Proceedings of the 12th International Conference on
Aluminium Alloys, September 5-9, 2010, Yokohama, Japan

pp. 1201-1206

Improvement in Deep Drawability by Texture Control for Rolled and Annealed Aluminum Alloy Sheets

Hirofumi Inoue and Takayuki Takasugi

Department of Materials Science, Graduate School of Engineering, Osaka Prefecture University, 1-1 Gakuen-cho, Naka-ku, Sakai, Osaka 599-8531, Japan

In order to determine the way of improving deep drawability for rolled and annealed aluminum alloys, the correlation between recrystallization texture, *r*-value and limiting drawing ratio (LDR) was investigated for sheet materials with various textures. Using various aluminum alloys, it was experimentally proven that LDR of fully recrystallized materials tended to increase with increasing average *r*-value. In addition, it was suggested that the existence of {111}<uvw> orientation was very effective in improving *r*-value and LDR. To realize the formation of {111}<uvw> texture in industrially manufactured aluminum alloy sheets, a new rolling process, which consists of symmetric cold rolling and subsequent asymmetric warm rolling at one pass, was adopted in AA6022 for automotive body panels. Under an appropriate rolling condition, this process led to significant development of {111}<110> recrystallization texture in the AA6022 sheet solution-treated at high temperature. As a result, it showed much higher average *r*-value and LDR as compared to the conventional sheet produced by cold rolling.

Keywords: *recrystallization texture, r-value, limiting drawing ratio, cold rolling, asymmetric warm rolling*

1. Introduction

In recent years, a demand for weight reduction in automobiles has increased considerably from the viewpoints of reducing CO_2 gas emission and fuel consumption. In particular, the application of aluminum alloys to automotive body panels is forwarded as a means of effective weight reduction. However, the use for aluminum alloy sheets is restricted to relatively flat components. Improving formability is indispensable to their wide application to the body panels and deep drawability is very important for the components with complex shape, which are produced by heavy press-forming, such as inner panels of the door. The ratio of true strain in width to that in thickness obtained from a tensile test of sheet specimen, namely the *r*-value ($r = d\varepsilon_w/d\varepsilon_t$) is generally used as a criterion for evaluating deep drawability. Low carbon steel shows a very high *r*-value of about 2.0, whereas Al-Mg-Si and Al-Mg alloys for body panels show low *r*-values of 0.6-0.7 in an annealed state. Moreover, although there is a positive correlation between *r*-value and limiting drawing ratio (LDR) in steel sheets, a similar correlation in aluminum alloy sheets has not so far been revealed experimentally, because the *r*-value of aluminum alloys produced by conventional processing exists in a narrow range of 0.55 to 0.85 [1]. On the other hand, since the *r*-value greatly depends on crystallographic orientation, we can expect an enhancement of *r*-value by controlling texture of sheet materials. Above all, the development of {111}<uvw> texture, which is difficult for fcc metals, will lead to a high *r*-value with small planar anisotropy in aluminum alloy sheets. In the previous work, it was found that the combination of symmetric rolling and subsequent asymmetric warm rolling induced the formation of {111}<110> recrystallization texture [2, 3].

In this paper, the correlation between experimental *r*-value and LDR obtained by using various samples with extensive *r*-values and the relation between texture and experimental *r*-value based on the prediction of *r*-value by orientation distribution function (ODF) [4] have been described to indicate the way of improving deep drawability for rolled and annealed aluminum alloy sheets. In addition, texture control of age-hardenable AA6022 through the symmetric/asymmetric combination rolling (hereafter SACR) mentioned above has been performed with the aim of improving the *r*-value.

2. Experimental Procedure

2.1 Correlation between *r*-value and limiting drawing ratio

Annealed aluminum alloy sheets with various recrystallization textures were prepared for measurements of the *r*-value and LDR [4]. The alloys employed in this experiment were commercial-grade pure aluminum, Al-Mg alloys and Al-Mg-Si alloys. In order to obtain high *r*-values over 1.0, artificial sheet specimens having {111} orientation in the sheet plane were cut from a hot-rolled AA1100 thick plate and an extruded AA6061 round bar at an appropriate angle.

The *r*-values were measured after tension of 10%, using test pieces cut out at seven directions of 0, 15, 30, 45, 60, 75 and 90° to the rolling direction (RD). In this case, the average *r*-value $\bar{r}$ can be defined by

$$\bar{r} = (r_0 + 2r_{15} + 2r_{30} + 2r_{45} + 2r_{60} + 2r_{75} + r_{90})/12. \qquad (1)$$

Cylindrical deep drawing tests were carried out to evaluate LDR using a flat head punch.

2.2 Relation between texture and *r*-value

Warm rolling develops shear texture in the surface layer and β-fiber texture in the mid-thickness layer [5, 6]. In order to prepare sheet materials with such textural change, Al-4.3%Mg-0.3%Fe and AA6016 alloys were warm rolled to ~90% reduction in thickness by four and three passes at starting temperatures of 623 and 673 K, respectively [4]. These rolled sheets were annealed to obtain a fully recrystallized state.

Since warm rolled materials show a remakable change in texture along the thickness direction, overall ODF through sheet thickness was analyzed from {111}, {100}, {110} and {311} incomplete pole figures measured up to a tilt angle of 75° on the cross section perpendicular to RD (RD-section) by the Schulz reflection method using CuKα radiation. The method for ODF calculation in this case can be referred to elsewhere [5]. In order to relate the measured *r*-values at various directions to recrystallization texture, planar anisotropy of *r*-value was calculated from the overall ODF through sheet thickness using the method proposed by Bunge [7], based on the Taylor full constraints (FC) model [8] and the relaxed constraints (RC) model [9] permitting shear strain perpendicular to the tensile direction.

2.3 Texture control through symmetric/asymmetric combination rolling

Hot rolled AA6022 plates were symmetrically cold rolled to 65-95% reductions in thickness and then asymmetrically warm rolled to 20-40% reductions by one pass at 473 K with a roll speed ratio of 1.5. The AA6022 sheets fabricated by this SACR process were solution treated at 813 K for 90 s.

The effects of reductions in cold rolling (CR) and asymmetric warm rolling (AWR) on recrystallization texture of the solution-treated material were investigated by means of electron back-scatter diffraction (EBSD) method using a scanning electron microscope.

3. Results and Discussion

3.1 Correlation between *r*-value and limiting drawing ratio

Figure 1 shows a correlation between average *r*-value and LDR for the sheet specimens with various average *r*-values ranging from 0.41 to 1.61 [4]. Strain ratio *q* [7] is given by the equation:

$$q = -\mathrm{d}\varepsilon_w / \mathrm{d}\varepsilon_l = r/(1+r) \qquad (2)$$

where $-\mathrm{d}\varepsilon_w$ and $\mathrm{d}\varepsilon_l$ are true strains in width and in gauge length, respectively. As shown in this figure, although LDR increases with increasing average *r*-value, it is certain that the correlation

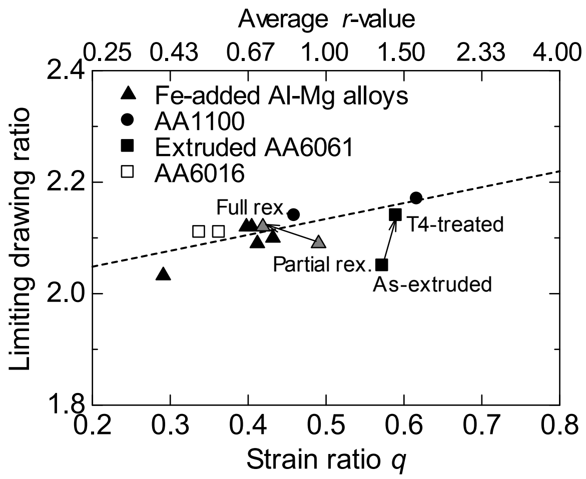

Fig. 1 Correlation between average *r*-value and LDR for aluminum alloys with various textures.

with LDR is better for q-value than for r-value, i.e. there is a nearly linear correlation between q-value and LDR, except for as hot-extruded AA6061 and partially (~80%) recrystallized Fe-added Al-Mg alloy. This is because a change in strain ratio ranging from $q = 0$ to $q = 1$ is equivalent to that ranging from $r = 0$ to $r = \infty$. Accordingly, the horizontal axis of q-value with regular intervals is more suitable for expressing the correlation with LDR than that of r-value.

Low LDRs of the as-extruded or partially recrystallized material as compared to the T4-treated or fully recrystallized material would result from deformed or recovered microstructure retained in their specimens. Locally unrecrystallized microstructure seems to strongly affect LDR, even if elongation of the specimens is apparently sufficient for deep drawing. Therefore, it is necessary to describe the correlation between q-value (or average r-value) and LDR in a fully recrystallized state. It is obvious from Fig. 1 that at least increasing average r-value leads to improvement in deep drawability.

Very high average r-values of 1.61 and 1.44 in Fig. 1 were obtained for the artificial sheet specimens having {111} component as a main orientation in the recrystallized state. This fact suggests that the existence of {111} texture component significantly enhances average r-value, resulting in an increase of LDR. The formation of {111} recrystallization texture is considered to be very effective in realization of high LDR.

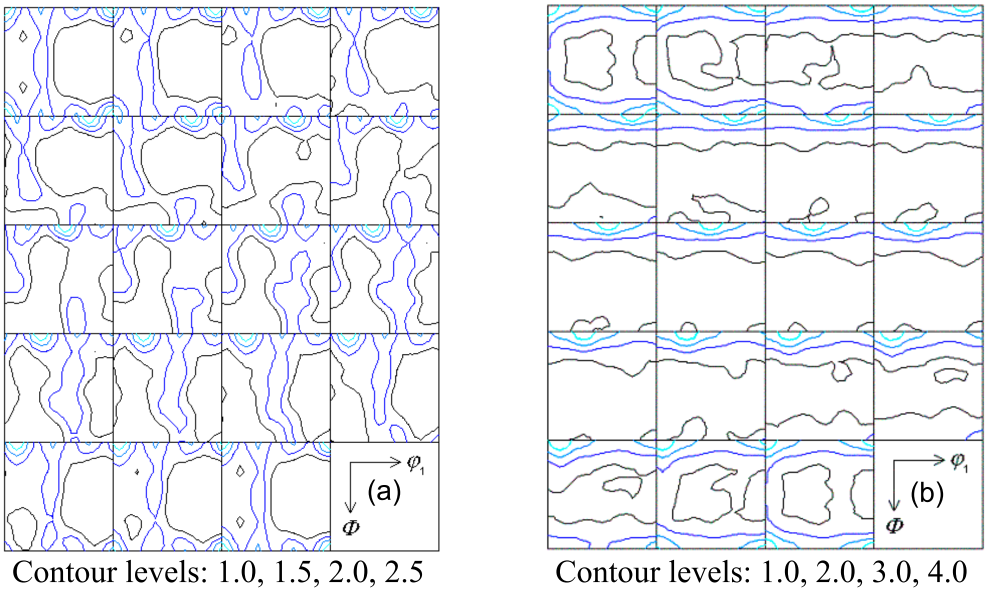

Fig. 2 Overall textures through sheet thickness for (a) Al-4.3%Mg-0.3%Fe alloy sheet annealed at 573 K for 10 ks and (b) AA6016 alloy sheet solution-treated at 793 K for 960 s after warm rolling to about 90% reduction.

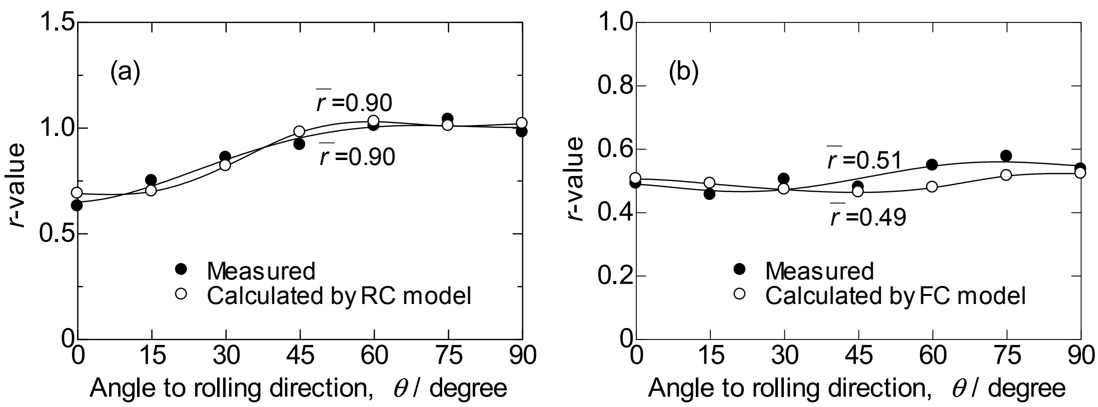

Fig. 3 Comparison between measured and calculated r-values for (a) Al-4.3%Mg-0.3%Fe and (b) AA6016 alloy sheets with recrystallization textures shown in Fig. 2.

3.2 Relation between texture and *r*-value

Al-Mg and Al-Mg-Si alloys were warm rolled to develop shear texture with {111} component in the range from the surface to the quarter-thickness. Overall recrystallization texture through sheet thickness and planar anisotropy of *r*-value calculated from it are shown in Figs. 2 and 3, respectively [4]. Both alloys have a relatively weak recrystallization texture affected by shear texture, but the influence of shear texture is observed more clearly in Al-Mg alloy than in Al-Mg-Si alloy annealed at a higher temperature. The comparison between measured and calculated *r*-values in Fig. 3 indicates that it is possible to predict planar anisotropy of *r*-value with good accuracy, using the RC model for Al-Mg alloy but the FC model for Al-Mg-Si alloy. The easiness of inhomogeneous deformation in Al-Mg alloy seems to be responsible for the fact that the RC model is more suitable for prediction of *r*-value as compared to Al-Mg-Si alloy.

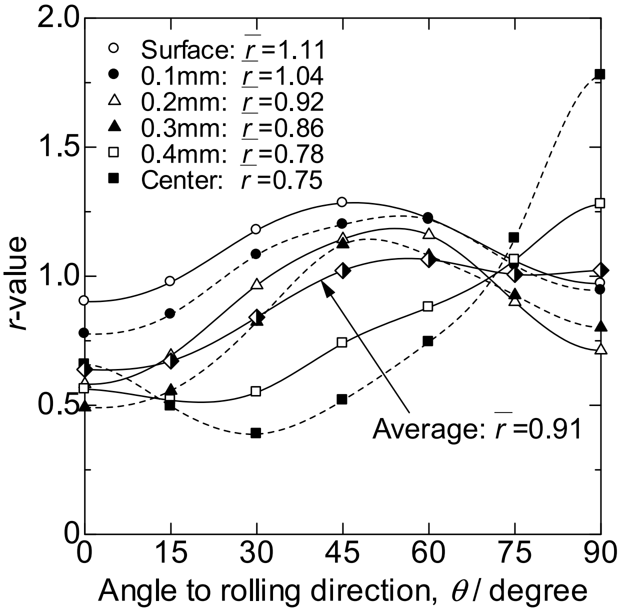

Fig. 4 Planar anisotropy of *r*-value at different locations calculated by the RC model from the texture at each layer for warm rolled and annealed Al-4.3%Mg-0.3%Fe alloy sheet.

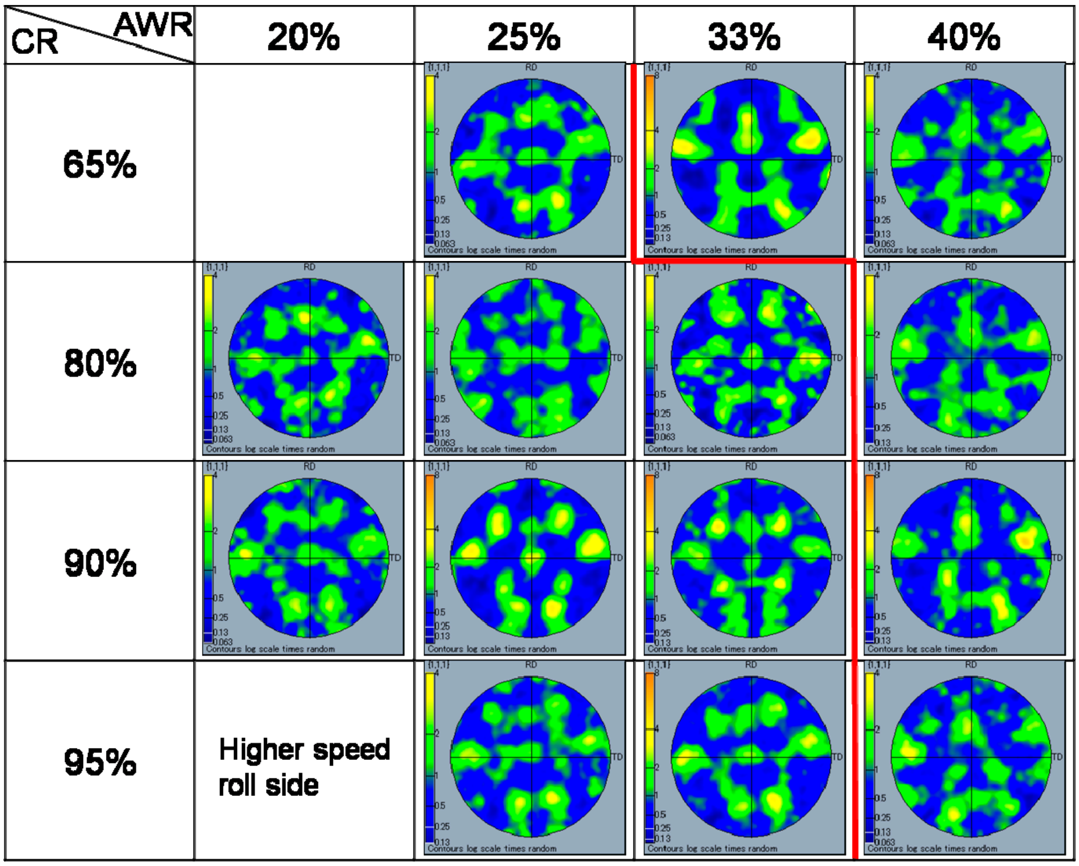

Fig. 5 {111} pole figures of recrystallization textures measured on the longitudinal section by the SEM-EBSD method for AA6022 alloy sheets solution-treated at 813 K for 90 s after cold rolling (CR) and subsequent asymmetric warm rolling (AWR).

Figure 4 shows planar anisotropy of r-values calculated by the RC model from the textures at different locations along the thickness direction for a 1 mm thick Al-Mg alloy sheet [4]. Although the r-value varies significantly depending on the location, the average of respective r-values calculated by taking the volume of each layer into account (0.91) is in good agreement with both the average r-value measured experimentally (0.90) and that calculated from overall texture through thickness (0.90) shown in Fig. 3 (a). This means that whether there is a great textural change or not, the r-value can be quantitatively related to overall texture through sheet thickness. As shown in Fig. 4, the surface and 0.1 mm inner layers strongly affected by shear texture indicate higher r-values in a wide range of 0 to 75° than the other layers, because a {111}<110> orientation, which is one component of shear texture, exists as a main component in these two layers even after recrystallization.

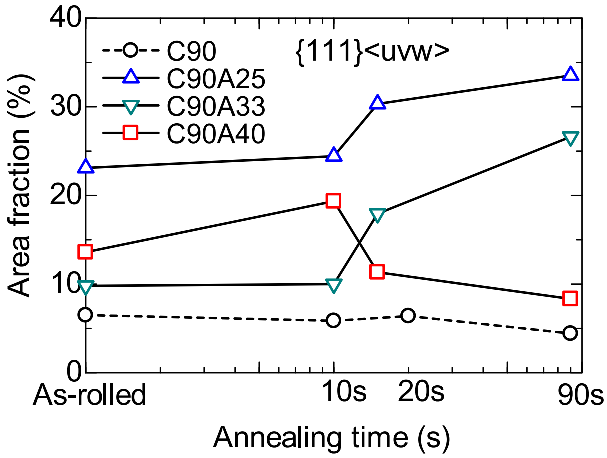

Fig. 6 Change in area fraction of {111}<uvw> component during annealing at 813 K for 90% cold rolled samples. Here C90A25 means a sample produced by the process of 90% cold rolling + 25% asymmetric warm rolling.

3.3 Texture control through symmetric/asymmetric combination rolling (SACR)

The effect of rolling reduction on recrystallization texture of the AA6022 sheets fabricated by the SACR process consisting of CR and subsequent AWR is shown by {111} pole figures in Fig. 5. The near-{111}<110> recrystallization texture is formed at relatively low reductions of AWR, while the {111} orientations hardly develop at all CR reductions under the condition of 40% AWR reduction. This fact suggests that excessive shear deformation by AWR is unfavorable for the development of {111} texture during recrystallization. On the other hand, the {111}<uvw> component develops most strongly during recrystallization in a sample with rolling conditions of 90% CR reduction and 25% AWR reduction (sample C90A25) and it reaches an area fraction of 33.5% in a fully recrystallized state, as shown in Fig. 6. The average r-value $\bar{r}$, anisotropic parameter Ar (Ar = r_{max}/r_{min}) and LDR measured for some representative samples are shown in Fig. 7. The sample with high average r-value and small planar anisotropy such as samples C90A25 and C90A33 exhibits the highest LDR of 2.11 in contrast to a conventional cold-rolled sheet with LDR of 2.05. Thus the SACR process is very effective in improving deep drawability.

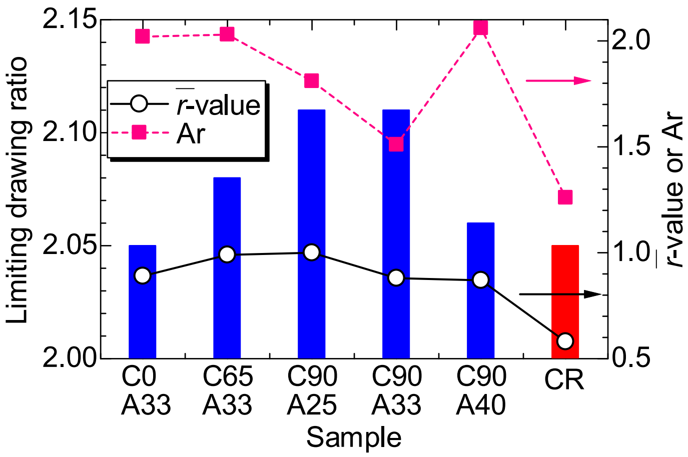

Fig. 7 Effect of r-value on limiting drawing ratio for samples produced by various rolling processes. Ar is the anisotropic parameter defined by Ar = r_{max}/r_{min}.

4. Summary

The chief results of this study on texture control of rolled and annealed aluminum alloy sheets are summarized below.

(1) Since LDR of fully recrystallized materials tends to increase with increasing average *r*-value, the enhancement of average *r*-value is indispensable for improving deep drawability. In addition, it is also important to reduce in-plane anisotropy of *r*-value.

(2) The *r*-value of aluminum alloy sheets can be predicted with good accuracy from overall orientation distribution through sheet thickness. From calculation of *r*-value at certain locations along the thickness direction, it has been found that the surface layer of warm rolled sheets including {111}<110> orientation after recrystallization exhibits relatively high *r*-values at various angles to the rolling direction.

(3) The SACR process consisting of cold rolling and subsequent asymmetric warm rolling at one pass greatly develops {111}<110> recrystallization texture in the age-hardenable AA6022 sheets solution-treated at high temperature, resulting in high average *r*-value, small planar anisotropy of *r*-value and thus vastly improved deep drawability.

References

[1] *Formability of Aluminum Alloy Sheets*, Ed. by Metal Forming Section, (Japan Institute of Light Metals, Tokyo, 1985).

[2] H. Inoue, M. Hori, T. Komatsubara, H. Tanaka and T. Takasugi: Mater. Sci. Forum 558-559 (2007) 207-212.

[3] H. Inoue, S. Kobayashi, M. Hori, T. Komatsubara and T. Takasugi: *Applications of Texture Analysis*, Ed. by A. D. Rollett, (John Wiley & Sons, Hoboken, 2009) pp. 445-452.

[4] H. Inoue and T. Takasugi: Mater. Trans. 48 (2007) 2014-2022.

[5] H. Inoue and T. Takasugi: Z. Metallkd. 92 (2001) 82-88.

[6] O. Engler, H. C. Kim and M. Y. Huh: Mater. Sci. Technol. 17 (2001) 75-86.

[7] H. J. Bunge: Kristall und Technik 5 (1970) 145-175.

[8] G. I. Taylor: J. Inst. Metals 62 (1938) 307-324.

[9] H. Honneff and H. Mecking: *Proc. 5th Int. Conf. on Textures of Materials*, Ed. by G. Gottstein and K. Lücke, (Springer-Verlag, Berlin, 1978) Vol. I, pp. 265-275.