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Influence of cold-rolling and annealing conditions on formability of aluminium alloy sheet

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Using an Al–Mg–Cu alloy developed for auto body panels, strip sheets are experimentally produced by various cold-rolling and annealing procedures. Tensile and metallographic properties of the sheets and their relations are examined to attain high formability. The elongation is closely related to the grain size, and increases with the final annealing temperature. The rolling texture influences the plastic anisotropy, the Lankford value of the sheets. The comparatively high Lankford values are obtained under the condition that both the intermediate and the final annealing temperatures are higher and the reduction ratio after the intermediate annealing is smaller.

1. Introduction

The use of aluminium to reduce car weight is drawing much attention from the viewpoint of environmental preservation [1–3]. Specifically, the use of aluminium alloy sheet in auto body panels will bring great improvement in weight reduction. However, the aluminium alloy sheets developed for auto body panels are, normally, much inferior to steel sheets in formability so far [3, 4]. Therefore, investigations on alloy design are being carried out to obtain aluminium alloy sheets with high formability as well as high strength [2–6]. On the other hand, the formability and the strength of materials depend greatly upon the production processes, and it is necessary to investigate the optimum rolling and annealing conditions for the aluminium alloy sheets for auto body panels.

In this study, therefore, using an Al–Mg–Cu alloy developed for auto body panels [5], strip sheets are experimentally produced under various cold-rolling and annealing conditions. Then the tensile tests and the metallographic observations are carried out for the strip sheets, and the influences of reduction schedule, annealing temperature, stage for intermediate annealing, etc. on the mechanical and metallographic properties of the sheets are examined. From the results so obtained the possibility of improvement in formability of the aluminium alloy sheets by optimizing the production processes is discussed.

2. Experimental procedure

The material used in this study is an Al–Mg–Cu alloy, and the chemical composition of the material is given in Table I.

The material was hot-rolled by an actual mill in operation, and provided for the experiments. The test pieces were cut from the hot-rolled coil with a thickness of 5.2 mm, and cold-rolled in the laboratory to a final thickness of 1.2 mm. Two pairs of rolls with diameters, d, of 70 mm and 400 mm were used as the working rolls. The reduction of a rolling pass, Δt, was set to be a constant value of 0.25 mm, 0.5 mm or 1.0 mm. The test pieces were rolled repeatedly and reversely until the final thickness was reached by the same pair of rolls.

The annealing procedures examined in this study are divided roughly into four cases (A to D) by the annealing times and the reduction stage for the intermediate annealing, as is indicated in Table II. In case A, only the final annealing was performed without the intermediate annealing. In cases B and C, the intermediate annealings were performed at the stages of sheet thickness of 2.2 mm and 3.2 mm, respectively. In case D, the initial annealing was performed before cold-rolling for 2 h at a temperature of 800 K, in addition to the intermediate and the final annealings in case B. The intermediate annealing was performed for 2 h at two temperatures, 600 K and 800 K, and the final annealing was done for 1 h at three temperatures, 600 K, 700 K and 800 K. (In the subsequent description we use the following abbreviations. B68 stands for the specimens which were annealed intermediately at 600 K and finally at 800 K in case B (see Table II).)

As well as the above procedures indicated in Table II the stage for the intermediate annealing and the final annealing time were further varied in the additional experiments.

From the strip sheets of 1.2 mm in thickness so obtained the tensile specimens were cut in such a way

TABLE I Chemical composition of test material (wt.%)

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.05	0.05	0.33	0.03	5.55	0.01	tr.	0.01	bal.

tr., trace
bal., balance

as to be parallel to the rolling direction. The width and the gauge length of the tensile specimens were set to be 12.5 mm and 50.0 mm, respectively. The tensile tests were carried out at room temperature.

The microstructures of the specimens were observed by optical microscopy, and the grain sizes were measured by the linear intercept method [7].

Furthermore, texture analyses by X-ray diffraction were performed on an automatic texture goniometer, using MoK_{α} radiation. For each texture two incomplete pole figures, (1 0 0) and (1 1 1), were recorded by the Schulz back-reflection method [8].

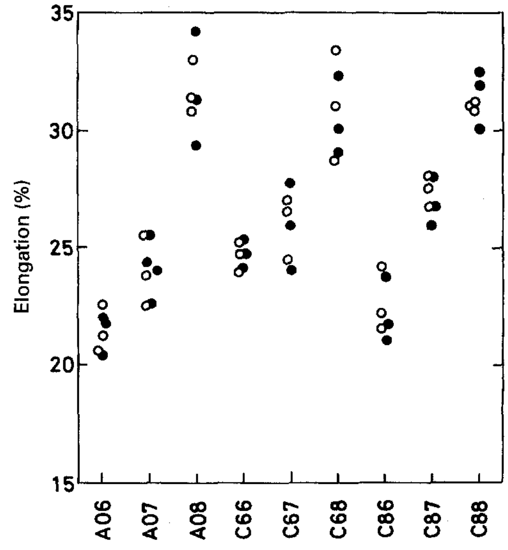

Figure 1 Effect of roll diameter, d, on elongation. ○, $d = 70$ mm; ●, $d = 400$ mm. $\Delta t = 0.5$ mm.

3. Results and discussion

Fig. 1 shows the elongations of various specimens, as an example of the effects of the roll diameter, d, on the tensile properties. In this figure the open and solid circles indicate the values for $d = 70$ mm and $d = 400$ mm, respectively. While the elongation depends greatly upon the annealing procedure, no significant difference due to the roll diameter can be seen in each procedure. Including other properties, the roll diameter has almost no influence on the tensile properties of the sheets.

Similarly, the difference depending on the reduction of a rolling pass, Δt, can hardly be recognized in any tensile property. However, in some cases, the elongations for $\Delta t = 1.0$ mm are fairly small in comparison with those for $\Delta t = 0.5$ mm and for $\Delta t = 0.25$ mm, as shown in Fig. 2. This suggests that the reduction Δt should not be too large. The experimental results for $\Delta t = 1.0$ mm are accordingly excluded from the following figures.

Fig. 3 shows the relation between the intermediate and the final annealing temperatures and the elongation. The results in cases where the intermediate annealing temperatures are 600 K and 800 K are indicated in Fig. 3(a) and (b), respectively, in groups of the same final annealing temperatures. In Fig. 3(b) the

TABLE II Procedures of cold-rolling and annealing

	Process	Final annealing	Specimen
A	5.2 mm —cold rolling→ 1.2 mm —annealing	600 K →	A06
		700 K →	A07
		800 K →	A08
B	5.2 mm —cold rolling→ 2.2 mm —annealing 600 K→ —cold rolling→ 1.2 mm —annealing	600 K →	B66
		700 K →	B67
		800 K →	B68
	800 K → —cold rolling→ 1.2 mm —annealing	600 K →	B86
		700 K →	B87
		800 K →	B88
C	5.2 mm —cold rolling→ 3.2 mm —annealing 600 K→ —cold rolling→ 1.2 mm —annealing	600 K →	C66
		700 K →	C67
		800 K →	C68
	800 K → —cold rolling→ 1.2 mm —annealing	600 K →	C86
		700 K →	C87
		800 K →	C88
D	5.2 mm —annealing 800 K→ —cold rolling→ 2.2 mm —annealing 600 K→ cold rolling→ 1.2 mm —annealing	600 K →	D66
		700 K →	D67
		800 K →	D68
	800 K → cold rolling→ 1.2 mm —annealing	600 K →	D86
		700 K →	D87
		800 K →	D88

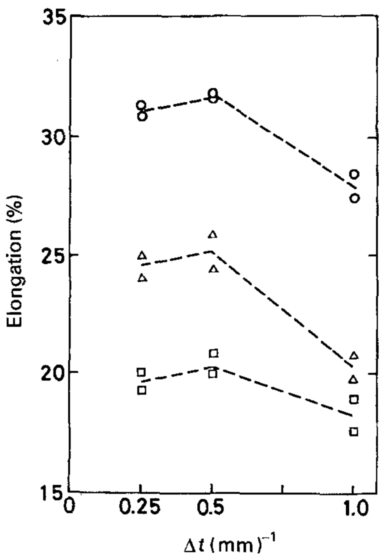

Figure 2 Effect of reduction of a rolling pass, Δt, on elongation. $d = 400$ mm. ○, B68; △, B66; □, B86.

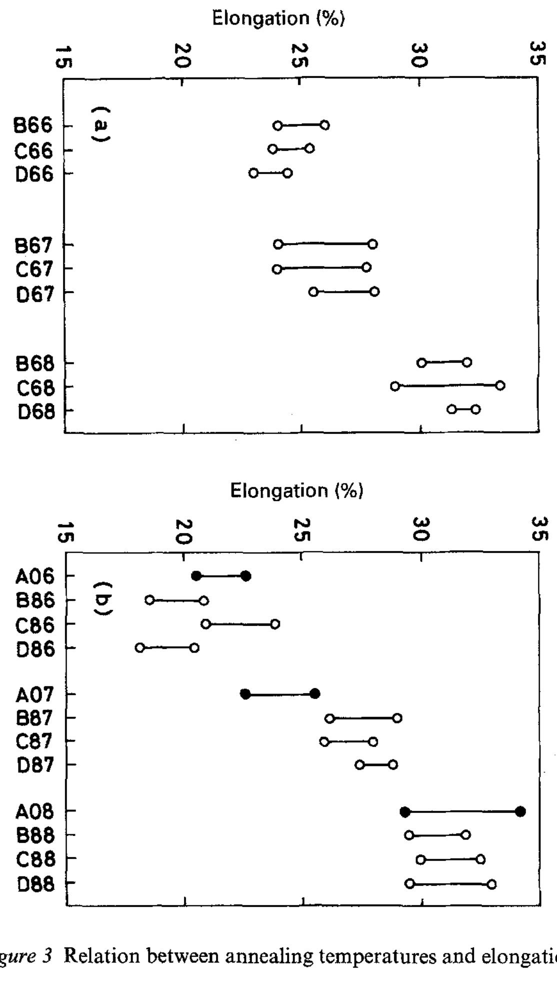

Figure 3 Relation between annealing temperatures and elongation.

results for the case without intermediate annealing, i.e., for case A, are additionally shown by the solid circles. For both the intermediate annealing temperatures of 600 K and 800 K the elongation increases with a rise in the final annealing temperature, and the elongations beyond 30% are attained at the final annealing temperature of 800 K.

The true stress–true strain ($\sigma - \varepsilon$) relation obtained from the tensile test can be approximately expressed with the work-hardening exponent, n, as

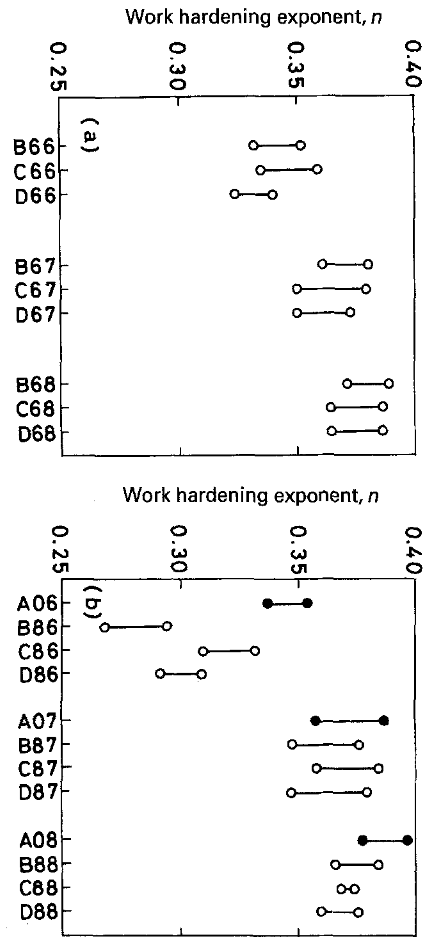

Figure 4 Relation between annealing temperatures and work-hardening exponent, n.

$$\sigma = F\varepsilon^n$$

where F is a constant. Fig. 4 shows the relation between the annealing temperatures and the n-value, in the same way as Fig. 3. There is a similarity between the relations shown in Figs 3 and 4, and it is considered that the n-value and the elongation are correlated.

Figs 5 and 6 show the relations of the annealing temperatures to the proof stress and the tensile strength, respectively. The proof stress and the tensile strength decrease with a rise in the final annealing temperature, almost independent of the intermediate annealing temperature. However, the decrease in the tensile strength is not so remarkable. The tensile strengths for the final annealing temperature of 800 K are about 280 MPa and smaller than those for 600 K by only 10% or so.

Fig. 7 shows the relation between the annealing temperatures and the average grain diameter of the microstructure. The grain size increases with the final annealing temperature. It is considered that the above-mentioned tensile properties are closely related to the grain size. In some cases where the final annealing temperature is 600 K the non-recrystallized microstructures are also observed.

Fig. 8 shows the effects of the final annealing time on the grain size and on the elongation, in the case of B88, obtained from the additional experiments. The

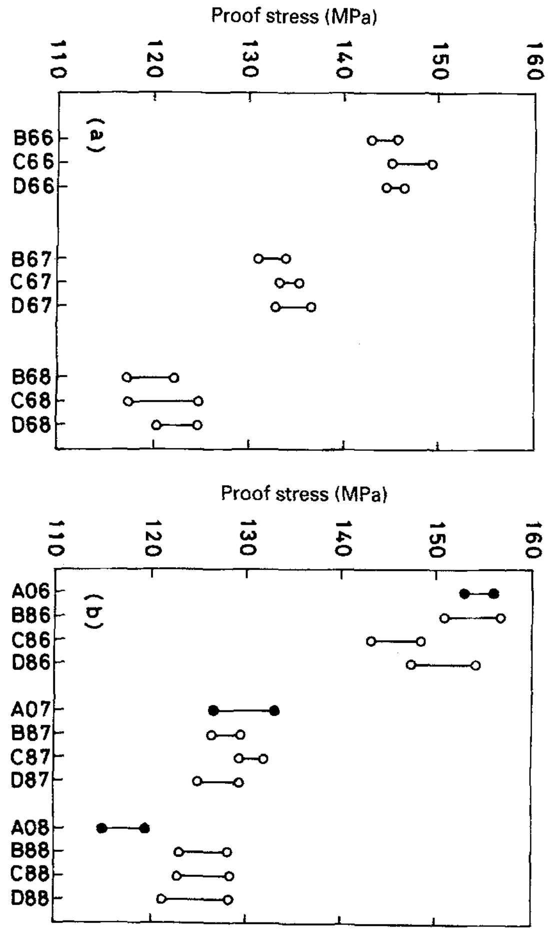

Figure 5 Relation between annealing temperatures and proof stress.

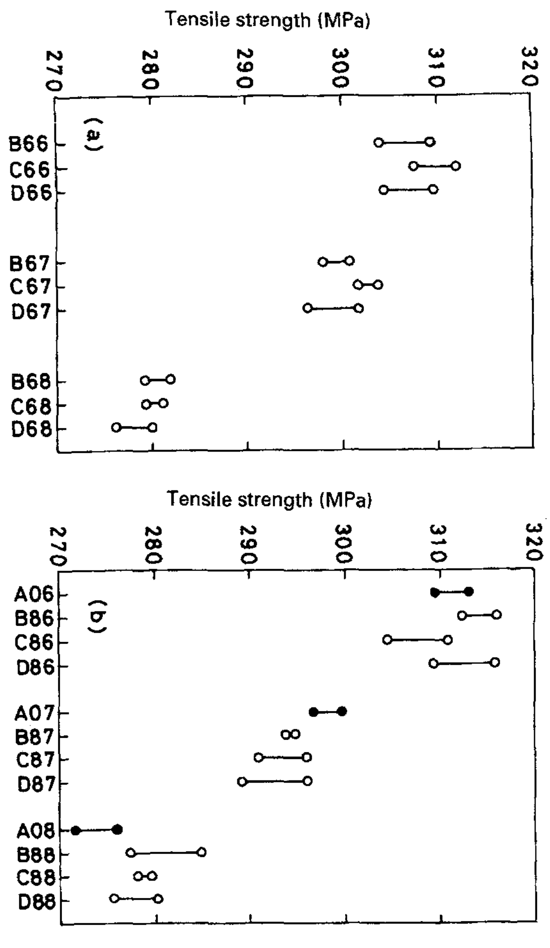

Figure 6 Relation between annealing temperatures and tensile strength.

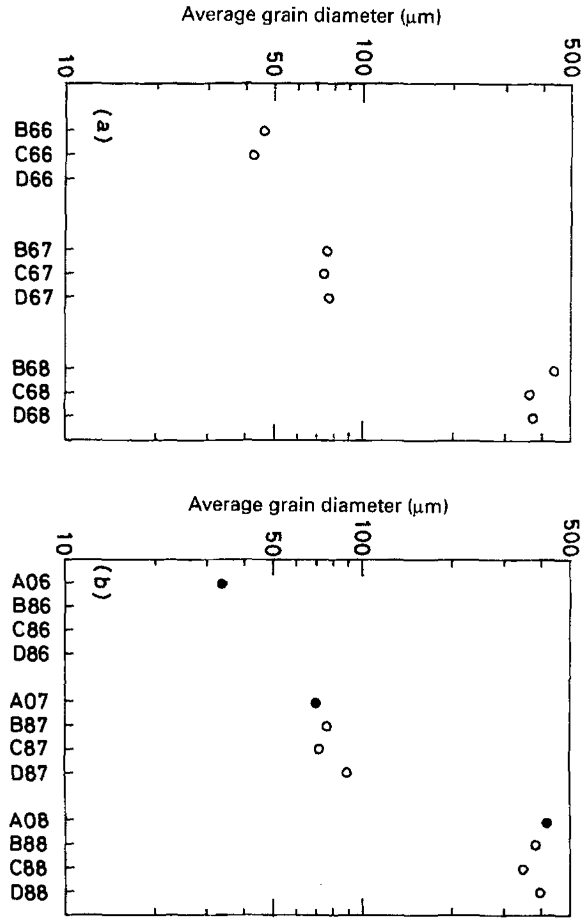

Figure 7 Relation between annealing temperatures and average grain diameter. (Note that samples D66, B86, C86 and D86 are non-recrystallized.)

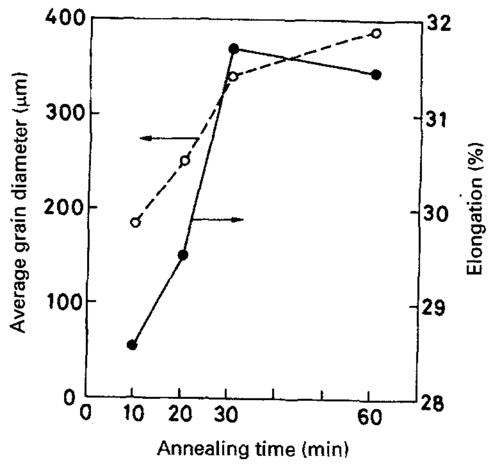

Figure 8 Effect of final annealing time on average grain diameter and elongation. ○, average grain diameter; ●, elongation.

grain size and the elongation increase with the annealing time, but their changes become smaller after 30 min.

As a measure of the sheet formability, especially the drawability, the Lankford value, *r* (which shows the plastic anisotropy of a sheet), is commonly used for the steel sheets. It is uncertain whether the *r*-value can measure the formability of the aluminium alloy sheets or not. However, it is reported that there is also a positive correlation between the *r*-value and the drawability of the aluminium alloy sheets (for the same kind of alloy) [3].

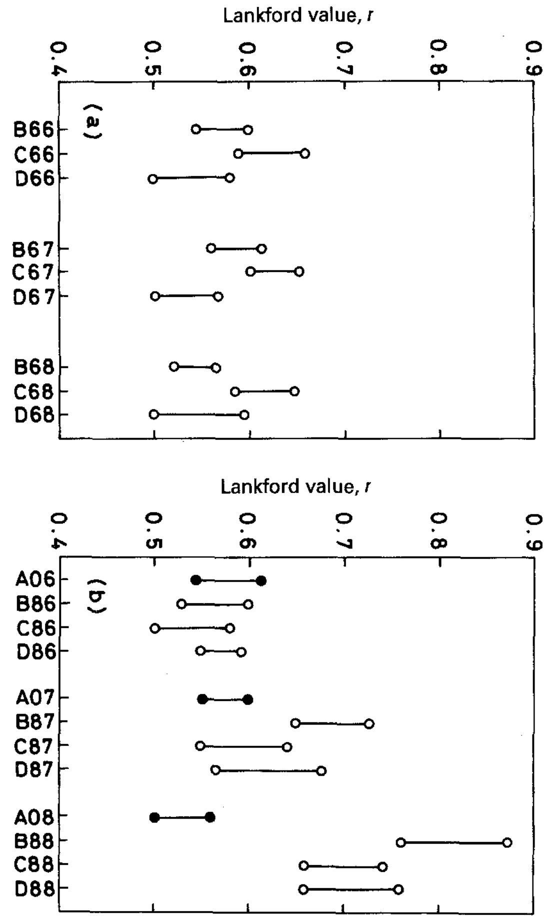

Figure 9 Relation between annealing temperatures and Lankford value, *r*.

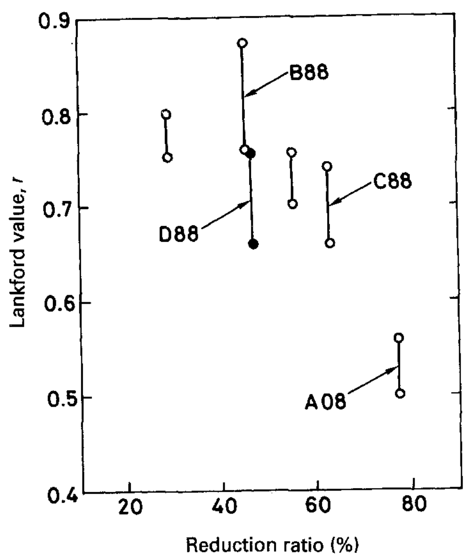

Figure 10 Effect of reduction ratio after intermediate annealing on Lankford value, *r*.

Fig. 9 shows the relation between the annealing temperatures and the Lankford value, *r*. The intermediate annealing temperature has a notable influence on the *r*-value, while it has no remarkable influence on the above-mentioned tensile properties such as elongation and strength. For the case where the intermediate annealing temperature is 600 K, the *r*-value remains at low values of 0.6 or so, independent of the final annealing temperature. On the other hand, for the case where the intermediate annealing temperature is 800 K, the *r*-value increases with the final annealing temperature.

It has been found that the specimens which are annealed at the highest temperature in the present experimental conditions both in the intermediate and the final annealings have the highest properties not only in the elongation but also in the *r*-value. For this group of specimens, again, the influence of the reduction stage for the intermediate annealing on the *r*-value are examined. Fig. 10 shows the relation between the reduction ratio after the intermediate annealing and the *r*-value, including the results of the additional experiments. Only for the case of A08 without the intermediate annealing, the abscissa exceptionally indicates the total reduction ratio. It proves to be necessary to lower the reduction ratio after the intermediate annealing in order to obtain the high *r*-value, as is commonly accepted for aluminium sheets. The *r*-value of D88 annealed initially before the cold-rolling is lower than that of B88, and this shows that the initial annealing is unnecessary, or rather has a bad influence on the *r*-value.

The plastic anisotropy is generally caused by the crystallographic anisotropy in texture. Fig. 11 shows the cold-rolling textures of A08, B88, C88 and D88 before the final annealing. It is observed that the texture of B88 which indicated the highest *r*-value in Figs 9 and 10 differs qualitatively from those of other specimens. The pole figures of A08, C88 and D88 (Figs 11(a), (c) and (d)) show qualitatively the same rolling texture typical for f.c.c. metals, which is composed mainly of (1 2 3) $[\bar{4}\bar{1}2]$, (1 4 6) $[\bar{2}\bar{1}1]$, (1 1 0) $[\bar{1}12]$, (1 1 0) [0 0 1] and (1 1 2) $[\bar{1}\bar{1}1]$ orientations. Also the specimens for the intermediate annealing temperature of 600 K show the similar and clearer rolling texture. On the other hand, it is observed in the pole figure of B88 (Fig. 11(b)) that the rolling texture is not yet completely formed and the annealing texture at the intermediate annealing remains. As a result, in the annealing texture of B88 after the final annealing, the growth of the component (1 0 0) [0 0 1] which is regarded as disadvantageous to the *r*-value is comparatively small (Fig. 12). Such a textural characteristic of B88 may cause the improvement in the *r*-value. However, in the annealing texture after the final annealing, the (1 0 0) plane is mainly oriented parallel to the sheet plane also for B88 similarly for other specimens, though the difference in the degree of clearness of texture exists. Therefore, the highest *r*-value obtained in the present experiments is only about 0.9, and the drastic improvement in the *r*-value might be difficult to attain.

4. Conclusions

In order to examine the optimum conditions of cold-rolling and annealing for the improvement in formability of the aluminium alloy sheets for auto body panels, the strip sheets of an Al–Mg–Cu alloy were experimentally produced by various cold-rolling and annealing procedures, and the tensile tests and the metallographic observations were carried out. The results so obtained are summarized as follows:

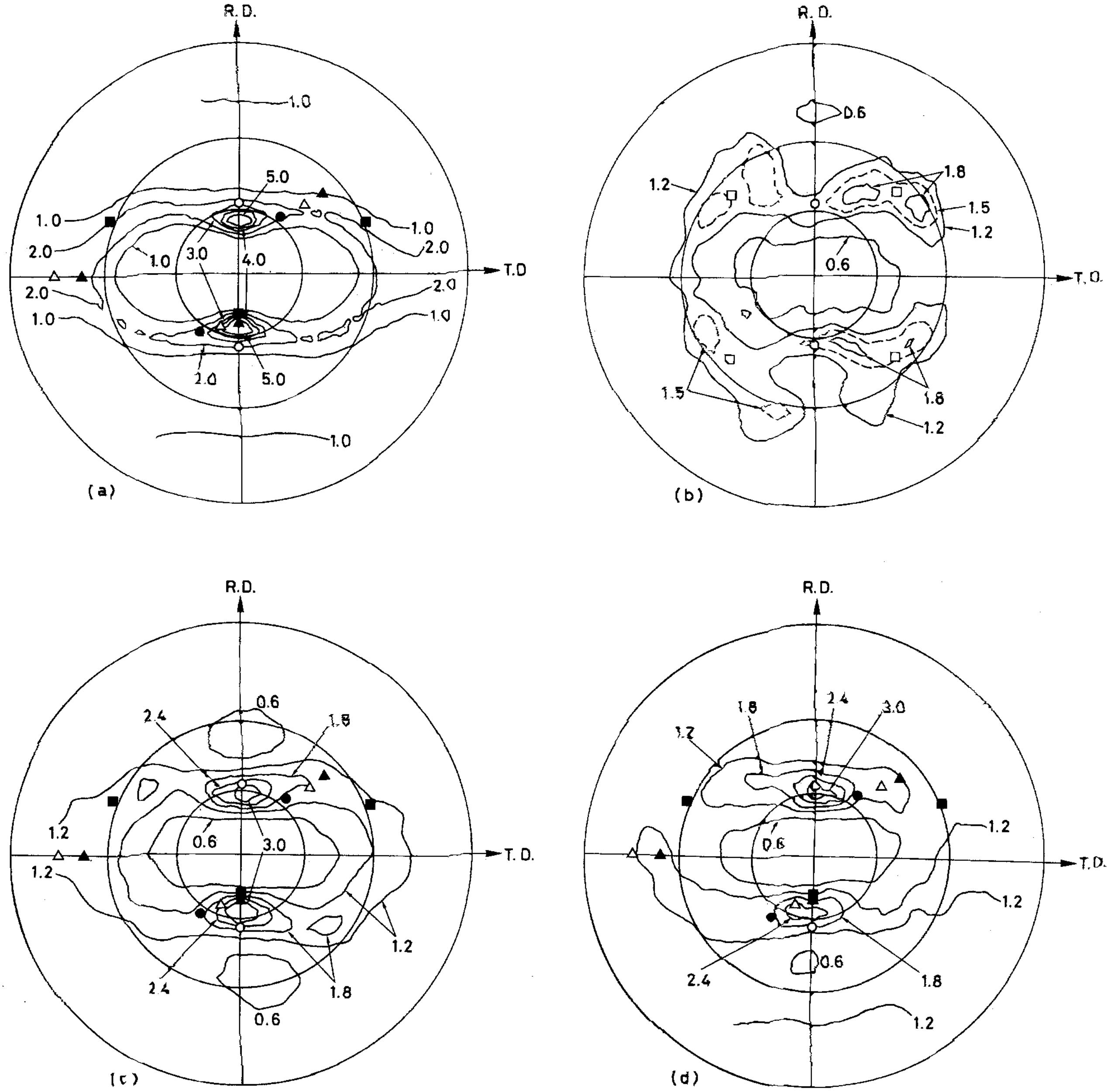

Figure 11 (1 1 1) pole figures of cold-rolling textures before final annealing for (a) A08, (b) B88, (c) C88, and (d) D88. ▲, (1 2 3) $[\bar{4}\,\bar{1}\,2]$; △, (1 4 6) $[\bar{2}\,\bar{1}\,1]$; ●, (1 1 0) $[\bar{1}\,1\,2]$; ○, (1 1 0) [0 0 1]; ■, (1 1 2) $[\bar{1}\,\bar{1}\,1]$; □, (1 0 0) [0 0 1].

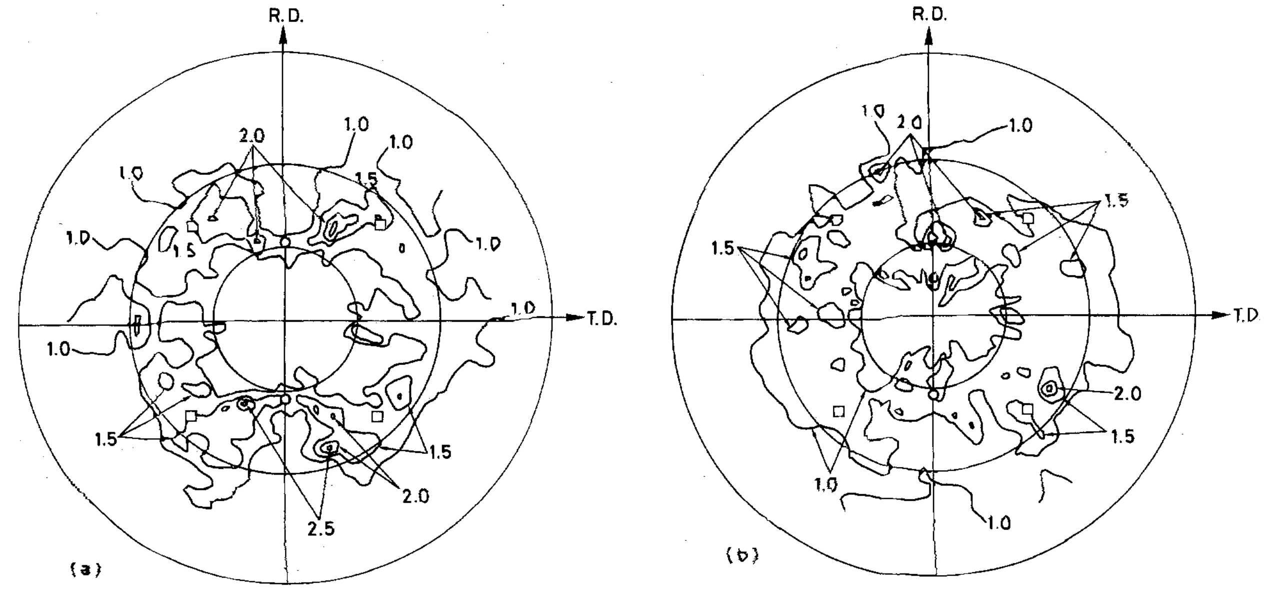

Figure 12 (1 1 1) pole figures of annealing textures after final annealing for (a) A08 and (b) B88. □, (1 0 0) [0 0 1]; ○, (1 1 0) [0 0 1].

(1) The elongation of the aluminium alloy sheet increases with the final annealing temperature, and exceeds 30% at the annealing temperature of 800 K.

(2) Though the proof stress and the tensile strength decrease with a rise in the final annealing temperature, the decrease of the tensile strength is comparatively small.

(3) The above tensile properties are closely related to the grain size.

(4) The roll diameter and the reduction in a rolling pass have almost no influence on the tensile properties.

(5) Under the condition that both the intermediate and the final annealing temperatures are higher and the reduction ratio after the intermediate annealing is smaller, the growth of the (1 0 0) [0 0 1] component in the final annealing texture is small, and the comparatively high Lankford value is obtained.

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