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Effect of Texture of AZ31 Magnesium Alloy Sheet on Mechanical Properties and Formability at High Strain Rate

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The mechanical properties and formability of AZ31 magnesium alloy strips having different textures were investigated at a high strain rate based on that occuring in mass production by press forming. Forming at a high strain rate on the order of $10^0\,s^{-1}$ requires a high temperature of over 473 K. To obtain accurate stress-strain curves, a high-speed testing machine that can maintain a constant true strain rate was used, and the change in gauge length on a test piece in a furnace was measured during the testing time of about 0.5 s. For the specimens, rolled strips consisting of fine grains (about 10 µm) and an extruded strip consisting of coarse grains (about 40 µm) were used. The {0001} textures of the extruded strip and one of the rolled strips were strongly oriented parallel to the rolled surface, but the texture of another rolling strip had two peaks that were inclined at 5 ~ 15 deg in front of and behind the rolling direction. At the high strain rate of $10^0\,s^{-1}$, elongation decreased for every specimen. Nevertheless, a limiting drawing ratio (LDR) of 2.1 ~ 2.2 was obtained under uniform heating above 503 K in all the specimens except for the extruded strip. The high LDR of the rolled strip having a two-peak texture was maintained in forming at temperatures down to 473 K, in contrast to the LDR of the strongly oriented rolled strip, which reduced rapidly when formed at temperatures less than 503 K.
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1. Introduction

When magnesium alloys began to attract attention as the next generation of light structural materials, the press forming of AZ31 alloy sheet also began to be studied for productivity improvement.[1–10)] The evaluation of formability,[10,11)] sheet processing for formability improvement[12,13)] and the anisotropy (formation of texture)[14–17)] were also simultaneously studied. Although low-speed forming in laboratories was easily accomplished by heating to 473 K,[2,3)] high-speed forming for mass production was difficult to achieve, even at higher temperatures. Moreover, the success of forming was strongly dependent on raw material quality. Recently, excellent formability of an AZ31 rolled strip, which has a different characteristic texture from conventional rolled sheets, has been confirmed.

In industrial production using a mechanical press, we need to consider a high strain rate of at least $10^0\,s^{-1}$. However, an accurate strain measurement under high-speed deformation in a furnace is very difficult. The material-testing machine developed for this study has a maximum crosshead speed of $100\,mm\cdot s^{-1}$ and can accurately measure the gauge length of a tensile specimen deforming at a high strain rate in a furnace. Press forming with heating is so sensitive to strain rate that a constitutive equation that can be faithfully describe a deformation under practical working conditions is essential for advanced simulations for process design.

In this paper, the tensile properties and press formability of commercial AZ31 alloy strips at high strain rate and high temperature were studied, and their association with textures was clarified.

2. Specimens, Apparatuses and Experimental Conditions

AZ31 magnesium alloy strips of 0.8 mm thickness produced by different manufacturers were used. These had little difference in chemical composition, as shown in Table 1. Among the strips, A and B were rolled strips and C was an extruded strip. They were used for several tests after homogenized annealing at 573 K for 1800 s.

The special testing machine, as shown in Fig. 1, was designed to realize a high strain rate of $10^0\,s^{-1}$. The maximum load was 20 kN and the maximum crosshead speed was $100\,mm\cdot s^{-1}$. The true strain rate under an assumption of uniform elongation was regulated by the feedback of measured elongation to the crosshead speed. Since the time to fracture was as short as only about 0.5 s at a strain rate of $10^0\,s^{-1}$, the crosshead caught the test piece after reaching the setting rate.

Table 1 Chemical composition of specimens.

(mass%)

Specimen	Al	Zn	Mn	Fe	Ni	Mg
A	3.1	0.9	0.36	0.0025	0.0008	Bal.
B	3.02	1.06	0.39	0.004	0.0005	Bal.
C	3.09	0.83	0.38	0.0032	0.001	Bal.

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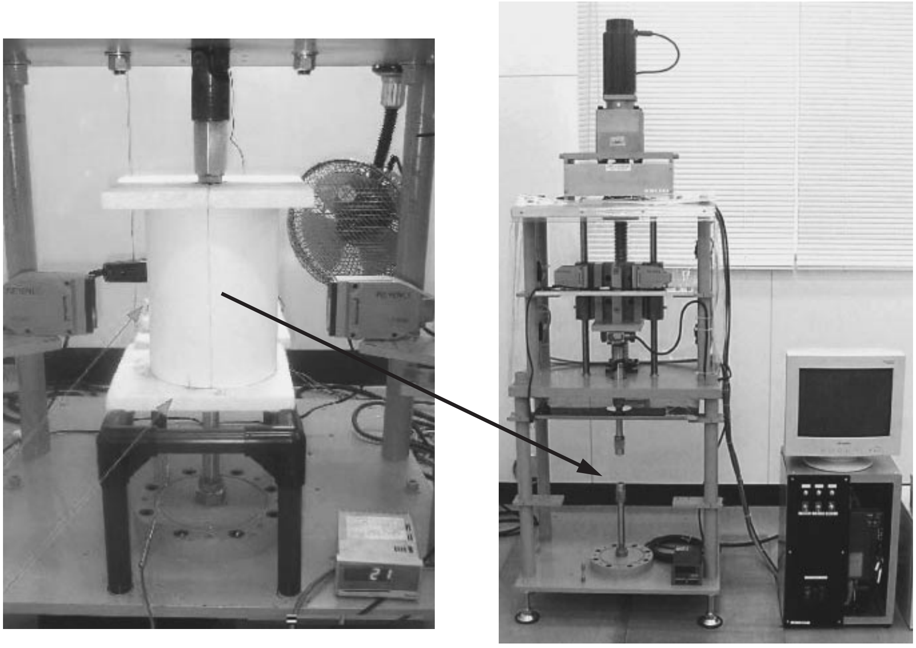

Fig. 1 High-speed tensile testing machine.

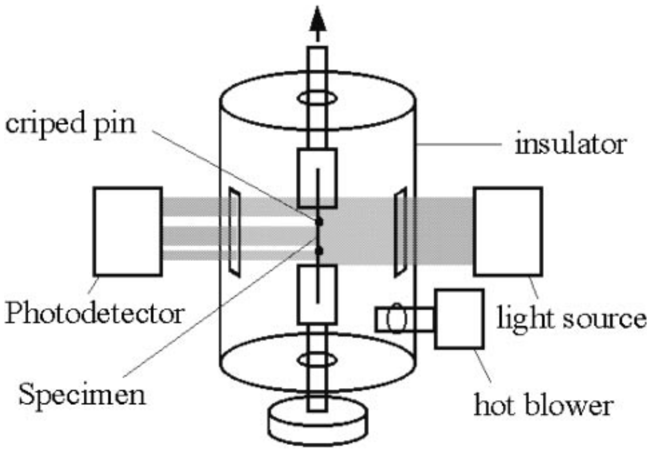

Fig. 2 Strain measurement system in furnace.

Figure 2 shows the developed strain measurement system, which could accurately measure elongation in a furnace using a non contact extensometer. The furnace had slits, and the gauge length was measured by interrupting a band of light-emitting diode (LED) light using two pins clipped to the test piece. The high sampling rate of $2400\,s^{-1}$ was also important for high-speed tests. The practical true strain rate was verified from saved strain data together with elapsed times. The test piece was heated uniformly by blowing hot air into the furnace, and the temperature was measured using a thermocouple in contact with the test piece. The tensile tests were carried out at $473 \sim 573\,K$ at a constant strain rate of $1 \times 10^{-2} \sim 1 \times 10^{0}\,s^{-1}$.

As a press formability test, a deep drawing test was performed. The equipment[2,3] was heated uniformly in a furnace and pressed by a testing machine. The punch diameter, punch profile radius and die profile radius were 15, 2 and 4 mm, respectively. Under these conditions, the ratio of punch profile radius to thickness, 2.5, was so small that a stretch bending on the punch shoulder predominated the forming limit. As a lubricant, molybdenum disulfide paste was used. The drawing rate was $1000\,mm{\cdot}min^{-1}$, which corresponded to a maximum strain rate of about $1 \times 10^{0}\,s^{-1}$.

3. Experimental Results and Discussion

3.1 Microstructures and textures

Figure 3 shows the microstructures of the annealed strips. All of strips consist of isometric crystal grains. The average grain size of the extruded strip C (about 40 μm) is significantly larger than that of A or B (about 10 μm).

Figure 4 shows the textures of the sheet surfaces as {0001} pole figures. The textures of rolled strips A and B are clearly different. The texture of A is broken into two peaks inclined to the rolling direction and the reverse direction; that of B consists of concentric rings strongly oriented at the center, which is the usual rolling texture of this alloy. That of C shows a stronger orientation, although its low level curve is extended vertically in the extruding direction. The difference between A and B in texture may be due to rolling temperature and reduction, which will be presently clarified.

3.2 Tensile characteristics

Figure 5 shows the nominal stress-strain relationships at 523 K and strain rates of 1×10^{-1} and $1 \times 10^{0}\,s^{-1}$. For each strain rate, a high temperature leads to decreases in proof stress and tensile strength and to an increase in elongation. For each temperature, a high strain rate leads to increases in proof stress and tensile strength and to a decrease in elongation. On the whole, rolled strip A having a two-peak texture, had lower strength and greater elongation than rolled strip B, having a concentric texture. The extruded strip had the highest strength and the smallest elongation, and it is considered that the significantly lower elongation was caused by the markedly coarser grain.

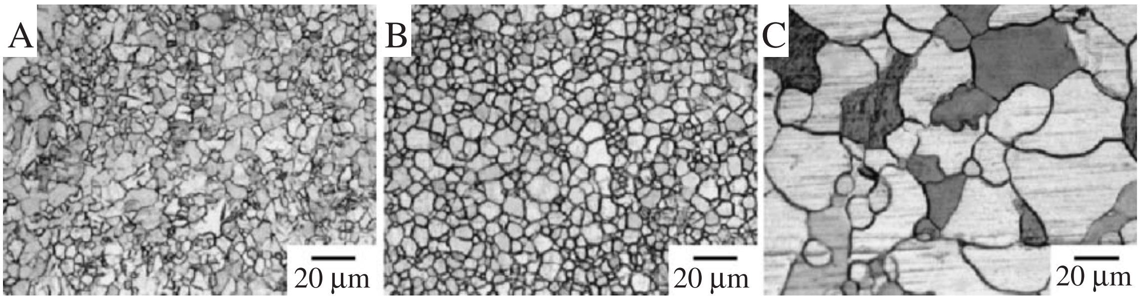

Fig. 3 Microstructures of specimens after annealing.

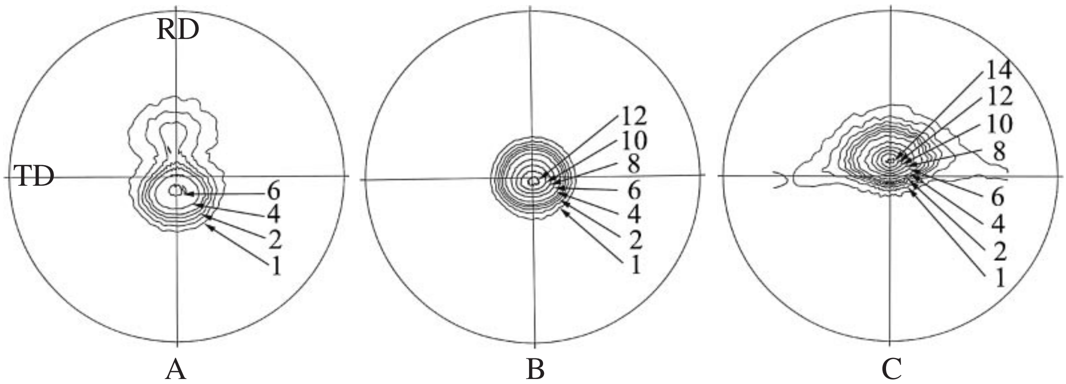

Fig. 4 {0001} pole figures of sheet surfaces of specimens.

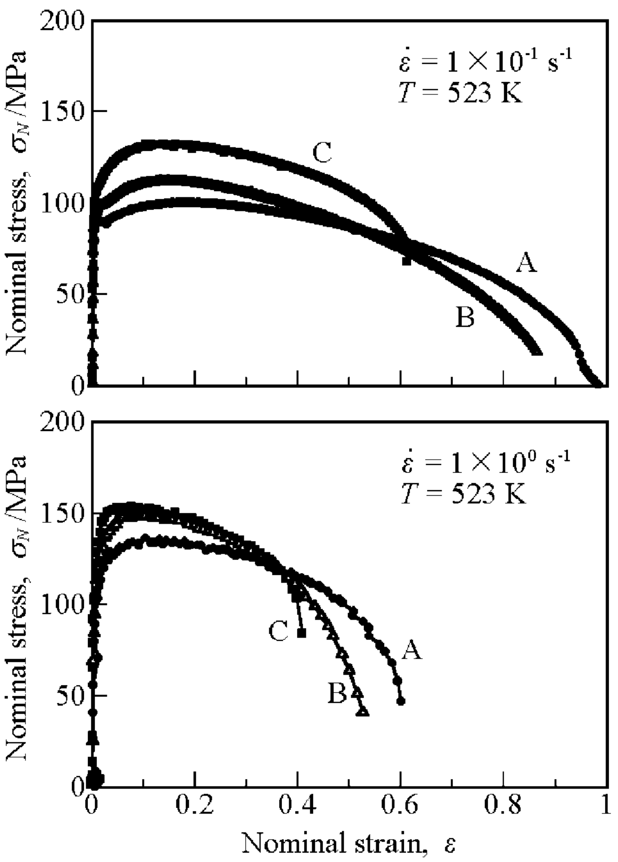

Fig. 5 Nominal stress-strain relationships at $\dot{\varepsilon} = 1 \times 10^{-1}$ and $1 \times 10^{0}\,s^{-1}$.

Figures 6–8 show the changes in tensile strength, elongation, and n-value at $1 \times 10^{0}\,s^{-1}$ with temperature, respectively. The n-values were found within the nominal strain range of $0.05 \sim 0.15$ (0.10 in part) that could be deemed to be nearly uniform elongation. Figure 9 shows the change in m-value at the nominal strain of 0.1 with temperature. With increasing temperature, the n-values decrease and the m-values increase for every strip. These values of the extruded strip C are lowest at every temperature, and those of rolled strip B are most sensitive to temperature in this temperature range. The elongation of rolled strip B at high temperatures is hold by the increased m-value compensating for the decreased n-value. Figure 10 shows the relationship between the n-value and the true strain rate for the rolled strip A. For low strain rates, the n-value is higher at lower temperatures. With increasing strain rate, the n-value decreases at low temperatures and increases at high temperatures, which reduces the differences among the n-values.

3.3 Formability in deep drawing

Figure 11 shows the relationship between the limiting drawing ratio (LDR) and temperature. The LDR of extruded strip C is low at all temperature, which is caused by the coarse grain. The LDRs of both sheets at high temperatures, $2.1 \sim 2.2$, are as large as that of aluminum in cold drawing. Below 503 K, the LDR of B is markedly reduced, although that of A maintains its high value. Figure 12 shows the deep cups formed in each strip. The rolled strip A is wrinkled at low temperatures, when the ears caused by in-plane anisotropy are released from the blank holder and are then drawn out. The ears are directed at 45 deg to the rolling direction.

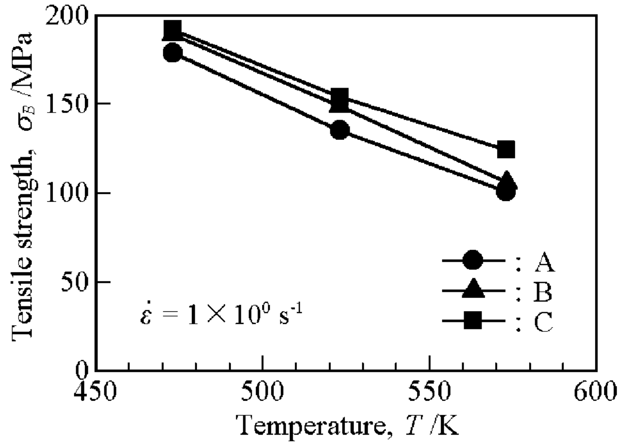

Fig. 6 Relation between tensile strength and temperature at $\dot{\varepsilon} = 1 \times 10^0\,s^{-1}$.

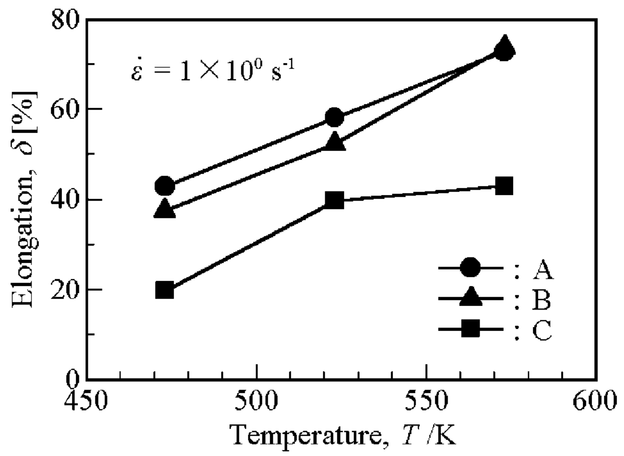

Fig. 7 Relation between elongation and temperature at $\dot{\varepsilon} = 1 \times 10^0\,s^{-1}$.

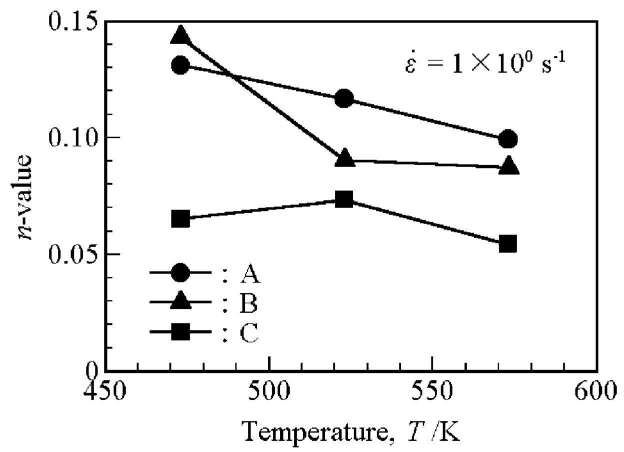

Fig. 8 Relation between n-value and temperature at $\dot{\varepsilon} = 1 \times 10^0\,s^{-1}$.

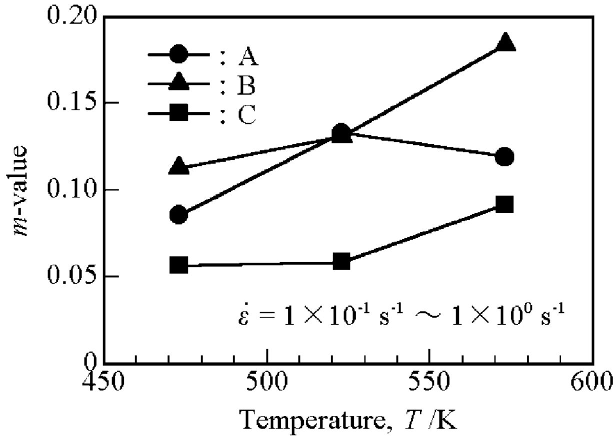

Fig. 9 Relation between m-value and temperature.

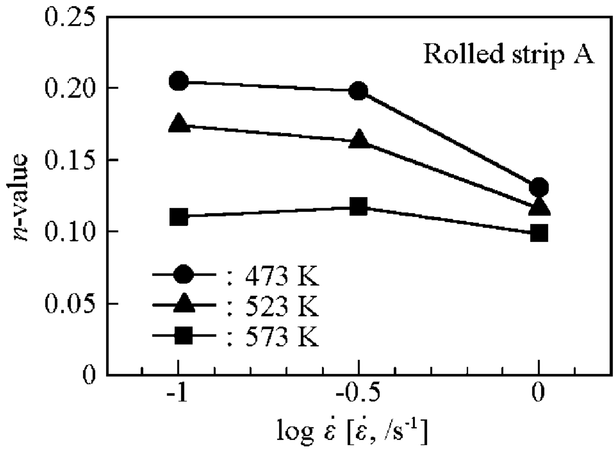

Fig. 10 Relation between n-value and true strain rate in rolled strip A.

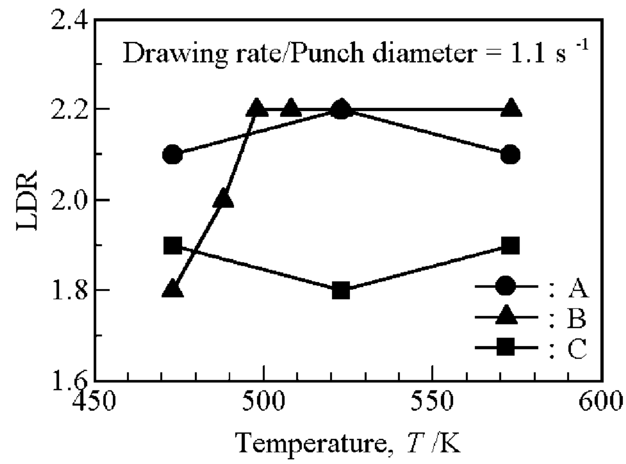

Fig. 11 Relation between limiting drawing ratio (LDR) and temperature.

However, the rolled strip B is drawn out without earing because of the in-plain isotropic texture. Figure 13 shows the cups of drawing ratio, 1.67, obtained by drawing the rolled strip A at the limiting temperature. The strip can be drawn out even at 353 K, although cracked, and complete cup without cracking is obtained at 373 K. However, the rolled strip B cannot be drawn at less than 473 K.

From the above results, the rolled strip B having a concentric texture may perform well at cylindrical drawing at high temperatures. For a tetragonal drawing, the in-plane anisotropy of strip A is suitable because it can be considered in a corner cut; thus, the rolled strip A, having a two-peak texture, is desirable in terms of the lower formable temperature. It will also be desirable for general press forming

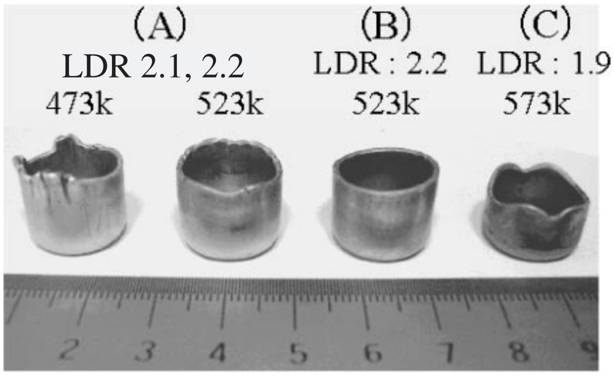

Fig. 12 Appearance of deep cups at drawing limit.

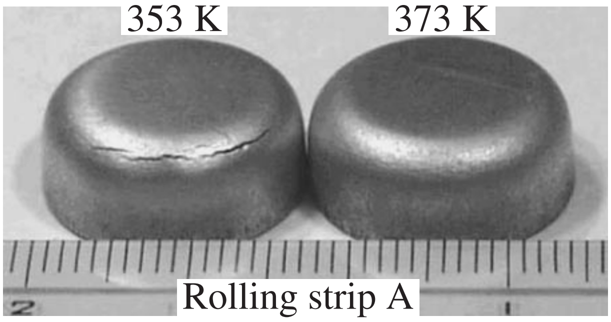

Fig. 13 Cups of drawing ratio, 1.67, drawn at limiting temperature.

combining bending, stretching and drawing, since it is ductile until appreciably low temperatures compared with the rolled strip B. If the drawing limit is predominated by local (thickness) necking, increasing the r-value is most effective for its improvement. However, rolled strip B is broken below 503 K by crack propagation from the outer surface of the bent portion on the punch shoulder before strain localization. In this case, the r-value has no effect on the forming limit, which is the most crucial when considering the formability of AZ31 magnesium alloy.[3,10)]

4. Conclusion

The excellent formability of the AZ31 alloy strip having a two-peak {0001} texture was confirmed by deep-drawing tests under practical forming conditions for mass production. Accurate stress-strain relationships at high strain rates and high temperatures were obtained by a special testing machine, which could be effectively utilized in press design. The differences in tensile characteristics between the two-peak texture and concentric-texture strips were confirmed; however, a prediction of the forming limit in press forming using only the tensile test was difficult. The fracture caused by the crack propagation before strain localization, which cannot be predicted from the n-value, m-value or r-value, is crucial when considering the formability of AZ31 magnesium alloy. The texture change was accompanied by secondary deformation, but the original texture had a large impact on the formability. At present, the two-peak texture is obtained only as a rolled strip with a narrow width. In the near future, industrial press forming at lower temperatures will be realized by the establishment of texture control techniques in the rolling process.

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