Temperature and Strain Rate Dependence of Mechanical Properties and Square Shell Deep Drawability of Al–Mg Alloy Sheets in Warm Working Condition *

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Uniaxial tensile tests and square shell deep drawing tests on 5000 series aluminum alloy sheets were carried out at temperatures ranging from room temperature (RT) to 300°C in order to investigate temperature and strain rate dependence of tensile properties and deep drawability. At these warm working temperatures, tensile strength (TS) decreases with the increase in testing temperature, and this decrease in TS becomes smaller at high strain rate. Elongation (El) is nearly constant in the range from RT to 100°C, but increases largely with the increase in temperature more than 100°C, and this increase in El becomes larger at low strain rate. This change in El mainly depends on local elongation (LEl). Limiting drawing ratio (LDR) of square shell deep drawing in high speed forming becomes slightly bigger than in low speed forming. The change in LDR is small in the temperature range from RT to 150°C. Above 150°C, the LDR value becomes larger, but it becomes smaller in high speed forming. The difference between the LDR value at elevated temperature and that at RT is designated as ∆LDR value, and this ∆LDR shows the effect of warm deep drawing. The correlation between ∆LDR and mechanical properties (TS, El, LEl) was investigated and the effective experimental equation was derived.

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1. Introduction

After the “Kyoto International Conference for Global Environment Problems” in 1997, the decrease of global warming gas such as CO2 became an urgent need for automobile manufacturers. For this purpose, the reduction of automobile weight has become one of the biggest needs, and the increase in the amount of high strength steel (HSS) sheet and aluminum sheet for car body has been remarkable. A prototype car with all aluminum body has been succeeded by a few other types of applications of aluminum alloy sheets. New aluminum alloy sheets, which have enough strength and ductility for automobile use, have been developed. However, forming techniques for the aluminum sheets are necessary because they have less r-value and ductility than cold-rolled steel sheets. Warm forming is one of these forming techniques for aluminum alloy sheets. As for mechanical properties of aluminum alloy sheets in warm working condition, temperature dependence and temperature and strain rate dependence have been investigated. Abe et al. conducted research on temperature dependence of tensile strength (TS), elongation (El), work hardening (n) value and r-value using an A5182-O sheet in the temperature range from room temperature (RT) to 300°C. Ayres also conducted research on temperature and strain rate dependence of El, in the temperature range from RT to 250°C, at the strain rate from 2.9 × 10−4 s−1 to 1.5 × 10−1 s−1, using a pure aluminum sheet and Al–(1–6)%Mg alloy sheets. The authors, in the previous paper, reported the correlation between deep drawability and temperature dependence of mechanical properties using 5000 series aluminum alloy sheets in warm working condition.

In this paper, temperature and strain rate dependence of TS, El, local elongation (LEl) of 5000 series aluminum alloy sheets, that of square shell deep drawability and the correlation between deep drawability and mechanical properties were investigated in warm working condition.

2. Experimental Procedure

2.1 Materials and uniaxial tensile tests

Materials were two aluminum alloy sheets of 5000 series of 1.0 mm thickness as shown in Table 1. Both materials were O-types and had low Fe and Si component. Mechanical properties were measured by uniaxial tensile test at room temperature (RT) using JIS No. 5 test piece with 25 mm gauge width and 50 mm gauge length, utilizing elongation meter. The cross-head speed of this tensile test was 10 mm/min (strain rate is 3.3 × 10−3 s−1).

Another type of test piece as shown in Fig. 1, 12 mm in width and 20 mm in gauge length without elongation meter, was used for uniaxial tensile test in the temperature range from RT to 300°C, utilizing a 98 kN tensile testing machine. The gauge portion was heated with an induction heating gas such as CO2.

Fig. 1 Test piece and testing method used to investigate the effect of the temperature and strain rate at RT and elevated temperatures.
heater. The temperature of test piece was controlled with thermo-controller by detecting the temperature of the test piece, with an R type thermocouple attached 15 mm from the center of the test piece (5 mm out from bottom gauge line). The length of induction heater is 60 mm and the temperature range of test piece within the parallel portion was ±5°C from the aimed temperature. The cross-head speed (strain rate) was changed from 5 mm/min (4.2 × 10⁻³ s⁻¹) to 100 mm/min (8.3 × 10⁻² s⁻¹). From the measured load curve, El was divided to UEI (the elongation up to peak load) and LEI (the elongation after peak load).

2.2 Square shell deep drawing tests

A 780 kN oil hydraulic double-action press was used for square shell deep drawing tests. Punch and die set are shown in Fig. 2. The punch was cooled from inside by coolant and the flange (die and blank holder set) was heated by inserted heaters. This type of test is called “cooled punch and heated flange” deep drawing test. In this paper, the forming temperature is the flange temperature. For example, 250°C forming was means deep drawing with RT punch and 250°C flange. As for the punch and die set dimensions, 75 mm square punch with punch radius (r_p) 5 mm and with punch corner radius (r_pe) 8 mm and 80 mm square die with die radius (r_d) 5 mm and with die corner radius (r_de) 8 mm were used.

As the testing machine has an accumulator in the oil hydraulic circuit, punch speed can be changed into low speed forming and high speed forming. In the low speed forming, the accumulator is not used and punch speed is 5 mm/s. The strain rate of low speed forming is calculated from the following conditions. The drawing ratio (DR) is 1.6 and formed height is 20 mm. In this sample, 5 mm scribed circles were etched on the specimen in advance, and average equivalent plastic strain measured using the circles near the die radius was 0.224. The strain rate of low speed forming becomes 5.6 × 10⁻² s⁻¹ by dividing the above equivalent plastic strain (0.224) by forming time (4 s). The authors think that this plastic equivalent strain value of 0.224 is reasonable, because Hanaki et al.14) reported that equivalent plastic strain at flange portion ranged from 0.17 to 0.26 in cylindrical deep drawing with DR of 1.49. In the high speed forming, the punch speed becomes 50 mm/s, utilizing the accumulator, and the strain rate of high speed forming is 5.6 × 10⁻¹ s⁻¹. The lubricant was mixed type of soapy water and MoS².

The valuation of deep drawability is made generally in terms of LDR (Limiting Drawing Ratio). The LDR value at each temperature is decided by changing flange temperature. The difference between LDR value at elevated temperature and at RT is decided as ∆LDR in this paper. This ∆LDR shows improvement in deep drawability by raising the forming temperature.

2.3 Experimental equation evaluating relationship between ∆LDR and mechanical properties

The relationship between ∆LDR and mechanical properties was investigated with reference to the experimental equation which was proposed in the previous paper. In the case of deep drawing, an idea exists that deep drawability depends on the balance of material strength at the punch shoulder portion and deformation resistance at the flange portion. The αTS in eq. (1) corresponds with this idea and it is calculated as follows. Material strength at the punch shoulder portion corresponds with TS_p (TS of material at punch temperature) and deformation resistance at the flange portion corresponds TS_r (TS of material at flange temperature). As the difference of the former and the latter is divided by TS_R (TS of material at RT), αTS has no dimension. The reason why TS_R is adopted for the denominator is that ∆LDR shows the effect of warm forming compared with RT forming. The larger the αTS, the more the ∆LDR. From another viewpoint, in square shell deep drawing, formability of flange is necessary because unequal deformation occurs near the flange corner. From this idea, the effect of local elongation (LEI) is considered as shown in eq. (2). As shown in the previous paper,13) for expressing the formability of the flange, LEI is better than El, and El at RT (El_R) is adopted for the denominator of eq. (2).

In eq. (3), α' is the sum of αTS and αLEI. The meanings of symbols are as follows;

\[ \alpha' = \frac{(TS_p - TS_r)}{TS_R} \]

\[ \alpha_{LEI} = \frac{LEI_R}{El_R} \]

\[ \alpha_{TS} = \frac{TS_p - TS_r}{TS_R} \]

\[ \alpha' = \alpha_{TS} + \alpha_{LEI} \]

The relationship between ∆LDR and mechanical properties is evaluated with this equation.
\[ \alpha_{LEl} = \frac{(LEl_F - LEl_R)}{El_R} \]  
\[ \alpha' = \frac{(TS_F - TS_R)}{TS_R} + \frac{(LEl_F - LEl_R)}{El_R} \]

3. Experimental Results

3.1 Temperature and strain rate dependence of mechanical properties

Temperature and strain rate dependences of tensile strength (TS) and elongation (El), in the temperature range from RT to 300°C, in the strain rate range from \(4.2 \times 10^{-3} \text{s}^{-1}\) to \(8.3 \times 10^{-2} \text{s}^{-1}\), are shown in Fig. 3 and Fig. 4, respectively.

The TS slightly changes from RT to 100°C, but it sharply decreases with the increase in temperature above 100°C, in both materials. The decreased amount of TS is greater at the lower strain rate. From Fig. 4, El slightly changes from RT to 100°C, but it increases much with the increase of temperature above 100°C, in both materials. The increase in El is larger at lower strain rate.

The strain rate dependences of TS, El, and local elongation (LEl) are shown in Figs. 5–7. In these figures, a line is used...
3.2 Temperature and strain rate dependence of square shell deep drawability

The relationship between LDR and flange temperature, in the temperature range from RT to 300°C, is shown in Fig. 8 for low speed forming (5.6 × 10⁻³ s⁻¹) and high speed forming (5.6 × 10⁻² s⁻¹) in the case of “cooled punch and heated flange” deep drawing. In this figure, LDR of high speed is a little larger than that of low speed, as Gotoh et al.¹⁵ showed, and this is assumed to be caused by the fluid lubricant effect. In the temperature range from 100 to 150°C, the change in LDR is small. Above 150°C, LDR increases with the increase in temperature, and LDR of high speed is less than that of low speed. The reason will be investigated in the next chapter.

4. Relationship between Square Shell Deep Drawability and Mechanical Properties

The relationship between ΔLDR and mechanical properties were examined with eqs. (1) to (3) in order to investigate the temperature and strain rate dependence of LDR. The strain rates used to assess the mechanical properties in the previous paper¹³ did not match that of deep drawing speed. In this paper, two of the strain rates are close to that of low speed as shown in Figs. 5–7. The values of TS, El and LEl, applied to eqs. (1) to (3), were derived from the intersections of dotted line and approximation lines or curves as shown in Figs. 5–7. The correlation between α’ and ΔLDR is shown in Fig. 9. In this figure, different symbols were used to recognize the material and the forming speed, and the coefficient of correlation (ρ) is shown in Table 2. From Table 2, the coefficients of correlation of Material A and that of Material B are the same value, and that of low speed forming and that of high speed forming become the same value of 0.96. As a result, the approximation methods of TS, El and LEl, as shown in Figs. 5–7, are reasonable near the strain rate of 1 s⁻¹. From another viewpoint, ρ value (0.96) between α’ and ΔLDR ex-
Table 2 Coefficient of correlation ($\rho$) between $\Delta LDR$ and $\alpha'$ for different materials and forming speeds.

<table>
<thead>
<tr>
<th>Material</th>
<th>Low speed</th>
<th>High speed</th>
<th>Whole</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material A</td>
<td>0.98</td>
<td>0.96</td>
<td>0.96</td>
</tr>
<tr>
<td>Material B</td>
<td>0.96</td>
<td>0.97</td>
<td>0.96</td>
</tr>
<tr>
<td>Whole</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
</tr>
</tbody>
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ceeds that (0.94) of $\sigma_{TS}$ and $\Delta LDR$. This is the same result as shown in the previous paper.\(^{13}\)

5. Conclusion

Uniaxial tensile tests and square shell deep drawing tests on 5000 series aluminum alloy sheets were carried out at temperatures ranging from room temperature to 300°C in order to investigate the temperature and strain rate dependence of deep drawability and of mechanical properties. The following conclusions were obtained.

1. As for tensile strength (TS), the change in TS is small from RT to 100°C, while TS decreases much with the increase in temperature above 100°C. And this decrease in TS becomes less marked at high strain rate.

2. As for elongation (El), El is nearly constant in the range from RT to 100°C, but it increases markedly with the increase in the temperature above 100°C. This increase in El becomes larger at low strain rate. This change in El is based mainly on that in local elongation (LEl).

3. Limiting drawing ratio (LDR) of square shell deep drawing in high speed forming becomes a little larger than in low speed forming. The change in LDR is small in the temperature range from RT to 150°C. Above 150°C, the LDR value becomes larger, but the tendency becomes less marked in high speed forming.

4. The difference between the LDR value at elevated temperature and that at RT is decided as $\Delta LDR$ value, and this $\Delta LDR$ shows the effect of warm deep drawing. The correlation between $\Delta LDR$ and mechanical properties (TS, El, LEl) was investigated and the effective experimental equation was developed.

REFERENCES