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Improvement of stretch formability of Mg–3Al–1Zn alloy sheet by high temperature rolling at finishing pass

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ABSTRACT

The effects of increasing rolling temperature from 723 K to 828 K at the last rolling pass on microstructure, texture, mechanical properties and stretch formability of a Mg–3Al–1Zn magnesium alloy previously rolled at 723 K were investigated. In the as-rolled condition, the basal texture strengthens slightly with increasing the rolling temperature whereas it weakens more remarkably after static recrystallization during annealing for the sheets rolled at higher temperatures. Only by increasing the rolling temperature from 723 K to 798 K, the Erichsen value is significantly increased from 4.5 to 8.6 due to the weakened texture for the annealed sheets. Further increasing the last rolling temperature does not appear to further improve the stretch formability.

1. Introduction

There has been an increasing demand for magnesium (Mg) alloys because they are a potential substitute for steel and aluminum parts as light-weight structural materials in automotive and electronic industries due to their high density-strength ratio. However, Mg alloy sheets generally exhibit a very poor formability at ambient temperatures and thus their applications are extremely restricted. This poor formability is originated from basal slip dominated deformation as well as strong basal texture existing in common wrought Mg alloys. It has been known that the formability can be improved by reduction of basal texture intensity and/or inclination of basal pole [1–4]. Thus, a great effort has been devoted to texture modification for the purpose of enhancing the formability. Addition of alloying elements including rare-earth elements and lithium is an effective method to weaken texture and/or to largely split basal pole, which may improve the formability considerably [4–8]. However, addition of those expensive elements substantially increases raw material cost. It is therefore a desirable approach to improve the formability of commercial Mg alloys composed of ubiquitous elements by texture control through plastic processing techniques. In recent years, some processing techniques such as asymmetric rolling [3,9], cross rolling [10], repeated unidirectional bending [11], repetitive bending [12], equal channel angular rolling [13], wavy roll forming [14], high temperature annealing before and after warm rolling [15], combination of high temperature and warm rolling [16,17], have been evolved for enhancing the formability of Mg alloy sheets. Compared with those processing techniques, high temperature rolling exhibits different deformation characteristics, e.g. enhanced activities of non-basal slips and grain boundary sliding (GBS), which may play an important role in weakening of texture [18,19]. However, hot rolling is generally carried out at temperatures not higher than 723 K only for avoiding cracking at a large reduction per pass at rough rolling stage for Mg alloys and less attention has been given to the possibility as a technique for texture control. Thus, research on the effects of the high temperature rolling on texture formation and formability of Mg sheets still remains quite limited.

In this study, the effects of increasing the rolling temperature from 723 K to 828 K at the last rolling pass on microstructure, texture, mechanical properties and stretch formability of the AZ31 Mg alloy previously rolled at 723 K were investigated. The only a single finishing pass was carried out at different temperatures in an attempt to understand the effects of the high temperature rolling more easily by eliminating the influences of inter-pass re-heating during multiple rolling.

2. Experimental procedure

The starting billets were cut from the commercial hot-extruded AZ31 (Mg–2.7Al–0.8Zn–0.4Mn in mass%) alloy plate with an initial thickness of 5 mm, and then were homogenized at 723 K for 20 h prior to rolling. The billets were rolled from 5 mm to 1.26 mm in thickness by 6 passes at 723 K, and were subsequently rolled

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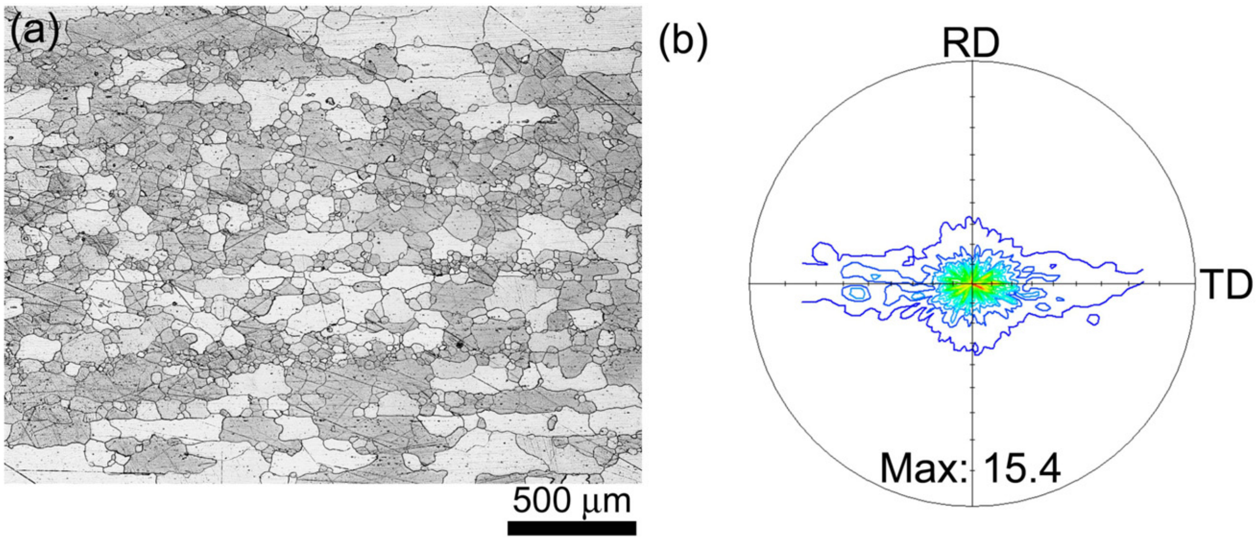

Fig. 1. (a) Optical micrograph taken in the longitudinal section with a horizontal extrusion direction (ED) and (b) (0 0 0 2) (intensity level: 1, 2, 3, 4. . .) pole figure of the extruded AZ31 alloy followed by homogenization.

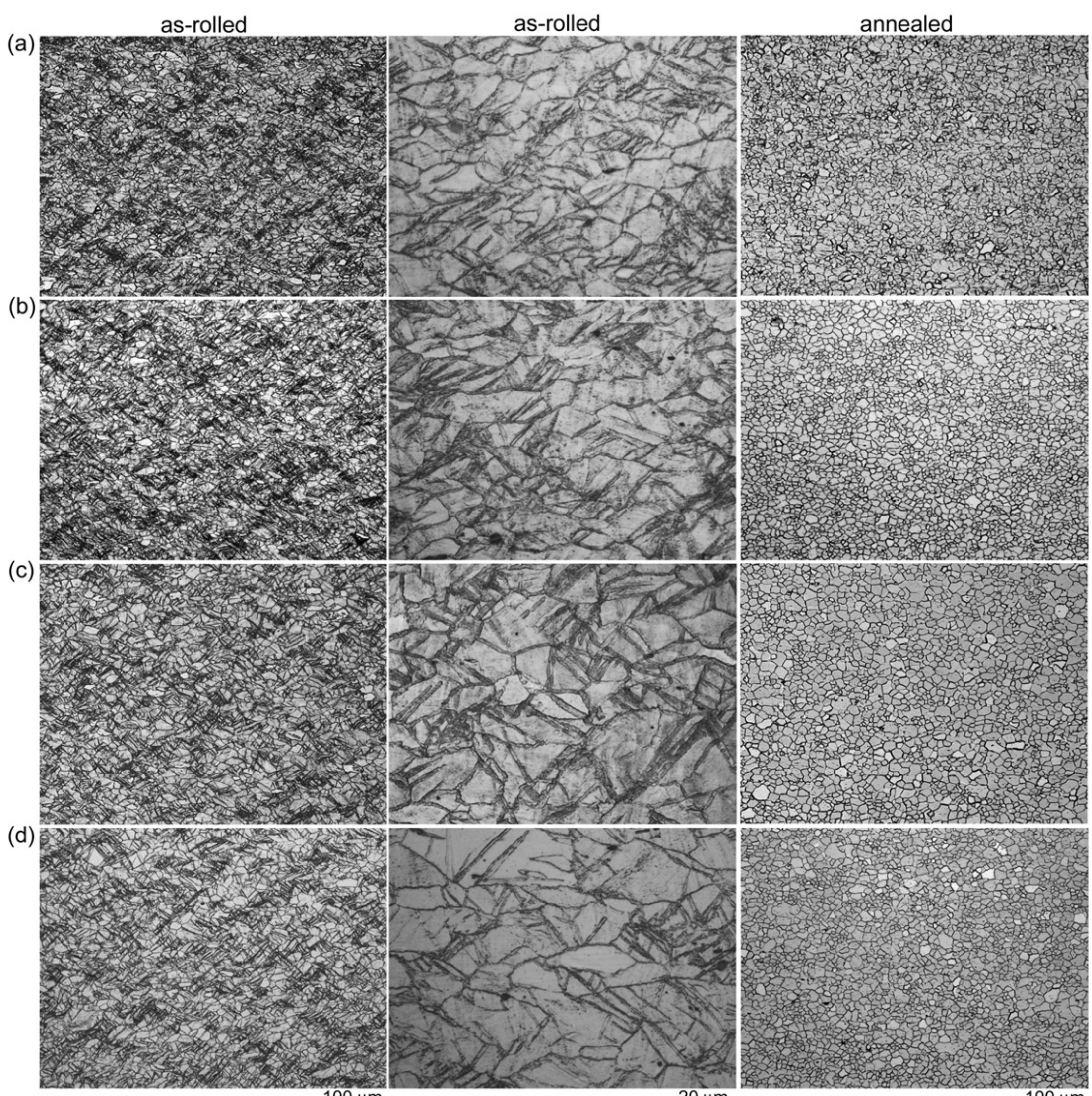

Fig. 2. Optical micrographs taken in the longitudinal sections of the as-rolled (low and high magnifications) and annealed (low magnification) sheets with the last rolling temperatures of (a) 723 K, (b) 763 K, (c) 798 K and (d) 828 K. The RD is horizontal.

down to 1 mm by a single pass at different temperatures of 723 K, 763 K, 798 K and 828 K. The highest billet temperature of 828 K is close to the solidus temperature (839 K) of the AZ31 alloy [20]. The reduction per pass was 21% for each pass and the total reduction was 80%. The sheets were quenched into water immediately after each pass and were re-heated to the rolling temperature before the next rolling. After the rolling process, the sheets annealed at 623 K for 1 h were used for tensile and Erichsen tests at room temperature.

The grain sizes were determined by analyzing the optical micrographs of the polished specimens with the line-intercept method. The (0 0 0 2) pole figures were measured at the mid-layers of the sheets by the Schulz reflection method using a X-ray apparatus (Rigaku RINT2000). The tensile tests were carried out at the angles of 0° (RD), 45° and 90° (TD) between the tensile direction and the rolling direction using an Instron universal testing machine (model: 5565) equipped with an extensometer. The Lankford values (r-value) were measured on the specimens deformed at a plastic strain of 9% and the strain hardening exponent values (n-value) were obtained by power law regression of the tensile test data over a strain interval from 4% to 14%. The Erichsen tests were conducted on the circular blanks with a diameter of 60 mm using a hemispherical punch with a diameter of 20 mm and graphite grease was used as a lubricant. The punch speed and the blank holder force were 5 mm/min and 10 kN, respectively. The average Erichsen values (IE) were given by averaging the IE from the two Erichsen tests for each sheet.

3. Results and discussion

The microstructure and the texture of the extruded AZ31 alloy followed by homogenization are shown in Fig. 1. The microstructure is heterogeneous with a distribution in grain size from several μm to hundreds of μm. Similar to the typical AZ31 extrusion texture, the basal texture is strong with a high intensity of 15.4 and the spread of (0 0 0 2) orientation in the TD also exists.

The as-rolled microstructures of the sheets with the last rolling temperatures of 723–828 K are shown in the left part of Fig. 2. The as-rolled microstructures contain crossed shear bands, which are more evident in the cases of lower rolling temperatures. As another feature, extensive twinning occurs during rolling for all sheets. The grain sizes appear to be larger for the as-rolled sheets with higher rolling temperatures. Because of no apparent occurrence of dynamic recrystallization (DRX) during rolling, the larger grain sizes for the sheets rolled at the higher temperatures may be attributed to the larger grain sizes prior to the last rolling pass, which may reasonably be considered due to more intensive grain coarsening during the heating to the higher target temperatures. Although the twinning behaviour restricts with increasing deformation temperature [21], the twins extensively exist even in the sheet rolled at a quite high temperature of 828 K. This might be due to the large grain size of the microstructure prior to the final rolling, which is favoured for twinning [21]. The twinning appears to contribute to the restriction of the DRX resulting from the effect of a relaxation of stress concentration and thus a reduction of stored strain energy at grain boundaries [16]. The shear banding results in localization of deformation and thus the weaker shear bands for the sheets rolled at higher temperatures indicate a more homogenous deformation.

After annealing, the twins disappear and the microstructures change to fully recrystallized grain structures with equiaxial grains for all sheets due to static recrystallization (SRX) as shown in the right part of Fig. 2. The grain sizes are approximately the same, which are 11, 10, 12 and 11 μm for the sheets with the last rolling temperatures of 723 K, 763 K, 798 K and 828 K, respectively. In comparison to the starting material (see Fig. 1), the rolled and annealed sheets exhibit much more homogenous microstructures.

Fig. 3 shows the (0 0 0 2) pole figures of the as-rolled (left part) and annealed (right part) sheets rolled at different last rolling temperatures. In the as-rolled condition, the splitting of basal pole in the RD is more noticeable for the sheets rolled at lower temperatures. The split angle of the double peak decreases with increasing the rolling temperature. This phenomenon is in agreement with the results in Ref. [22]. On the other hand, the basal texture intensity strengthens from 5.4 to 6.4 with increasing the last rolling temperature from 723 K to 828 K, even though the non-basal slips and the GBS may enhance their activities under high temperature deformation and thus the weakening effects of basal texture can be expected. This may be related to the inhomogeneous deformation acting as shear banding with a strain concentration during rolling for the sheets rolled at lower temperatures (see Fig. 2). This inhomogeneous deformation may result in a relatively smaller strain accommodation and in turn a relatively limited strengthening of basal texture in the remaining regions without shear banding, which should give a dominant influence on the macro-texture because of their much larger volume ratio compared with the shear bands.

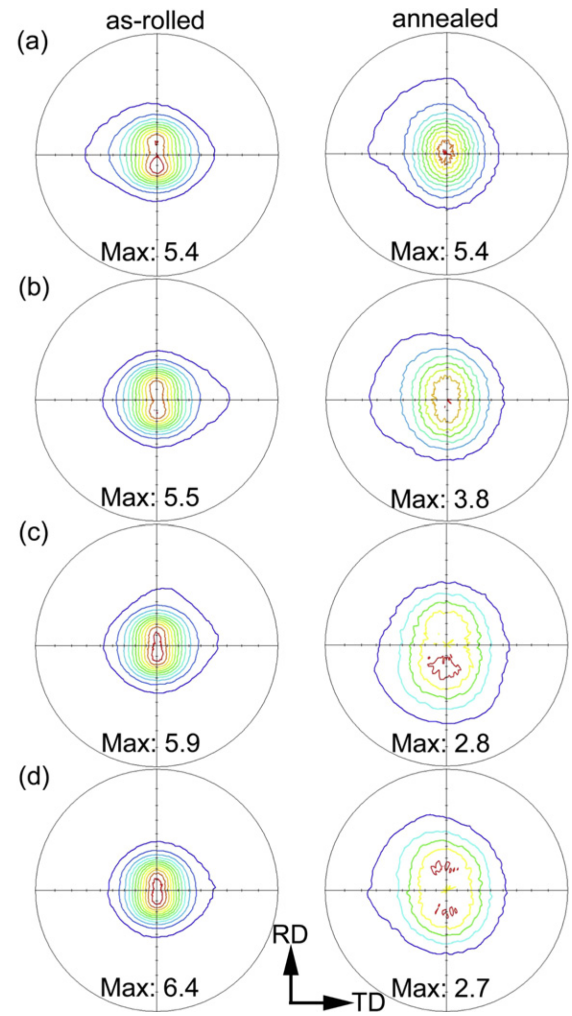

Fig. 3. (0 0 0 2) pole figures (intensity level: 0.5, 1, 1.5, 2. . .) of the as-rolled (left part) and annealed (right part) sheets with the last rolling temperatures of (a) 723 K, (b) 763 K, (c) 798 K and (d) 828 K.

As shown in the right part of Fig. 3, the basal texture remarkably weakens with increasing the last rolling temperature from 723 K to 798 K with a decrease in intensity from 5.4 to 2.8 after annealing, and it becomes a tiny change when increasing the temperature from 798 K to 828 K further. No change in the basal texture intensity occurs but the double peak is replaced by the single peak for the sheets rolled at the lowest temperature of 723 K. By contrast, the sheets rolled at temperatures higher than 798 K exhibit significantly weakened textures and the double peaks also greatly increase their splitting angles to ∼20° in the RD. In the previous work, some of the authors reported that a significant weakening of texture may be achieved by annealing a rolled AZ31 alloy with a deformation microstructure without an occurrence of DRX

[16,17], which has also been revealed to be due to discontinuous SRX at pre-existing grain boundaries [23]. However, all sheets obtained in the present study have a similar appearance of deformation microstructure (see Fig. 2). The twin related SRX has been well observed in deformed Mg alloys and orientations of SRXed grains tend to depend on the twin type. It has been reported that new grains forming at the intersections of two double twins retain basal orientation because of the rotation around the *c*-axis with respect to the matrix grains [24], while those forming within compression twins exhibit non-basal orientations [25]. It can therefore be expected that the textures of the sheets rolled at higher temperatures weaken more remarkably during annealing if more compression twins are contained in those sheets. On the other hand, increasing deformation temperature enhances activities of non-basal slips and GBS, which may affect the SRX kinetics. Deformation at higher temperatures increases orientation gradients near grain boundaries due to GBS and/or shearing connected with grain boundary serration [26]. In addition, grain coarsening may occur during the heating to the target temperature. The larger grain sizes prior to the final rolling at higher temperatures may enhance orientation gradients and dislocation accommodation near grain boundaries due to inhomogeneous deformation. The large orientation gradients and the high local dislocation densities near grain boundaries are likely to induce SRX at pre-existing grain boundaries as observed in Ref. [23]. When a high density of non-basal dislocations exists, it is suggested that absorption of non-basal dislocations in boundaries may promote rotation of nuclei and/or quite small SRXed grains in various directions, which results in largely altered orientations and in turn a remarkably weakened texture. The final annealing texture is generally also affected by subsequent grain growth [23]. It is therefore an important future work for us to investigate the type and fraction of twins as well as the SRX and grain growth behaviors during annealing for understanding the relationship between the texture formation mechanism and the rolling temperature.

The mechanical properties including the ultimate tensile strength (UTS), the 0.2% proof stress (YS), the fracture elongation (FE), the uniform elongation (UE), the *r*-value and the *n*-value of the annealed sheets with the different last rolling temperatures are summarized in Table 1. The YS and the *r*-value increase with increasing the angle between the RD and the tensile direction while the *n*-value exhibits a converse behaviour. This is due to the spread of the (0 0 0 2) orientation and the inclination of basal poles in the RD, which are favoured for basal slip during deformation in this tensile direction.

Fig. 4 shows the average values ($\bar{X} = (X_{RD} + 2X_{45^\circ} + X_{TD})/4$) of the mechanical properties as well as the difference between the *r*-values of the TD and RD tensile directions of the annealed sheets with different last rolling temperatures. Considering approximately the same grain size, the influences on the mechanical properties can be mainly attributed to the texture effects. As mentioned above, the basal texture weakens with increasing the last rolling temperature. The lower YS for the sheets rolled at higher temperatures is due to the weakening of texture strengthening effect. The FE, UE and the *n*-value increase and the *r*-value decreases with increasing the last rolling temperature nearly saturating at 798 K, which is in good agreement with the change in the basal texture intensity. The formability of the Mg alloys is strongly affected by the *r*-value and *n*-value. A smaller *r*-value and a larger *n*-value are beneficial for a sheet thinning capability under a biaxial tension stress state of stretch forming and in turn enhance the stretch formability [3]. As shown in Fig. 4(d), the difference between the *r*-values of the TD and RD tensile directions deceases gradually from 0.48 to 0.20 with increasing the rolling temperature from 723 K to 828 K. This indicates a weakened planar anisotropy on *r*-value due to the weakened texture achieved by the high temperature

Table 1
Results of the tensile tests carried out in the tensile directions of RD, 45° and TD of the annealed sheets with different last rolling temperatures (LRT).

LRT	UTS (MPa)			YS (MPa)			FE (%)			UE (%)			*r*-value			*n*-value		
	RD	45°	TD	RD	45°	TD	RD	45°	TD	RD	45°	TD	RD	45°	TD	RD	45°	TD
723 K	263	262	265	165	168	173	26.1	25.3	25.2	19.0	17.8	17.9	1.67	1.90	2.15	0.244	0.239	0.236
763 K	258	259	262	151	155	161	26.6	26.6	26.4	19.8	19.7	18.5	1.38	1.54	1.69	0.271	0.265	0.253
798 K	256	257	260	144	149	154	27.3	28.1	26.8	20.6	20.8	19.3	1.04	1.19	1.27	0.291	0.285	0.272
828 K	256	257	260	144	148	154	28.2	27.8	26.7	22.0	21.0	19.1	1.00	1.13	1.20	0.297	0.285	0.268

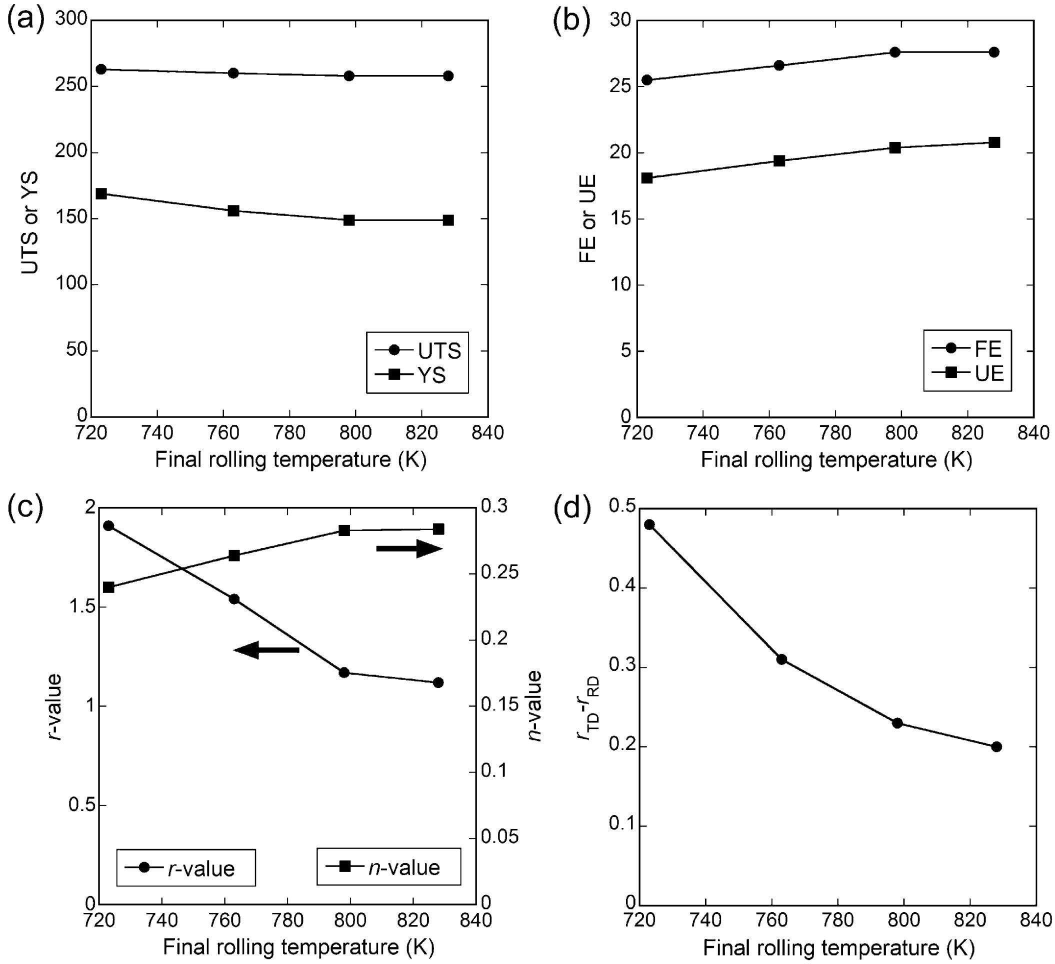

Fig. 4. Average values of (a) the UTS and the YS, (b) the FE and the UE, (c) the *r*-value and the *n*-value, and (d) the planar anisotropy on *r*-value (r_{TD}–r_{RD}) of the annealed sheets with the last rolling temperatures of 723–828 K.

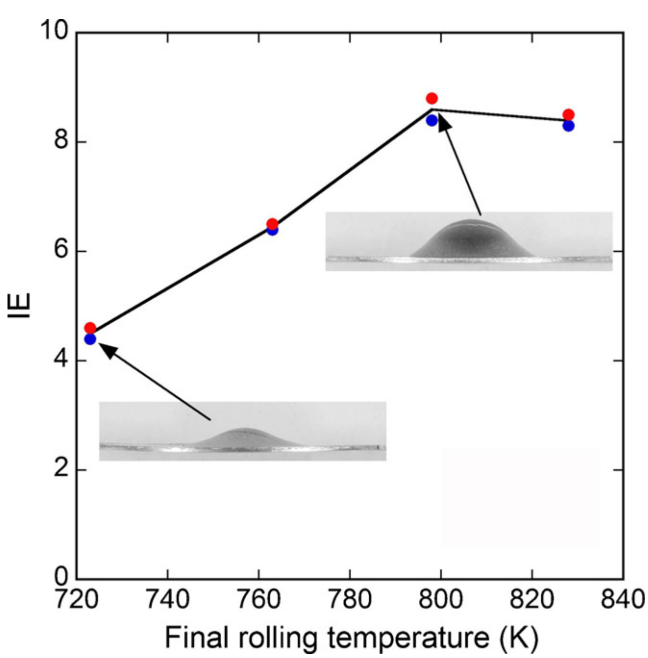

Fig. 5. IE of the annealed sheets with the rolling temperatures of 723–828 K at the last rolling pass. The deformed blanks of the annealed sheets rolled at 723 K and 798 K at the last rolling pass with the minimum and maximum IE are inset.

rolling, which should also benefit for enhancing the stretch formability.

The change in the IE of the annealed sheets with increasing the last rolling temperature is shown in Fig. 5. Only by increasing the last rolling temperature from 723 K to 798 K by 75 K, the average IE is significantly increased from 4.5 to 8.6 by about two times due to the decreases in the *r*-value and the planar anisotropy on the *r*-value together with the increase in the *n*-value, which are originated from the weakened basal texture. The IE (8.6) of the sheet rolled at 798 K is much higher than those (3–5) of common AZ31B alloy sheets [1,3], and is even comparable to those (8–11) of typical structure aluminum alloys (O temper) [27]. Further increasing the last rolling temperature from 798 K to 828 K does not appear to further improve the stretch formability. This is due to the similarity of the textures and the mechanical properties between the two sheets as mentioned above.

4. Conclusions

In summary, significant improvement in stretch formability can be achieved only by a single finishing pass at a high temperature. The basal texture strengthens slightly with increasing the rolling temperature in the as-rolled condition, whereas it remarkably weakens after SRX during annealing for the sheets rolled at higher temperatures and no change in texture intensity occurs for the sheet rolled at the lowest temperature of 723 K. With increasing the rolling temperature, the annealed sheets exhibit the decreases in the *r*-value and the planar anisotropy on the *r*-value together with the increase in the *n*-value, which are originated from the weakened basal texture and consequently enhance sheet thinning capability. Resulting from the texture effects, the Erichsen value is significantly increased from 4.5 to 8.6 only by increasing the rolling temperature from 723 K to 798 K. Further increasing the last rolling temperature from 798 K to 828 K does not appear to further improve the stretch formability due to the similarity of the textures and the mechanical properties.

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