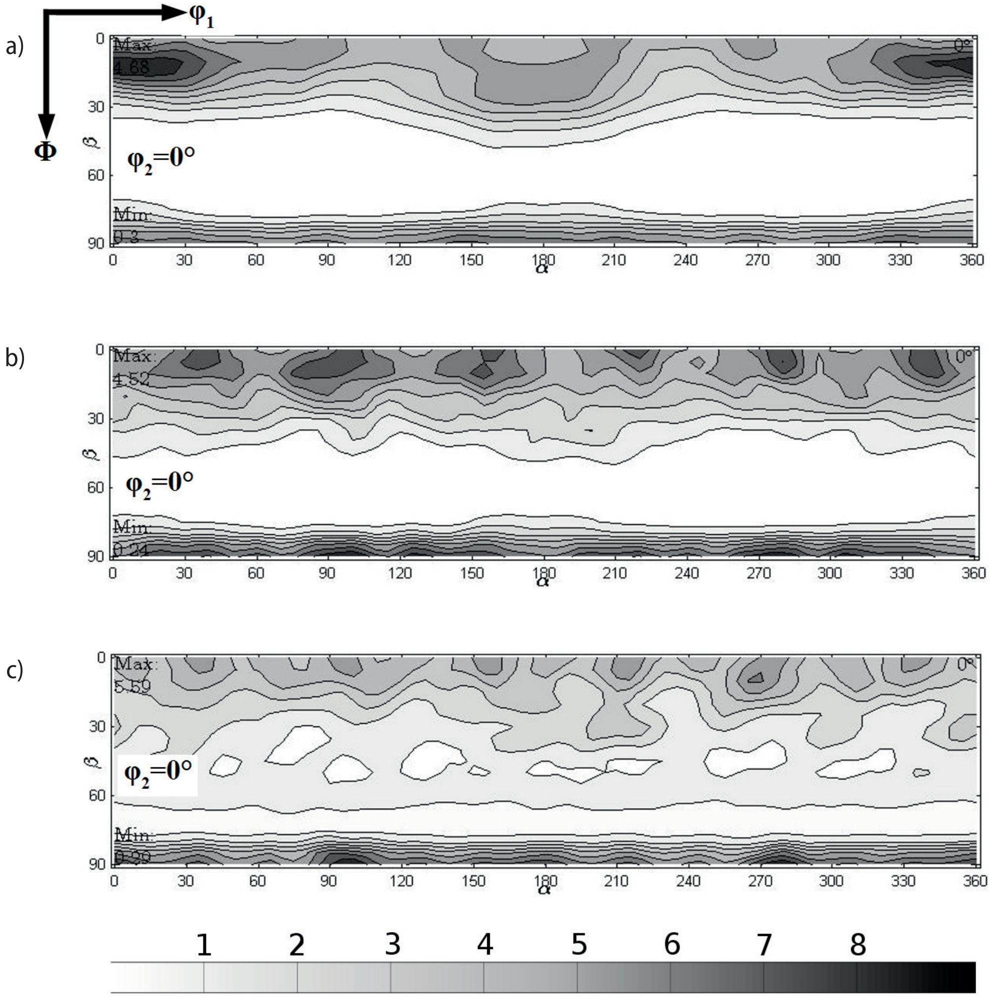

Fig. 5. ODF $\varphi_2 = 0°$ section of AZ61 hot-rolled and annealed

In Figure 5, it can be seen that, after the hot rolling of AZ61, the basal type texture has developed with additional components. According to Wang [12], these components are $\{11\bar{2}0\}$ fiber and $\{01\bar{1}3\}\langle 2\bar{1}\bar{1}0\rangle$. After annealing AZ61 for 15 minutes, the texture changed (compare Figs. 6a and 6b). In this case, strong $(0001)\langle 11\bar{2}0\rangle$ has appeared, the $\{11\bar{2}0\}$ fiber component has strengthened, and the $\{01\bar{1}2\}\langle 11\bar{0}2\rangle$ component is no longer observed. After annealing AZ61 for 1 hour, (Fig. 5c) weak (0001) $<11\bar{2}0>$ and $\{11\bar{2}0\}$ fiber texture components can be observed. The changes in the texture components may have great impact on the plasticity of deformed magnesium and its alloys due to the influence on the slip system activity in a particular grain [4, 5, 11]. In the magnesium alloy with the basal fiber texture (the case of AZ61 after hot rolling in the present study), the grains are oriented in a way that the c-axis is perpendicular to the rolling direction and parallel to the normal direction (ND); see Figure 1. This orientation hampers the activation of the basal slip systems during such processes as rolling or tension and may lead to the failure of AZ61 during rolling [4, 11, 13]. However, after annealing AZ61 for 1 hour, the samples are free of twins, and most of the grains are oriented in such a way that the $<11\bar{2}0>$ direction is parallel and $<10\bar{1}0>$ is perpendicular to the RD. This kind of texture favors the activation of soft slip systems during the plastic deformation of magnesium and its alloys [13].

The texture effects described in the present study have a great effect on the plastic and mechanical properties of magnesium alloys after hot rolling and annealing, and this has been reported before [5, 11]. The texture changes observed in the present study during annealing after hot rolling of the AZ61 magnesium alloy may help us better understand the deformation processes in magnesium alloys and to design a deformation scheme composed of several thermodynamic passes for the effective processing of magnesium alloys.

4. Conclusions

- After hot rolling AZ61 at 450°C and at a high strain rate, twins formed in the grains, impacting the increase of hardness.
- During annealing, the average size of the grains increased overall.
- The texture after hot rolling AZ61 was a basal type texture with additional components. These components are a strong $\{11\bar{2}0\}$ fiber and $\{01\bar{1}3\}<2\bar{1}\bar{1}0>$ for AZ61.
- During annealing, the texture changed. The basal component disappeared, and new components appeared, which were weak (0001) $<11\bar{2}0>$ and $\{11\bar{2}0\}$ fibers.
- The texture changes have an impact on the plastic and mechanical properties of deformed and annealed magnesium alloys.

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