

Mechanical Properties and Press Formability at Room Temperature of AZ31 Mg Alloy Processed by Single Roller Drive Rolling

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Mechanical properties and press formability at room temperature of AZ31 Mg alloy processed by single roller drive rolling were compared with those of the one processed by normal rolling. The single roller drive rolled specimens showed the weaker intensity of (0002) texture. As a result of tensile tests, there was no difference in unidirectional elongation between them. However, results of conical cup tests show that the press formability of the single roller drive rolled specimen was rather better. The planar anisotropy was lower and twins were observed for the single roller drive rolled specimen, indicating that the weaker intensity of texture leads to twinning, resulting in the lower planar anisotropy.

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1. Introduction

Deformation modes of Mg crystals are mainly the (0001){11 $\bar{2}$ 0} basal slip, the {10 $\bar{1}$ 0}{11 $\bar{2}$ 0} prismatic slip, the {10 $\bar{1}$ 1}{11 $\bar{2}$ 0} pyramidal slip, the {11 $\bar{2}$ 2}{11 $\bar{2}$ 3} second-order pyramidal slip and the {10 $\bar{1}$ 2}{10 $\bar{1}$ 1} twinning.^{1,2} The critical resolved shear stresses for the non-basal slips of the prismatic and pyramidal slips are much larger than that for the basal slip at room temperature,^{3,4} and hence the non-basal slips are hardly operative at room temperature. Five independent slip systems are necessary for a polycrystalline material to be able to undergo a general homogeneous deformation without producing cracks. However, the number of independent mode for the basal slip is only 2.¹ This leads to poor formability at room temperature for a polycrystalline Mg and its alloys.

The flow stress is strongly affected by the grain size for hcp metals such as Mg, compared to that for fcc and bcc metals, due to the lack of slip systems.⁵⁻⁷ This indicates that grain refinement is effective for high strength in Mg and its alloys. Furthermore, it was shown that grain refinement leads not only to high strength, but also to high ductility for Mg alloys.⁷⁻⁹ Some works¹⁰⁻¹³ showed that grain refinement is attained by plastic forming processing such as hot rolling, extrusion, pressing and forging. Hence, Mg alloys fabricated by plastic forming processes exhibit a good combination of high strength and high ductility. However, the plastic forming processes cause a strong intensity of texture for Mg alloys.^{14,15} The intensive texture gives rise to anisotropy of mechanical properties. This results in poor press formability of rolled Mg sheets. Therefore, it is important not only to attain grain refinement, but also to control the texture for improvement of pressing formability at room temperature for Mg alloys.

Recently, it was shown that single roller drive rolling is one of effective methods for control of texture in Al and its alloys.^{16,17} Thus, aims of the present paper are to attain both

grain refinement and control of texture by single roller drive rolling and to improve the press formability of a rolled AZ31 Mg alloy. In the present investigation, mechanical properties and press formability at room temperature of the Mg alloy processed by single roller drive rolling are compared with those of the one processed by normal rolling by tensile tests and conical cup tests.

2. Experimental Procedure

An AZ31 (Mg–3 mass% Al–1 mass% Zn–0.15 mass% Mn) alloy ingot was prepared. The ingot was annealed at 691 K for 2.6×10^5 s. Blocks with 7 mm in thickness and 45 mm in breadth were cut from the annealed ingot. The blocks were rolled from 7 mm to 1 mm in thickness at 473, 523, 573, 623 and 673 K by single roller drive rolling. The rolling reduction was 85.7%. For comparison, normal rolling, namely, two rollers drive rolling where each rolling speed was the same was conducted under the same conditions. Some of the rolled specimens were annealed at 673 K for 1.8×10^3 s.

Microstructures of the RD-TD plane, the ND-RD plane and the TD-ND plane of the rolled sheets were observed by optical microscope, where the RD is the rolling direction, the TD is the transverse direction and the ND is the normal direction. From the measurement of the apparent grain size of each plane by the intercept method, the grain size was determined by

$$d = 1.73 \times (d_{RT} \times d_{NR} \times d_{TN})^{1/3} \quad (1)$$

where d is the grain size, d_{RT} is in the RD-TD plane, d_{NR} is in the ND-RD plane and d_{TN} is in the TD-ND plane. The (0002) and (10 $\bar{1}$ 1) pole figures of the RD-TD plane in the specimens rolled at 673 K were measured at the position of the depth of about 0.2 mm from the surface.

Tensile specimens with 10 mm in gauge length, 5 mm in gauge breadth and 1 mm in gauge thickness were machined from the rolled sheets. Tensile tests were carried out at room

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temperature, where the angle between the tensile direction and the rolling direction was 0 deg. Additional tensile tests were conducted for the specimens rolled at 673 K, where the angle between the tensile direction and the rolling direction was 45 deg and 90 deg to investigate the anisotropy of tensile properties. The Lankford value (r -value) for each direction was measured on the specimens deformed to $\varepsilon = 5\%$.

Specimens with 50 mm in diameter and 1 mm in thickness were machined from the sheets rolled at 673 K. Conical cup tests were carried out at room temperature to investigate the press formability, as shown in Fig. 1. The forming speed was 60 mm/min. Microstructures of the specimens deformed to failure by conical cup tests were observed by optical microscopy.

3. Results

3.1 Microstructure

Microstructure of the specimen prior to rolling is shown in Fig. 2. The grain size was 91 μm . Microstructures of the as-

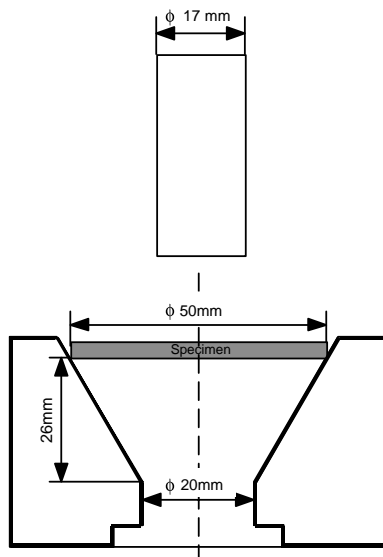


Fig. 1 Schematic illustration of the conical cup test.

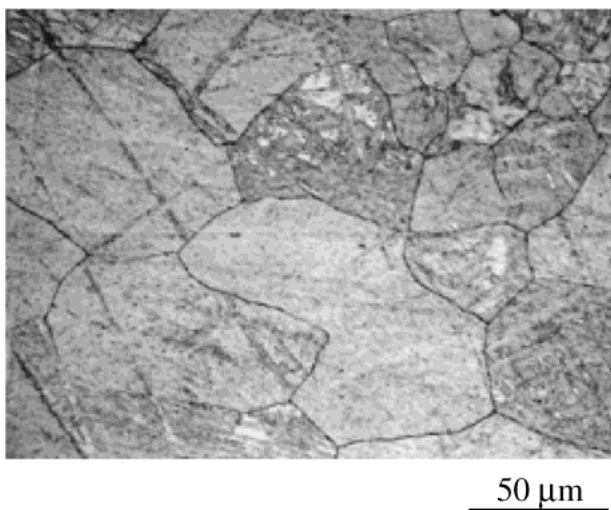


Fig. 2 Microstructure of the specimen prior to rolling.

rolled specimens processed by single roller drive rolling are shown in Fig. 3, where the RD-TD plane is observed. The rolling temperature is (a) 473 K, (b) 573 K and (c) 673 K, respectively. The grains of the rolled specimens were not elongated to the rolling direction and the grain sizes were smaller than that of the specimen prior to rolling, indicating dynamic recrystallization occurred by rolling. Microstructure of the normal rolled specimens at each rolling temperature was al-

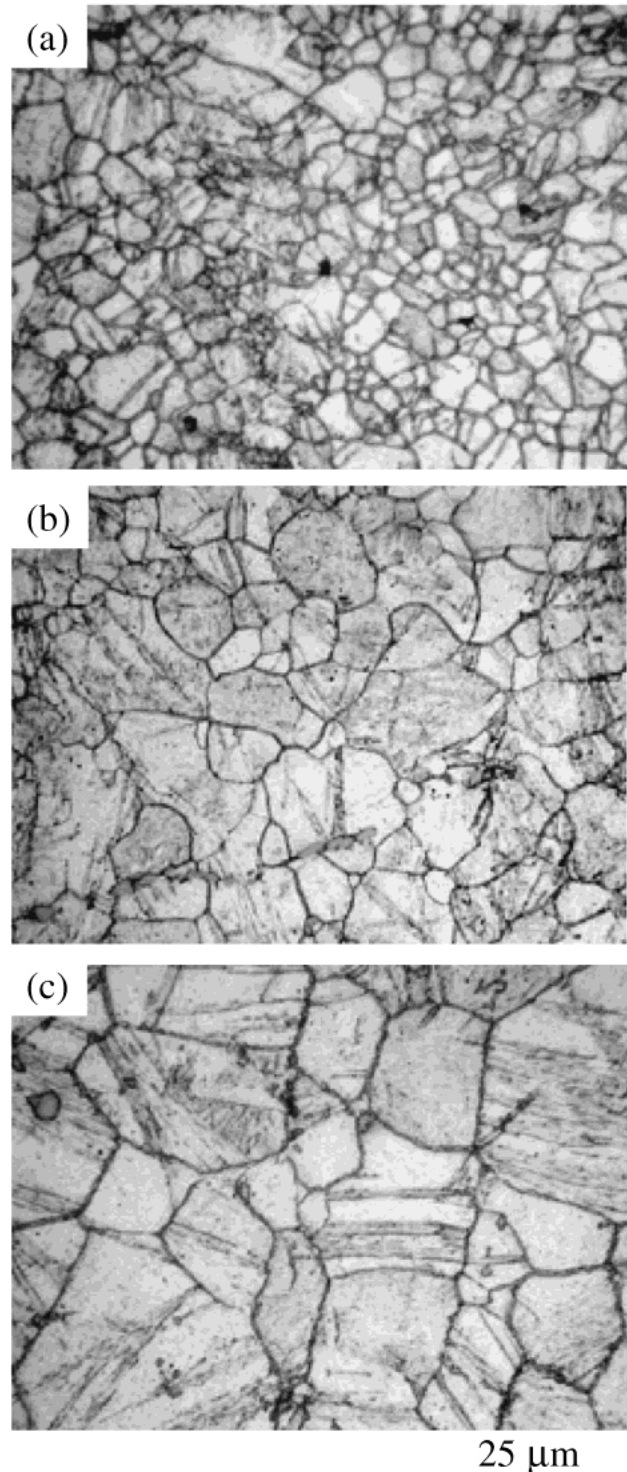


Fig. 3 Microstructures of the as-rolled specimens processed by single roller drive rolling, where the RD-TD plane is observed. The rolling temperature is (a) 473 K, (b) 573 K and (c) 673 K.

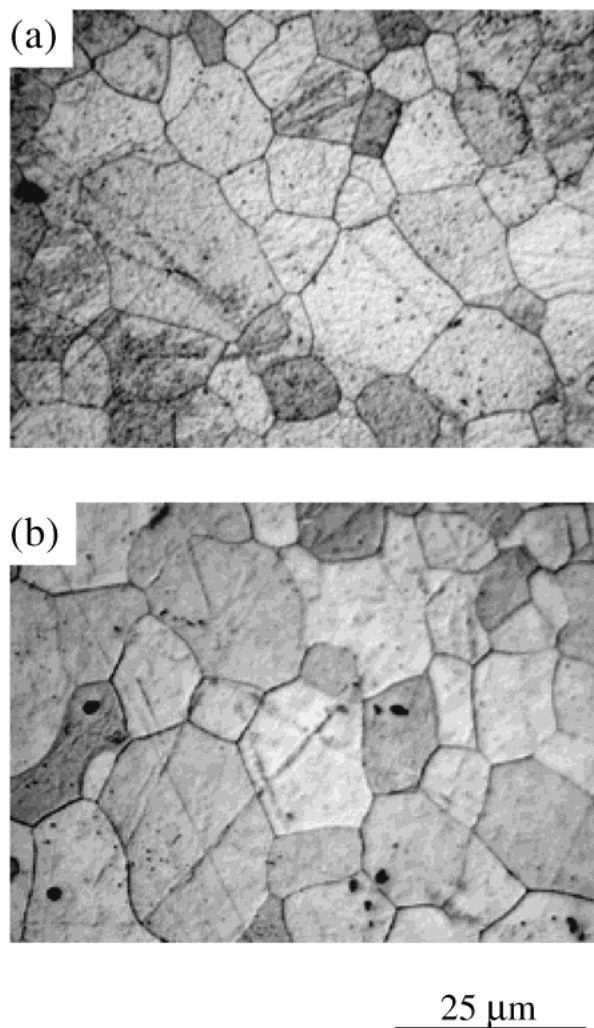


Fig. 4 Microstructures of the annealed specimens processed by single roller drive rolling at (a) 473 K and (b) 673 K, where the RD-TD plane is observed. The annealing is conducted at 673 K for 1.8×10^3 s.

most the same as that of the single roller drive rolled specimens.

Microstructures of the annealed specimens processed by single roller drive rolling at (a) 473 K and (b) 673 K are shown in Fig. 4, where the RD-TD plane is observed. The annealing was conducted at 673 K for 1.8×10^3 s. Grain growth occurred by annealing for the specimen rolled at 473 K, on the other hand, little grain growth occurred for the specimen rolled at 673 K. As a result, the grain size of the annealed specimen which was rolled at 473 K was almost the same as that of annealed specimen which was rolled at 673 K. Microstructure of the annealed specimens processed by the normal rolled specimens at each rolling temperature was almost the same as that of the single roller drive rolled specimens. Thus, there was not large difference in grain growth characteristics as well as grain refinement between the single roller drive rolled specimens and the normal rolled specimens.

The grain size of the as-rolled specimens and the annealed specimens processed by single roller drive rolling and normal rolling is listed in Table 1. Concerning to the as-rolled specimen and the annealed specimen, there was not large difference in grain size of the ND-RD plane and TD-ND plane as well as the RD-TD plane between the single roller drive rolled

Table 1 The grain size of the as-rolled specimens and the annealed specimens by single roller drive rolling and by normal rolling.

Rolling temperature (K)	Grain size (μm)			
	Single roller drive rolling		Normal rolling	
	As-rolled specimen	Annealed specimen	As-rolled specimen	Annealed specimen
473	5.0	19.0	5.2	17.3
523	6.0		6.4	
573	7.6		12.2	
623	10.7		13.9	
673	17.3	17.8	21.5	19.4

specimen and the normal rolled specimen when the rolling temperature was the same. On the other hand, the grain size was strongly affected by the rolling temperature concerning to the as-rolled specimen.

The (0002) and (10 $\bar{1}$ 1) pole figures of the single roller drive rolled specimen and the normal rolled specimen are shown in Fig. 5 and Fig. 6 for the specimens rolled at 673 K, respectively. The basal plane tended to be parallel to the RD-TD plane for the normal rolled specimen, however, the basal plane tended to incline at about 10 deg to the RD-TD plane for the single roller drive rolled specimen. Furthermore, it is of interest to note that the intensity of (0002) texture for the single roller drive rolled specimen was weaker than that for the normal rolled specimen. On the other hand, for the (10 $\bar{1}$ 1) pole figures, there was not large difference in intensity of texture between the single roller drive rolled specimen and the normal rolled specimen. These trends about texture of the rolled specimens did not change by annealing.

3.2 Tensile tests

The 0.2% proof stress, ultimate tensile strength and elongation to failure by tensile tests are shown in Table 2 for the as-rolled specimens processed by the single roller drive rolling and by the normal rolling and also for the annealed specimens processed by the same procedure, respectively. It should be noted that the single roller drive rolled specimens showed the lower 0.2% proof stress than the normal rolled specimens. The 0.2% proof stress decreased with rolling temperature for the as-rolled specimens. However, it hardly changed with rolling temperature for the annealed specimens. This is attributed to grain growth by annealing. The single roller drive rolled specimens showed a little lower ultimate tensile strength than the normal rolled specimens. The ultimate tensile strength hardly changed with rolling temperature for both the as-rolled specimens and the annealed specimens. There was not difference in elongation to failure between the single roller drive rolled specimens and the normal rolled specimens. The elongation was significantly increased by annealing for both the specimens. Thus, although, there was large difference in 0.2% proof stress between the single roller drive rolled specimens and the normal rolled specimens, difference in ultimate tensile strength and elongation between them was rather small or negligible.

The relationship between the 0.2% proof stress for a polycrystalline metal and the grain size can be given by

$$\sigma_{0.2} = \sigma_0 + Kd^{-1/2} \quad (2)$$

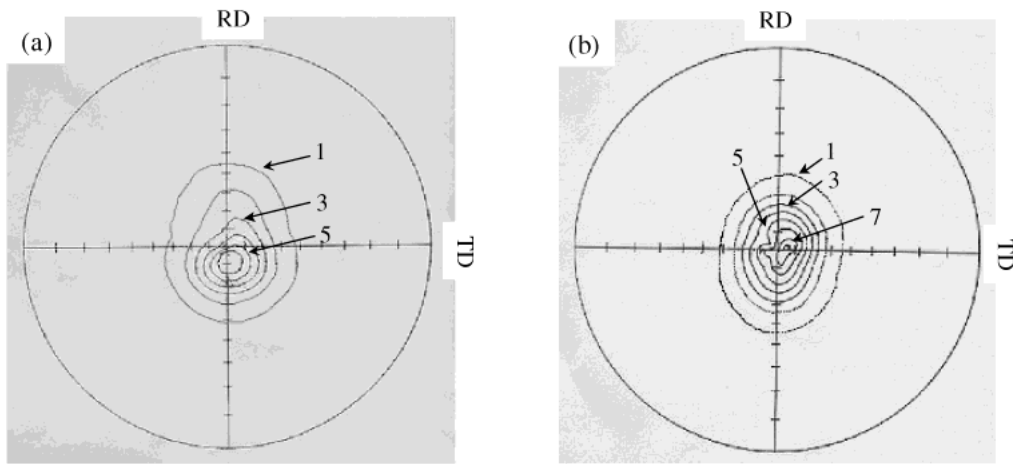


Fig. 5 The (0002) pole figures of (a) the single roller drive rolled specimen and (b) the normal rolled specimen for the specimens rolled at 673 K.

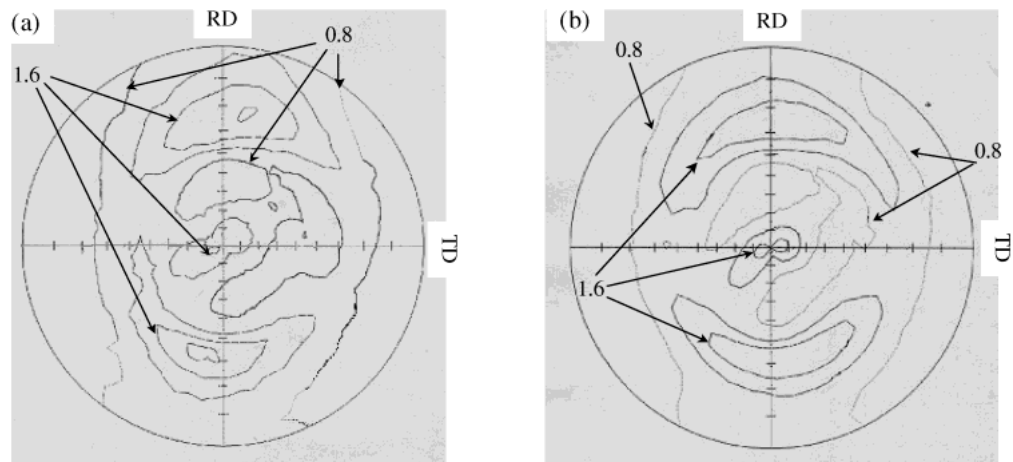


Fig. 6 The (10 $\bar{1}1$) pole figures of (a) the single roller drive rolled specimen and (b) the normal rolled specimen for the specimens rolled at 673 K.

Table 2 The 0.2% proof stress, ultimate tensile strength and elongation to failure by tensile tests for the as-rolled specimens and the annealed specimens by single roller drive rolling and by normal rolling.

	Rolling temperature (K)	0.2% Proof stress (MPa)		Tensile strength (MPa)		Elongation (%)	
		As-rolled	Annealed	As-rolled	Annealed	As-rolled	Annealed
Single roller drive rolling	473	152	127	276	240	6	38
	523	139	98	242	229	16	22
	573	126	119	258	225	10	30
	623	113	120	260	216	7	28
	673	99	125	252	245	11	30
Normal rolling	473	187	127	276	240	10	39
	523	181	131	291	252	14	26
	573	162	141	276	250	5	34
	623	145	123	252	283	11	34
	673	137	136	269	243	4	27

where $\sigma_{0.2}$ is the 0.2% proof stress for a polycrystalline metal σ_0 is the stress the slip band could sustain if there were no resistance to slip across grain boundaries, K is a constant and d is the grain size. The variation in 0.2% proof stress as a function of the inverse of square root of grain size is shown in Fig. 7 for the as-rolled specimens. Inspection of Fig. 7 reveals that the difference in 0.2% proof stress between the single

roller drive rolled specimen and the normal rolled specimen is attributed to the difference in stress the slip band could sustain if there were no resistance to slip across grain boundaries. The difference in stress the slip band could sustain if there were no resistance to slip across grain boundaries is likely to be related to the difference in texture.¹⁴⁾

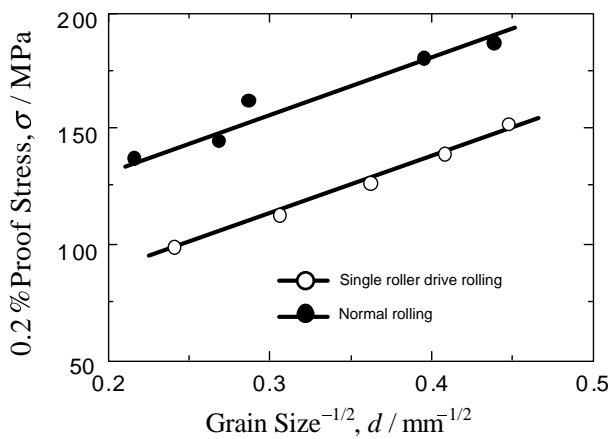


Fig. 7 The variation in 0.2% proof stress as a function of the inverse of square root of grain size for the as-rolled specimens.

3.3 Conical cup tests

Press formability at room temperature was investigated by conical cup tests on the specimens rolled at 673 K. The result is summarized in Fig. 8 for (a) the as-rolled specimen processed by single roller drive rolling, (b) the annealed specimen processed by single roller drive rolling and (c) the annealed specimen processed by normal rolling, respectively. For the single roller drive rolled specimens, sufficient forming was not attained for the as-rolled specimen, as shown in (a), but the formability was improved by annealing, as shown in (b). It should be noted that the single roller drive rolled specimen exhibited rather better formability than the normal rolled specimen as shown in (c).

Thus, the conical cup tests showed that the press formability of the single roller drive rolled specimen was rather better than that of the normal rolled specimen. From the results of tensile tests, as shown in Table 2, where the angle between the tensile direction and the rolling direction was 0 deg, the difference in elongation between them was negligible. Clearly, the press formability does not correspond to the unidirectional ductility.

4. Discussion

It is known that press formability is related to the strain-hardening exponent (*n*-value) and the Lankford value (*r*-value). The true stress-true strain curves of the annealed specimens processed by single roller drive rolling and by normal rolling at 673 K are shown in Fig. 9. From Fig. 9, the *n*-value of the single roller drive rolled specimen was almost the same as that of the normal rolled specimen.

To investigate the *r*-value, additional tensile tests were conducted for the specimens rolled at 673 K, where the angle between the tensile direction and the rolling direction was 45 deg and 90 deg. The *r*-value for the specimens rolled at 673 K is listed in Table 3. It is important to investigate the anisotropy of the *r*-value because the anisotropy of flow characteristics leads to poor formability. The average *r*-value and planar anisotropy may be given by¹⁷⁾

$$\bar{r} = (r_0 + r_{90} + 2r_{45})/4 \quad (3)$$

$$\Delta r = (r_0 + r_{90} - 2r_{45})/2 \quad (4)$$

Table 3 The *r*-value for the specimens rolled at 673 K.

	Angle*	Single roller drive rolling	Normal rolling
As-rolled	0 deg	0.56	0.14
	45 deg	1.57	2.62
	90 deg	1.13	1.14
Annealed	0 deg	1.08	1.30
	45 deg	3.00	2.50
	90 deg	2.90	1.05

*The angle between the tensile direction and the rolling direction.

where \bar{r} is the average *r*-value, Δr is the planar anisotropy, r_0 is the *r*-value where the angle between the tensile direction and the rolling direction is 0 deg, r_{45} is the *r*-value for the angle of 45 deg and r_{90} is for 90 deg. The average *r*-value and planar anisotropy are listed in Table 4 for the specimens processed by single roller drive rolling and by normal rolling at 673 K. It should be noted that the average *r*-value is large and the absolute value of planar anisotropy is low for the annealed specimen processed by single roller drive rolling, compared to those for other specimens except the *r*-value of the as-rolled specimen processed by single roller drive rolling. Therefore, it is likely that not only the large average *r*-value, but also the low planar anisotropy lead to improvement of press formability for the annealed specimen processed by single roller drive rolling.

The number of independent modes for the basal slip in hcp metals is 2.¹⁾ Hence, it is required to accommodate discontinuity of flow due to the lack of slip systems by twinning for a polycrystalline Mg.^{1,18)} Microstructures of the specimens formed by the conical cup tests are shown in Fig. 10, where (a) the annealed specimen processed by single roller drive rolling at 673 K and (b) the annealed specimen processed by normal rolling at 673 K. It is of interest to note that twins were observed in many grains for the single roller drive rolled specimen, however, no twins were observed for the normal rolled specimen. As shown in Fig. 5, single roller drive rolling served to reduce the intensity of (0002) texture, compared to normal rolling. Therefore, it is suggested that the weaker intensity of (0002) texture leads to twinning as accommodation of slip deformation, resulting in the low planar anisotropy for the single roller drive rolled specimen. This points out the importance of control of texture for improvement of press formability at room temperature for Mg based materials.

5. Conclusions

Mechanical properties and press formability at room temperature of AZ31 Mg alloy processed by single roller drive rolling were compared with those of the one processed by normal rolling using tensile tests and conical cup tests. The results are concluded as follows.

(1) The single roller drive rolled specimen showed the weaker intensity of (0002) texture than the normal rolled specimen. On the other hand, the grain size of the single roller drive rolled specimens was almost the same as that of the normal rolled specimens.

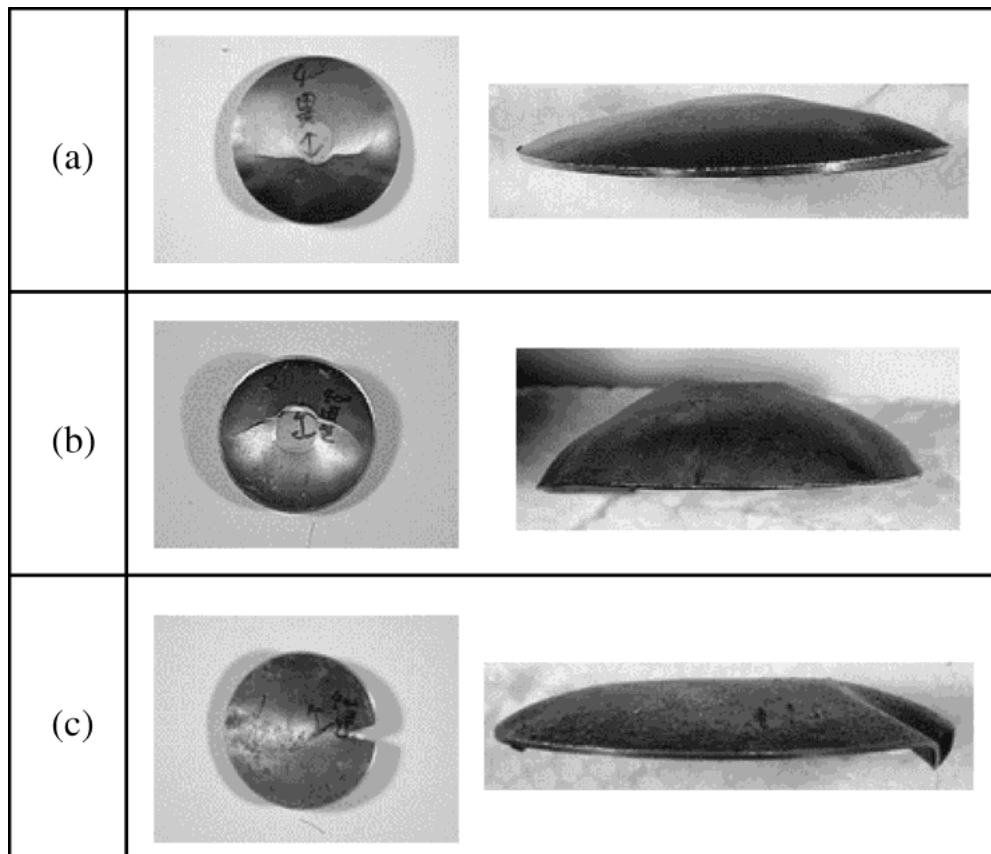


Fig. 8 The results of the conical cup tests for (a) the as-rolled specimen processed by single roller drive rolling at 673 K, (b) the annealed specimens processed by single roller drive rolling at 673 K and (c) the annealed specimens processed by normal rolling at 673 K.

Table 4 The average r -value and planar anisotropy for the specimens processed by single roller drive rolling and by normal rolling at 673 K.

	Average r -value		Planer anisotropy	
	Single roller drive rolling	Normal rolling	Single roller drive rolling	Normal rolling
As-rolled	1.2	1.6	-0.8	-2.0
Annealed	2.5	1.8	-1.0	-1.3

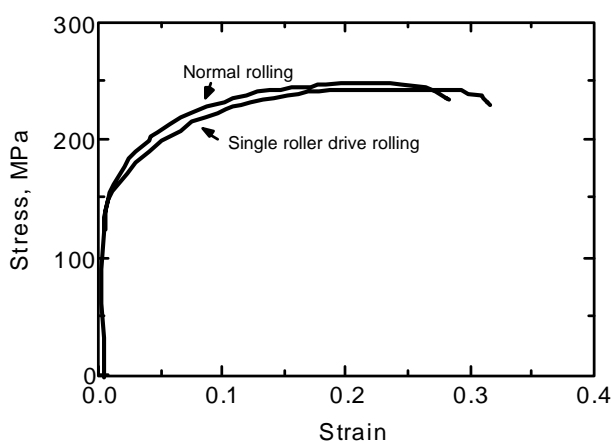


Fig. 9 The true stress-true strain curves of the annealed specimens processed by single roller drive rolling and by normal rolling at 673 K.

(2) The single roller drive rolled specimens showed the lower 0.2% proof stress than the normal rolled specimens.

This is likely to be related to the difference in intensity of texture. On the other hand, the difference in unidirectional elongation between them was negligible.

(3) The conical cup tests showed that the press formability of the single roller drive rolled specimen was rather better than that of the normal rolled specimen. Clearly, the press formability did not correspond to the unidirectional ductility.

(4) The average r -value was large and the planar anisotropy was low for the single roller drive rolled specimen, compared to for the normal rolled specimen. This resulted in improvement of the press formability by single roller drive rolling.

(5) Twins were observed for the single roller drive rolled specimen formed by the conical cup test, however, no twins were observed for the normal rolled specimen. Therefore, it is suggested that the weaker intensity of (0002) texture leads to twinning as accommodation of slip deformation, resulting in the low planar anisotropy for the single roller drive rolled specimen.

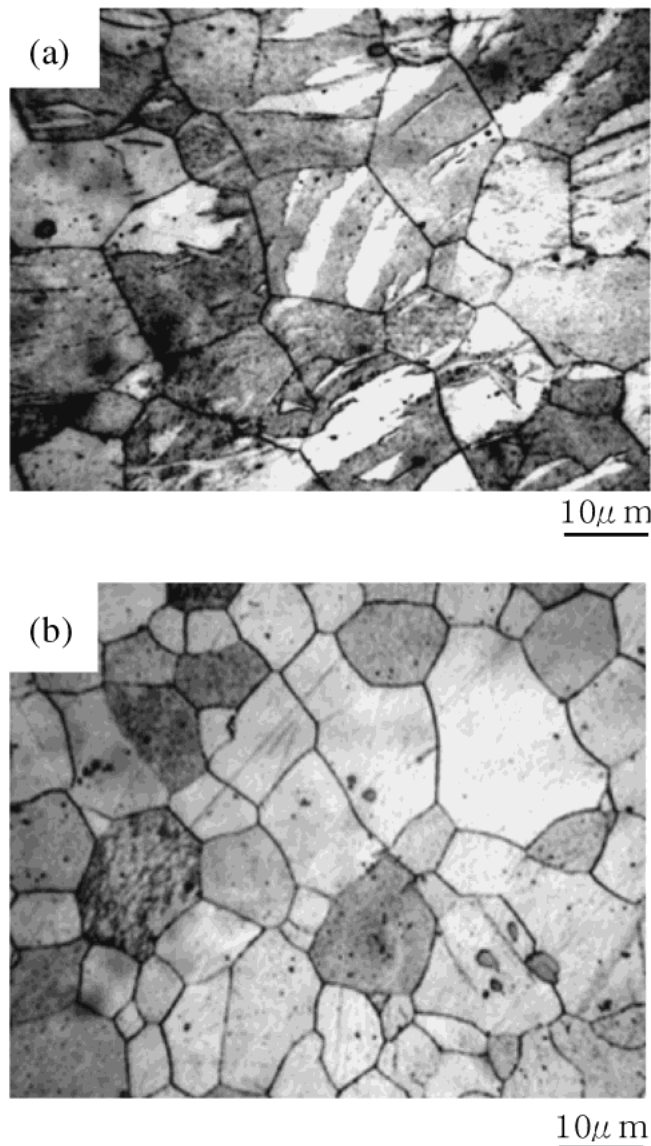


Fig. 10 Microstructures of the specimens formed by the conical cup tests, where (a) the annealed specimen processed by single roller drive rolling at 673 K and (b) the annealed specimen processed by normal rolling at 673 K.

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