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Structure and properties of AZ31B magnesium alloy sheets processed by repeatedly unidirectional bending at different temperatures

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Abstract: Repeatedly unidirectional bending (RUB) was applied to the magnesium alloy sheet to improve the basal texture. The effect of RUB temperature on resulting structure and room temperature properties was investigated. The texture components of the sheet undergoing RUB at recovery temperature were similar to those of the sheet undergoing RUB at room temperature (RT). As the RUB temperature increased to above recrystallization temperature, the texture components became more disperse and the pyramidal components increased. With the increase of RUB temperature, the grain size near the surface of the sheets undergoing RUB tended to grow up. When the sheets were processed by RUB at medium-high temperature followed by annealing at 533 K, the yield strength and fracture elongation were lower than those of the cold rolled sheet; however, the Erichsen value was slightly higher than that of the cold rolled sheet. The sheet undergoing RUB at RT followed by annealing at 533 K represented the best mechanical properties.

Key words: magnesium alloy sheets; repeatedly unidirectional bending; deformation temperature; texture

1 Introduction

Magnesium alloys have great potential as lightweight structural materials especially in automotive applications[1]. They attract more and more attention because of their superior performance such as high strength, good thermal conductivity and shock-absorbing characteristics[2−3]. However, the applications of magnesium alloy, especially wrought magnesium alloy, are still limited due to its poor plasticity and formability. Rolled magnesium alloy sheet has a strong basal texture, which exhibits low press formability at near room temperature (RT) because the basal slip systems hardly become active[4−6].

It is an effective method to improve mechanical properties of magnesium alloy sheet by weakening basal texture. Differential-speed rolling (DSR)[7−10] can obtain a Mg-3Al-1Zn alloy with a tilted basal texture. Compared with a normal symmetrically rolled sheet, the DSR-processed sheet showed a larger uniform elongation, especially in the rolling direction. Cross rolling exhibited higher press formability compared with normal rolling, and the (0002) texture of the cross-rolled specimen was inclined by about 10° to the transverse direction (TD)[11−13].

In the previous studies, the repeatedly unidirectional bending (RUB)[14−15] was used to change the texture components of cold-rolled magnesium alloy sheet at RT. It can promote the activity of the basal-plane slip system by increasing the Schmid factor, thus obtaining outstanding formability. It is well known that deformation temperature has an important effect on texture components of magnesium alloys. With the increase of deformation temperature, especially above 498 K, the non-basal plane slips are activated, and the dynamic recrystallization and preferred growth of grain can also determine the texture components of magnesium alloy sheets. In this study, the effect of RUB temperature on the microstructure and texture evolution of the magnesium alloy sheets undergoing RUB was investigated systematically. The mechanical properties of

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magnesium alloy sheets processed by RUB at different temperatures followed by annealing at 533 K were discussed.

2 Experimental

Commercial AZ31B magnesium alloy (Mg-3Al-1Zn, mass fraction, %) sheets with a thickness of 0.8 mm, cut into 1000 mm (length) × 200 mm (width) pieces, were used in the experiments. Figure 1 shows an abridged general view of the RUB process, where the magnesium alloy sheets were bent on a cylindrical support under a constant force *T* with a constant speed *v*. The radius of the cylindrical support was 1 mm and the bending angle was 90˚. The RUB process used in this experiment was six-pass bending at two orientations. This meant that after each bending pass, the sheet was turned over and the bending orientation was also changed in the next pass. In the experiments, commercial AZ31B magnesium alloy sheets were subjected to RUB at intermediate and high temperatures, by heating and insulating them in a furnace for 30 min at 473, 573 and 673 K, respectively. Before each RUB pass, insulation was necessary. The microstructure was observed with a metallographic microscope. The samples undergoing RUB were annealed at 533 K for 60 min. The mechanical properties were tested on a CMT5105 universal test machine and the formability was measured by the Erichsen test. X-ray texture analysis was performed for acquiring texture data using an X-ray diffractometer (Philips APD-10) with Cu K_α radiation, a voltage of 40 V and a current of 100 mA. Four pole figures of $(10\bar{1}0)$, (0002), $(1\bar{1}01)$, $(1\bar{1}02)$ were measured to calculate the orientation distribution function (ODF) by using the LEO1450 (backscattering orientation analysis system). Because of the symmetry of the hexagonal crystal structure, φ_2=0° and φ_2=30° were taken to show the orientation distribution sufficiently for the present analyses.

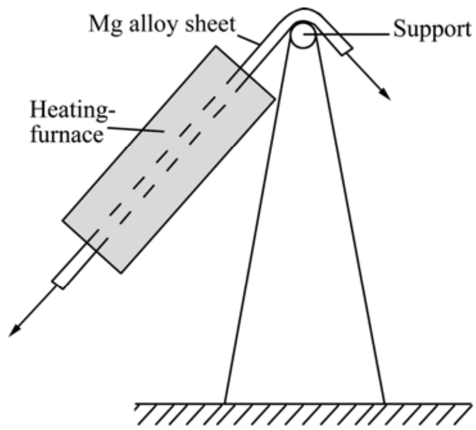

Fig.1 Schematic diagram of apparatus for RUB

3 Results and discussion

3.1 Microstructure

Figure 2 shows the cross-sectional microstructures of magnesium alloy sheets undergoing RUB at different temperatures. Before RUB, the grains were equiaxed with a fine grain (Fig.2(a)) and the microstructure was uniformly distributed through thickness direction in cold-rolled sheet. When plastic deformation took place during RUB at RT and 473 K, there were still equiaxed grains of 3−10 μm, and a few twins appeared. The twins mainly concentrated near the surface of sheets. For magnesium alloys, when the deformation temperature is below 528 K, plastic deformation depends mainly on

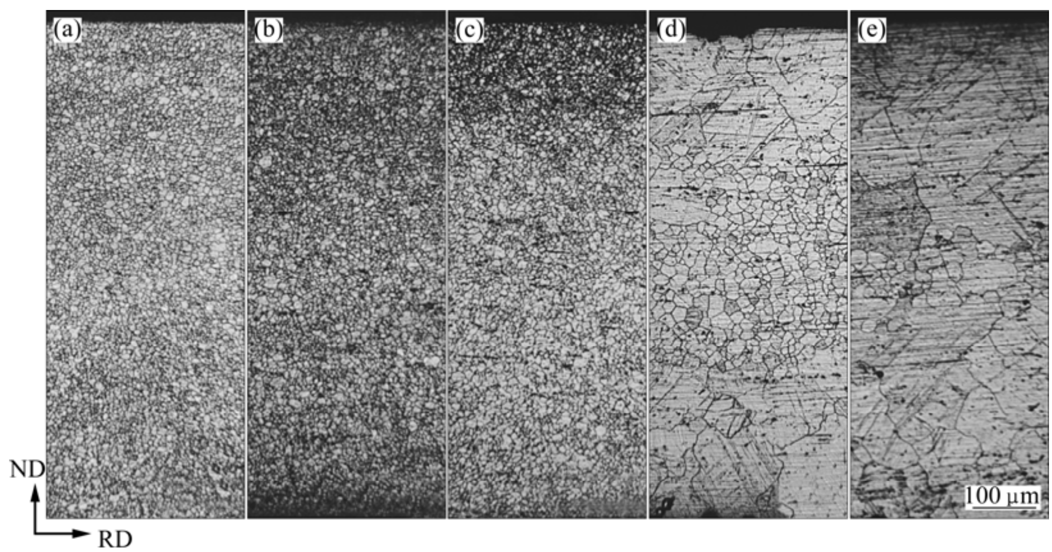

Fig.2 Microstructures of AZ31B magnesium alloy sheets: (a) Cold-rolled; (b) RUB processed at RT; (c) RUB processed at 473 K; (d) RUB processed at 573 K; (e) RUB processed at 673K

prismatic slip and pyramidal twins. When the deformation temperature is above the recrystallization temperature of magnesium alloy, after RUB, the grain-boundary diffusion and migration ability both increase, leading to dynamic recrystallization and grain growth. There was a gradient of strain during bending of a sheet, and the microstructure gradient showed a coarse-grained layer near the surface and the fine-grained layer in the middle of the sheet, as shown in Fig.2(d) and Fig.2(e). With the increase of RUB temperature, the fine-grained layer in the middle of the sheet tended to become narrow and finally disappeared.

In order to investigate when the coarse grains near the surface of magnesium alloy sheet formed during RUB at higher temperature, the magnesium alloy sheet was processed by a pass of RUB at 573 K. Figure 3 shows the microstructure evolution of the AZ31B magnesium alloy sheet undergoing a pass of RUB at 573 K. After the cold-rolled sheet was processed by heat insulation at 573 K for 30 min, a part of grains grew up slightly and the microstructure change was very little. This is because the cold-rolled sheets have been annealed. Then, the sheet was processed by a pass of RUB at 573 K, the microstructure was still equiaxed grains of 3−15 μm. After the magnesium alloy sheet undergoing a pass of RUB at 573 K was processed by heat insulation at 573 K for 30 min, the grain near the surface of magnesium alloy sheet became coarse. The phonmenon indicated that the formation of the coarse grains near the surface of the magnesium alloy sheet undergoing RUB at higher temperature was mainly attributed to heat insulation between adjacent passes. The energy accumulating near the surface was larger and the lattices in these grains subjected to severe plastic shear deformation were seriously distorted during RUB. Thus, recrystallization temperature of magnesium alloy near the surface tended to decrease, which easily induced grain growth and formation of coarse grain structure during heat insulation. Previous research[16] also showed that if 80%−95% of grains arose from dynamic recrystallization, the subsequent annealing would lead to abnormal coarse grains.

The magnesium alloy sheets undergoing RUB at different temperatures were annealed in order to eliminate the work-hardening. When these magnesium alloy sheets undergoing RUB at different temperatures were annealed at 533 K for 60 min, the changes of their grain size were very little (no shown in this work). For the magnesium alloy sheets that underwent RUB at RT followed by annealing at 533 K, the twins disappeared owing to static recrystallization and the grains near the surface of the magnesium alloy sheet grew obviously[14−15]. However, the average grain size was hardly changed[17]. After annealing at 533 K, the microstructure evolution of the magnesium alloy sheet undergoing RUB at 473 K was similar to that of the magnesium alloy sheet undergoing RUB at RT. When the RUB temperature was above the recrystallization

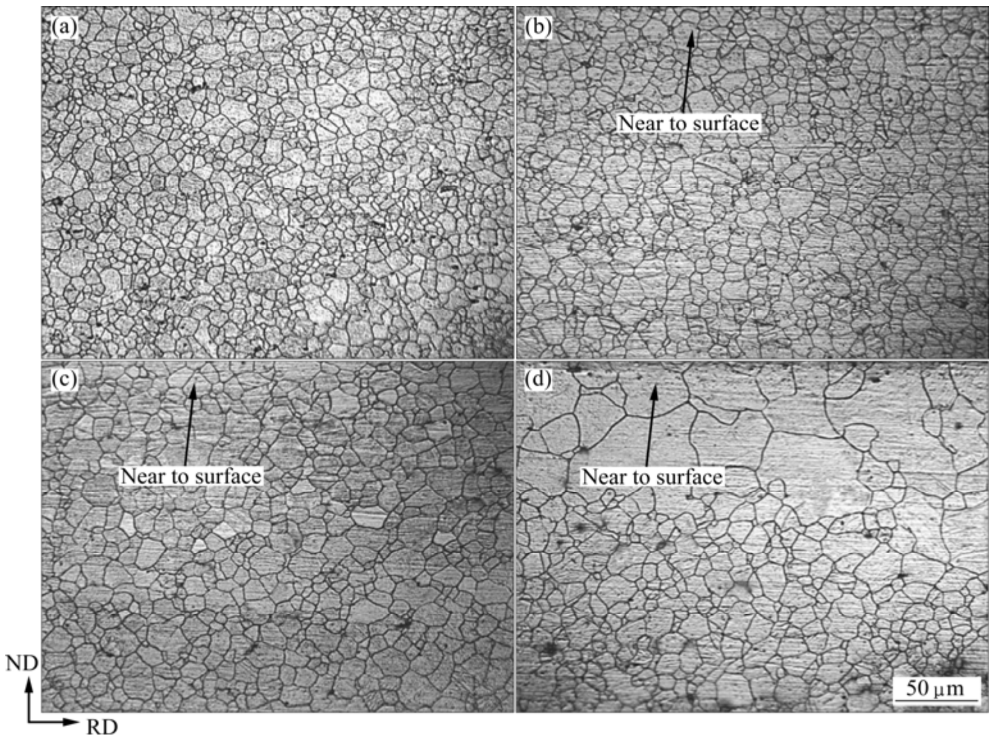

Fig.3 Evolutional process of microstructure undergoing a pass of RUB at 573 K in AZ31B magnesium alloy sheet: (a) Cold-rolled; (b) Heat insulation at 573 K for 30 min before a pass of RUB; (c) A pass of RUB at 573 K; (d) Heat insulation at 573 K for 30 min after a pass of RUB

temperature, the effect of annealing on the grain size was lower because the heat insulation between adjacent passes was about the same as recrystallization annealing.

3.2 Texture evolution

Figure 4 shows that the cold-rolled magnesium alloy sheet had a strong (0002) basal texture. In addition, there were some pyramidal textural components, but they were very weak compared with the basal texture. After RUB at RT, the grain orientation changed considerably and the original basal texture was greatly weakened. Strong $(1\bar{2}12)$, $(1\bar{2}11)$, $(10\bar{1}0)$ textural components appeared with densities close to those of the basal texture. Meanwhile, a small quantity of $(12\bar{1}2)$, $(10\bar{1}1)$ components also appeared. Compared with the magnesium alloy sheet undergoing RUB at RT, similar texture components were formed in the magnesium alloy sheet undergoing RUB at 473 K. However, $(1\bar{2}12)$, $(1\bar{2}11)$ and $(10\bar{1}0)$ pyramidal texture components were weaker and the (0001) texture component was stronger. After the magnesium alloy sheet was processed by RUB at 673 K, the basal texture component decreased much more and the grain orientation had a disordered distribution.

The texture components of the magnesium alloy sheets processed by RUB at intermediate and high temperatures were different from those of the magnesium alloy sheet undergoing RUB at RT. First, with the increase of RUB temperature, the deformation mechanism changed during RUB. Second, the heat insulation between adjacent passes was almost the same as the heat treatment process. The mechanism of texture evolution involved in magnesium alloy sheet undergoing RUB at RT had been discussed in previous studies, and Fig.2(b) also shows that the twins were formed during RUB at RT. Thus, the variation of texture components was attributed to the alternating operations of slip and twinning during RUB at RT[14−15]. According to the reported data[18], the critical resolved shear stress (CRSS) of basal slip at RT is approximately 1/55 that of non-basal slip, and becomes 1/12 at 523 K. Thus, the plastic deformation mainly depends on basal slip at 473 K, and with the decrease in the CRSS of non-basal slips, the contribution of twins for plastic deformation tends to decrease. Figure 2 also indicates that the fraction of twins in the sheet undergoing RUB at RT is larger obviously than that of the sheet undergoing RUB at 473 K. For magnesium alloys, 473 K is a recovery temperature which represents relatively early stage of microstructure evolution[19]. Thus, the texture evolution of the magnesium alloy sheet undergoing RUB at 473 K was similar to that of the magnesium alloy sheet undergoing RUB at RT. The conclusion indicated that the deformation texture formed due to RUB was retained to a large extent during heat insulation at 473 K. Some pyramidal texture considered as the grains with larger

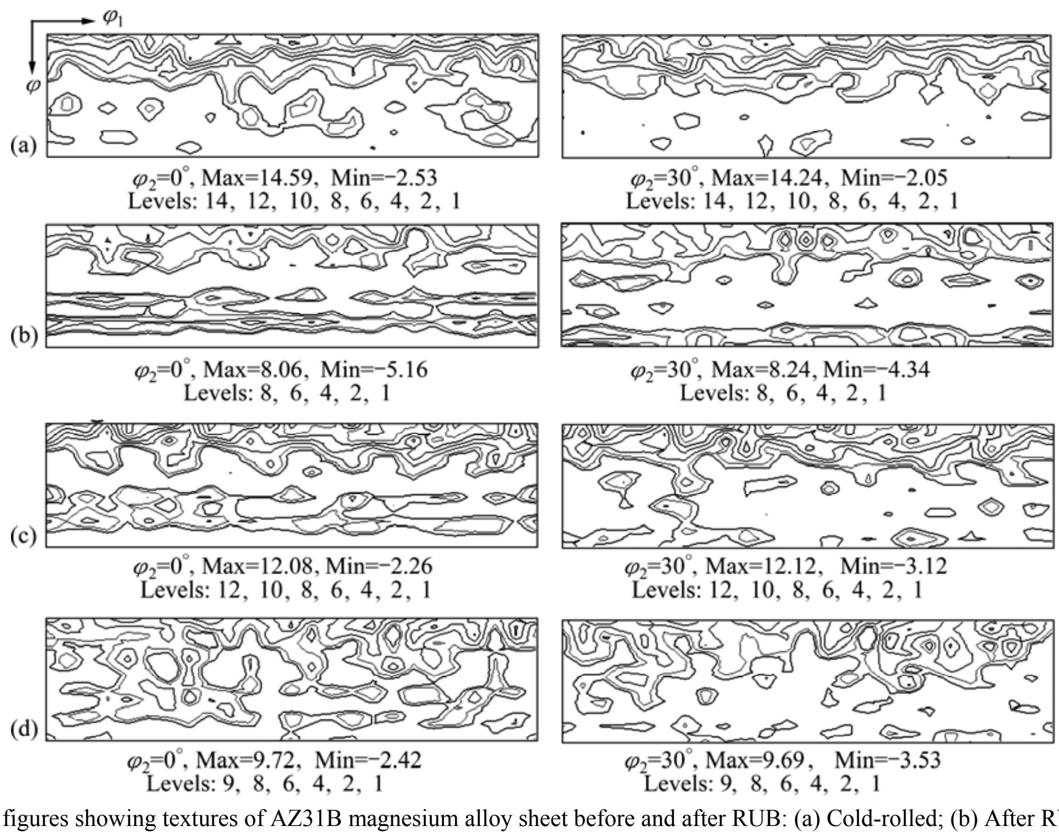

Fig.4 ODF figures showing textures of AZ31B magnesium alloy sheet before and after RUB: (a) Cold-rolled; (b) After RUB at RT; (c) After RUB at 473 K; (d) After RUB at 673 K

misorientation with basal texture tended to disappear. This phenomenon could be the results that the contribution of basal slip and twining decreased and heat insulation is carried out at a recovery temperature. When the deformation temperature is above 498 K, the prismatic slip and pyramidal slip can be started up by thermal activation. The activation of prismatic slip, first-order pyramidal slip and second-order pyramidal slip requires temperature beyond 450 K, 623 K and 573 K, respectively[20]. And with the increase of deformation temperature, the grains will grow up. During RUB processing above recrystallization temperature, the twins are formed more easily in the coarse grains near the sheet surface during RUB, as shown in Fig.2(d) and Fig.2(e). Thus, when the RUB was carried out above the recrystallization temperature (considered as 533 K), the change of deformation mechanism and preferred orientation of grown grain led to the different distributions of texture components. After the magnesium alloy sheet underwent RUB at 673 K, the basal component decreased much more and the distribution of c-axis within an angle of 70° between the [0001] directions of the grains and the normal direction (ND) were almost equal.

Figure 5 shows the ODFs of magnesium alloy sheets undergoing RUB at different temperatures followed by annealing. After the sheet undergoing RUB at RT was annealed at 533 K, the textural components became more complex, mainly consisting of the (0002) basal texture and pyramidal texture including $(\bar{1}2\bar{1}2)$, $(\bar{1}2\bar{1}1)$, $(10\bar{1}2)$ and $(10\bar{1}1)$. The phenomenon was explained in the previous work[14]. For the sheet undergoing RUB at 473 K followed by annealing at 533 K, the similar texture evolution was found and $(01\bar{1}0)$ prismatic texture was also formed. As the RUB temperature increased to 673 K, the effect of recrystallization annealing on the texture components tended to weaken because the heat insulation between adjacent passes was about the same as recrystallization annealing. These results also indicated that the basal texture of magnesium alloy sheet had a slight spread and was weakened during annealing.

3.3 Effect of grain size and texture on mechanical properties

Table 1 illustrates the room-temperature mechanical properties of magnesium alloy sheets undergoing RUB at different temperatures followed by annealing at 533 K. For magnesium alloy sheet undergoing RUB at RT followed by annealing, the 0.2% yield strength decreased and the tensile elongation and Erichsen value increased obviously. Thus, the RUB at RT followed by annealing could effectively improve the mechanical properties. In contrast to the RUB at RT followed by annealing, the decreasing degree of 0.2% yield strength of magnesium alloy sheet undergoing RUB at 473 K followed by annealing was smaller. With the increase of RUB temperature, the elongation and Erichsen value tended to decrease. It was interesting to note that the elongation of magnesium alloy sheets undergoing RUB above 473 K followed by annealing at 533 K was lower than that of the cold-rolled sheet; however, their Erichsen values were higher than those of the cold-rolled sheet.

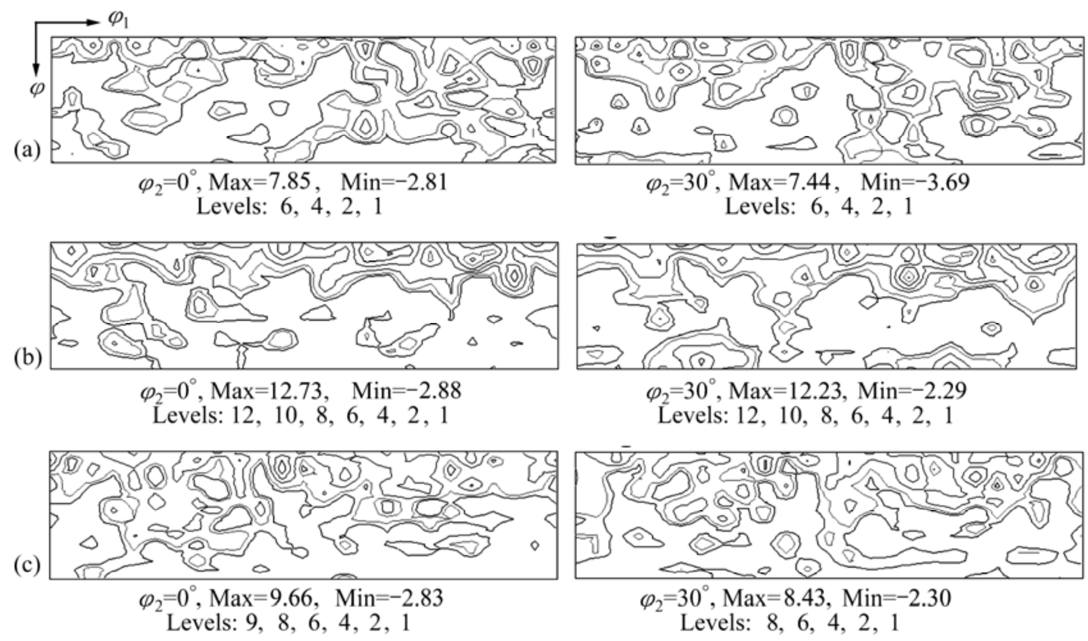

Fig.5 ODF figures showing textures of AZ31B magnesium alloy sheets undergoing RUB followed by annealing at 533 K: (a) RUB at RT + annealing at 533 K; (b) RUB at 473 K + annealing at 533 K; (c) RUB at 673 K + annealing at 533 K

Table 1 Mechanical properties of magnesium alloy sheets under different states

State	$\sigma_{0.2}$/MPa	σ_b/MPa	δ/%	$\sigma_{0.2}/\sigma_b$	Erichsen value/mm
Cold-rolled	139.2	235.6	14.21	0.59	3.96
RUB at RT	85.2	197.1	25.3	0.43	5.90
RUB at 473 K	105.4	224.8	11.28	0.47	4.88
RUB at 673 K	81.8	221.6	9.03	0.36	4.17

Sheets undergoing RUB were annealed at 533 K for 60 min

The mechanical properties of the magnesium alloy sheet undergoing RUB at RT followed by annealing were discussed in previous work[14−15]. Compared with the cold-rolled sheet, its average grain size had little change. Thus, the improvement of mechanical properties was mainly attributed to the change of grain orientation. For the magnesium alloy sheets with title basal texture, the activation of basal slip leading to the dynamic recovery tended to be depressed due to the limited non-basal slips and a high work-hardening was maintained. Further, the $(10\bar{1}2)$ extension twin could be activated in the early stage of deformation[21]. Some researches[22−23] showed that the activation of extension twin can appear to increase the uniform elongation and decrease the proof strength in tensile tests. BOHLEN et al[24] found the improvement of elongation and described that this texture provided the favored orientation for $\{10\bar{1}2\}$ extension twinning, which induced the increase in work hardening and in turn led to a larger uniform elongation. For the magnesium alloy sheet undergoing RUB at 473 K followed by annealing, the basal texture component increased and the pyramidal texture components weakened compared with the magnesium alloy sheet undergoing RUB at RT followed by annealing. Though the $(01\bar{1}0)$ texture component was easy to activate extension twin (about 86° rotated from the parent grain[22]), which could decrease the yield strength under uniaxial tension, the basal slip was still harder to activate. Thus, the mechanical properties were worse. The texture components of the magnesium alloy sheet undergoing RUB at 673 K followed by annealing at 533 K were similar to those of the magnesium alloy sheet undergoing RUB at RT followed by annealing. The texture components were favorable to the formability of magnesium alloy sheets, but the mechanical properties were worse due to coarse grains. Researches[25−26] indicated that the relation of strength and the grain size is in accordance with Hall-Petch relation for magnesium alloys; in other words, the yield strength tends to decrease with the increase of grain size. The grain refinement increases the barrier of dislocation movement and decreases the length of dislocation pile-up within grain, thus the yield strength increases. For the magnesium alloy sheet with fine grains, the non-basal slips are suppressed in the early stage of deformation due to the activation of basal slip, and a higher work-hardening is maintained. With the increase of the stress concentration, the prismatic slip is activated and attributes to a width strain[27]. Thereby, a large elongation is obtained. For the magnesium alloy sheets with coarse grains, the dislocation glide path is larger and the non-basal slips are hard to activate, thus the severe stress concentration near the grain boundary leads to the formation of a large number of twins[20, 27]. Work-hardening rate will rapidly decrease during the formation of these twins[27] and the elongation is very low. At present, the studies about interaction of texture and grain size on the Erichsen value are few. In Ref.[21], it is thought that the higher Erichsen value for the DSR processed sheet can be attributed to the larger uniform elongation and the lower *r*-value. For the magnesium alloy sheets undergoing RUB at 473 K and 673 K followed by annealing, the elongation is lower than that of the cold-rolled sheets; however, the Erichsen value is slightly higher than that of the cold-rolled sheet. The phenomenon can be due to the change of grain orientation. And with the increase of RUB temperature, the tensile ratio tends to decrease. The lower tensile ratio can lead to a larger Erichsen value. However, the detailed deformation mechanism is not very clear for the Erichsen value, and will be an interesting topic for further researches. When the RUB is carried out above recrystallization temperature, the gradient of through-thickness microstructure is very obvious. It is very necessary to research the mechanical properties of the magnesium alloy sheet with sandwich microstructure for further enriching the plastic deformation mechanism.

4 Conclusions

1) With the increase of RUB temperature, the grain size near the surface of magnesium alloy sheets undergoing RUB tended to grow up. As the RUB temperature increased to 673 K, all of the through-thickness grains grew up.

2) The RUB processed at medium-high temperature could still improve the basal texture of magnesium alloy sheet. The texture components of the magnesium alloy sheet undergoing RUB at recovery temperature were similar to those of the magnesium alloy sheet undergoing RUB at RT. As the RUB temperature increased to above recrystallization temperature, the texture components became more disperse and the pyramidal components increased.

3) RUB above recrystallization temperatures led to strong grain growth. Thus, the mechanical properties were degraded and the formability was improved slightly.

4) RUB at medium-high temperatures with complex working procedure was hard to operate. And it had very limited improvement for the mechanical properties of cold-rolled magnesium alloy sheet. Therefore, the RUB at RT was more realistically significant.

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