Assessment of Deep-Drawability of Commercially Pure Titanium Sheets in Consideration of r -Value Change During Processing*

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In the previous study, the deep-drawabilities of commercially pure aluminum sheets and mild steel sheets were studied in detail taking account of the change of r value during the processing. From the same viewpoint, this paper discusses the deep-drawability of commercially pure titanium sheets which have a crystal structure of hexagonal close-packed lattice, different from aluminum and steel. The limiting drawing ratio, LDR, increases with the average r value ($\bar{r}$ value), but the rate of increase $\Delta\text{LDR}/\Delta\bar{r}$ is relatively small. The fracture strength correlates positively with the $\bar{r}$ value, as in the theory, but the maximum drawing load remains constant irrespective of the $\bar{r}$ value, against the theory. This relation can be connected with the result of the LDR, and resembles that of mild steel sheets. These experimental results can be well explained by the change of $\bar{r}$ value during equibiaxial and pure-shear straining. The change of r value is confirmed by texture analysis.

Key Words: Forming, Deep-Drawing, Titanium Sheet, r Value, Limiting Drawing Ratio, Fracture Strength, Drawing Load, Strain Path, Texture

1. Introduction

The authors have discussed in detail the deep-drawability of commercially pure aluminum sheets⁽¹⁾ and mild steel sheets⁽²⁾. In both cases, the limiting drawing ratio, LDR, correlated positively with the r value averaged in a plane ($\bar{r}$ value). However, the rate of increase $\Delta\text{LDR}/\Delta\bar{r}$ was relatively small in commercially pure aluminum sheets, and the relation between the LDR and the $\bar{r}$ value was nonlinear in mild steel sheets, different from the results reported hitherto. The reason was sought from the fracture strength, T_{cr} , and the maximum drawing load, T_{max} , separately. It was found that the r value changed during processing and so the above result was induced. The change of r value was affected by the kind of sheet metal and the plastic strain path, and these facts

were considered to be attributed to the crystal structure.

This study deals with commercially pure titanium sheets which have a hexagonal close-packed lattice (*hcp*), different from the face-centered cubic lattice (*fcc*) of aluminum, or the body-centered cubic lattice (*bcc*) of mild steel. The deep-drawability is examined in detail and discussed in consideration of r -value change during processing.

2. Test Materials and Sheet Making Processes

For this study, sheets of 0.8 mm in thickness with various r values were self-made by the processes shown in Fig. 1. The process program was decided by referring to the study of Hasegawa et al.⁽³⁾. One of the starting materials was a hot-rolled commercially pure titanium sheet of JIS class 2 with a thickness of 4 mm. The chemical composition is shown in Table 1. A lower r -value sheet was made by repetitions of cold rolling and intermediate annealing. The direction of cold rolling was the same as in the original. A higher r -value sheet was made by cold rolling without intermediate annealing. In this case, the direction of the cold rolling crossed at right angles with the original.

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Table 1 Chemical composition of titanium sheet (Wt%)

(a) Sheet A and sheet C (JIS class 2)

C	Fe	N	O	H	Ti
-	0.064	0.0034	0.072	0.0014	Re

(b) Sheet B (JIS class 1)

C	Fe	N	O	H	Ti
-	0.039	0.0018	0.038	0.0032	Re

Fig. 1 Sheet-making processes

All annealings were treated under $700^{\circ}\text{C} \times 3$ hours heating in a vacuum and then furnace cooling for 5 hours. The roll oil of 4.6 cSt in viscosity was spread on both surfaces of the sheet at every rolling. The cold reduction was about 5% per one pass.

Hereafter, the lower and the higher r -value sheets were designated sheet A and sheet C, respectively. In addition to these sheets, a commercially pure titanium sheet termed B on marketing was prepared for comparison. However, sheet B was 0.9 mm in thickness and JIS class 1 purer than class 2. Sheet B was cold rolled to 0.8 mm of the same thickness as sheet A and C and final annealed, and then tested.

3. Experimental Conditions

3.1 Uniaxial tensile test

JIS 13B type specimens were machined out from the sheets. Tensile directions were 0° , 45° , and 90° to the rolling direction in the sheet plane. The tensile speed was 10 mm/min. The r value was estimated by the equation $r = -\epsilon_b / (\epsilon_l + \epsilon_b)$, where ϵ_b was the logarithmic width strain and ϵ_l was the logarithmic length strain measured from the specimen tensioned by

Table 2 Working conditions of deep-drawing test

Tools	Punch	Diameter $2r_1=40$ mm Profile radius $r_p=4$ mm (Flat-headed punch), 20 mm (Round-headed punch)
	Die	Diameter $2r_2=42.5$ mm Profile radius $r_d=6$ mm
Lubricant		Teflon sheet + Bright stock
Punch speed		0.2 mm/sec
Blank holding force		$2 \times$ Siebel's semi-theoretical value ⁽⁴⁾
Drawing ratio interval for determining LDR		0.025

nominal length strain $e_l=15\%$. The n value was calculated by the least squares method within the strain range from $e_l=4\%$ to the uniform elongation e_u , assuming the n -power law $\sigma = F\epsilon^n$ between the stress σ and the strain ϵ . Total elongation was the nominal length strain at the instant when the load lowered rapidly in a load-elongation diagram.

The average value, $\bar{X}$, was calculated by $\bar{X} = (X_0 + 2X_{45} + X_{90})/4$, where X_0 , X_{45} , and X_{90} were the measurements in the tensile direction 0° , 45° , and 90° .

3.2 Deep-drawing test

Deep-drawability was examined by a flat-headed punch (diameter $\phi=40$ mm and punch profile radius $r_p=4$ mm) and a round-headed punch ($\phi=40$ mm, $r_p=20$ mm). Table 2 shows the test conditions used. Both surfaces of the blank were lubricated by teflon sheets with bright stock oil. Limiting drawing ratio LDR was determined by the Swift method with a drawing ratio interval of 0.025⁽⁵⁾.

3.3 Loading methods for prestrain and r -value measurements of prestrained sheets

The r value were measured from equibiaxially tensioned and pure-sheared sheets. These strain paths resemble those for the punch profile and the flange of a cup⁽¹⁾⁽²⁾ respectively. An equibiaxially tensioned sheet was obtained from the flat bottom of a cup which was pure stretched by using a flat-headed punch of $\phi=40$ mm and $r_p=4$ mm⁽⁶⁾. A pure-sheared sheet was obtained from the strip drawn in width by a die which had a wedge-shaped gap in width and a constant gap in thickness. The outlet width of the die was 20 mm and the wedge angle was 20° . The constant gap was about 0.8 mm to prevent wrinkling. The value of prestraining was adjusted by changing the width of the strip before drawing.

The elongation of the prestrained sheet was sometimes less than a few percent. Then, the following were adopted as the standard of r -value measurements: when the specimen elongated uniformly larger than the length strain $e_l \div 4\%$, the r value was measured from the specimen tensioned by $e_l \div 4\%$; when the elongation was less than 4%, it was measured from the specimen tensioned just before necking. The

specimen size of the prestrained sheet was one-fifth of JIS 13B type, due to the size limitation.

3.4 Measurement of texture

A specimen of about 0.1 mm in thickness was etched out from the middle layer of the sheet, by using the aqueous solution of hydrogen fluoride. The {0002} pole figure was drawn by the Decker method using transmitted $Mo-K\alpha$ X rays, and the Schultz method using reflected $Mo-K\alpha$ X rays.

4. Tensile properties

The r value measured in the tensile test sometimes changed markedly by increasing the tensile strain, which was attributed to the few slip systems of titanium. Figure 2 shows the relation between the nominal length strain e_l and the obtained r value. The same symbol in the figure shows all data obtained under the same condition. In sheet A, the r value does not change irrespective of e_l in any direction. In 90° of sheet B, and 45° and 90° of sheet C, where the r value indicates larger than 3 at $e_l=4\%$, the r value decreases considerably with increasing e_l . To assess the deep-drawability from the r value, the question of which r value should be adopted must be discussed. However, all the curves of r -value change do not cross one another within this experiment and so the order of r value does not vary. So, this study adopted the r value at $e_l=10\%$ referring to previous data⁽³⁾. Table 3 shows these r values and other tensile properties.

The r values of sheet A and sheet C both indicate $r_{90} > r_{45} > r_0$, but they are appreciably different from each other for the values $\bar{r}=1.580$ and 2.465 respectively. The r value of sheet B indicates $r_{90} \approx r_{45} > r_0$ differently from sheet A and C, and becomes $\bar{r}=1.686$ analogously in sheet A.

It is shown in the table that the $\bar{n}$ value of sheet

B is relatively larger, the total elongation considerably larger, and the tensile strength smaller than the others. The result can be attributed to the purity of the starting material.

5. Assessment of Deep-Drawability

5.1 Correlation between limiting drawing ratio LDR and r value

In the deep-drawing test, all specimens fractured at the punch profile region after necking. It had been confirmed by the authors' study that the LDR in this case correlates positively to the $\bar{r}$ value⁽⁷⁾. Figure 3 shows the relation between the LDR and the $\bar{r}$ value, where previous results obtained by the authors in commercially pure aluminum sheets (symbol ●)⁽¹⁾ and mild steel sheets (symbol △)⁽²⁾ are also presented. The LDRs in the flat-and the round-headed punch both correlate positively to the $\bar{r}$ value, although that of sheet B is relatively higher. This can be attributed to the larger n value of sheet B mentioned above. Then, the results for sheet B are kept only for reference. The ratio of increase, $\Delta LDR/\Delta \bar{r}$, of the titanium

Table 3 Tensile properties

	To RD	r	n	S_T (MPa)	λ (%)
A	0°	1.195	0.121	387.8	33.2
	45°	1.550	0.120	390.3	32.7
	90°	2.026	0.119	383.8	33.4
	ave	1.580	0.120	388.1	33.0
B	0°	0.756	0.293	330.1	50.7
	45°	2.000	0.128	307.5	54.1
	90°	1.948	0.126	326.8	39.4
	ave	1.686	0.169	318.0	49.6
C	0°	1.427	0.179	389.4	39.3
	45°	2.596	0.131	381.0	33.7
	90°	3.242	0.115	386.1	29.8
	ave	2.465	0.139	384.4	34.1

S_T : Tensile strength, λ : Total elongation

Fig. 2 Relation between r value and tensile strain

(a) Flat-headed punch

(b) Round-headed punch

Fig. 3 Relation between LDR and $\bar{r}$ value

sheets is smaller than that of mild steel sheets and is analogous to that of aluminum sheets in both the flat- and the round-headed punch.

To explain these results, the fracture strength, T_{cr} , and the maximum drawing load, T_{max} , which control LDR directly, are examined separately.

5.2 Fracture strength, T_{cr}

Figure 4 shows the relation between the normalized fracture strength, $T_{cr}/2\pi r_1 t_0 S_T$, and the $\bar{r}$ value in the flat- and the round-headed punch. T_{cr} is the fracture load measured from blank immediately above LDR and calculated from the fracture punch load, P_{cr} , by the relation $T_{cr} = P_{cr}/\sin \alpha$, where α is the geometric contact angle of a blank to the punch profile at the fracture stage. The r_1 is the punch radius, t_0 is the initial thickness of the blank, and S_T is the average tensile strength; then $2\pi r_1 t_0 S_T$ means the nominal strength of a cup wall. In the figure, the solid line shows the instability load by Yamada's theory⁽⁸⁾. In the theory, the plane strain condition is assumed for a flat-headed punch, and the equibiaxial condition for a round-headed punch. The n values of $n = 0.13, 0.2$, and 0.28 in the calculation agree with the $\bar{n}$ value of the titanium sheet, the mild steel sheet, and

(a) Flat-headed punch

(b) Round-headed punch

Fig. 4 Relation between fracture strength and $\bar{r}$ value

the commercially pure aluminum sheet, respectively.

The fracture strength of sheet B is extremely high for both the flat- and the round-headed punch. The values of sheets A and C have positive correlation to the $\bar{r}$ value, but the rate of increase $\Delta T_{cr}/\Delta \bar{r}$ is smaller than that of the theory. A similar result was reported by Hasegawa et al.⁽³⁾. This result should be discussed mainly based on the r value, because sheet A and sheet C have almost the same n value. The positive correlation between T_{cr} and the $\bar{r}$ value in titanium sheets is approximately the same as in mild steel sheets, but the value $\Delta T_{cr}/\Delta \bar{r}$ in titanium sheets is smaller than that of mild steel. On the other hand, the value $\Delta T_{cr}/\Delta \bar{r}$ in aluminum sheets is about zero, or slightly negative.

5.3 Maximum drawing load, T_{max}

Figure 5 shows the relation between the normalized maximum drawing load, $T_{max}/2\pi r_1 t_0 S_T$, and the $\bar{r}$ value. In the figure, the solid line indicates the numerical solution calculated by Woo's difference method⁽¹⁾ when the drawing ratio B_0 was 2.0, the n value was 0.13, and the friction coefficient μ between blank and dies was 0.14. The value of μ was chosen to accord the calculation with the experiment. The

experimental $T_{\max}$ of sheet A is approximately the same as that of sheet C against the numerical solution which correlates negatively with the r value. The same result was reported by Hasegawa et al.⁽³⁾. The tendency in titanium sheets is similar to that of mild steel sheets⁽²⁾. The $T_{\max}$ in aluminum sheets, however, correlates negatively with the $\bar{r}$ value as in the numerical solution.

From the discussion mentioned above, it is found that the positive correlation between the LDR and the $\bar{r}$ value in titanium sheets is caused by the positive correlation between T_{cr} and the $\bar{r}$ value and the

Fig. 5 Relation between maximum drawing load and $\bar{r}$ value

(a) Sheet A

(b) Sheet C

Fig. 6 Change of r value with equibiaxial tension

constant $T_{\max}$ irrespective of the $\bar{r}$ value. To explain these experimental results, not understandable by numerical solution, the only idea proposed is that the r value of the sheet changes during the deep-drawing.

6. Dependence of r -value Change on Strain Path

6.1 r -value of equibiaxially tensioned sheet

The strain paths of the fracture site in a flat- and a round-headed punch were under nearly equibiaxial tension in the early stage of the deep-drawing. Then, the r values of equibiaxially tensioned sheet A and sheet C were examined. Figure 6 shows the change of r value with straining, which is presented by absolute thickness strain $|\epsilon_t|$. The r value at $e_t=4\%$ in Fig. 2 is plotted as the one at $|\epsilon_t|=0$ in the figure to unify the tensile strain in the r -value measurement.

The r values in all directions of both sheet A and C decrease toward the same value with increasing prestrain. However, the $\bar{r}$ value of prestrained sheet C is still larger than that of sheet A. This relation coincides well with the result of the T_{cr} .

6.2 Texture of equibiaxially tensioned sheet

The change of r value is confirmed by texture

Fig. 7 $\{0002\}$ pole figure of equibiaxially tensioned sheet

analysis. Figure 7 shows the {0002} pole figure of the equibiaxially tensioned sheet. In hcp material, plastic slide occurs mainly parallel to the {0002} plane. Then, if the {0002} plane exists parallel to the sheet surface, the r value will become relatively large, because there is no slip system to induce the change of thickness. If the {0002} plane faces toward the longitudinal direction of the sheet, the r value will become approximately unity. If the {0002} plane faces the transverse direction of the sheet, the r value will become relatively small. The changes of r value in Fig. 6 should be explained from this point of view.

Sheet A in Fig. 7(a) is composed of approximate random orientation and a slightly strong {0002} plane parallel to the sheet surface. This explains the small anisotropy in the plane, and the r value slightly larger than unity. Sheet C in Fig. 7(c) has two strong peaks of the {0002} plane, almost parallel to the sheet surface (symbol B in the figure). So, the relatively strong anisotropy in the r value and the higher $\bar{r}$ value can be understood. When these sheets are prestrained equibiaxially, both {0002} planes parallel and perpen-

dicular to the sheet surface, which are shown as symbol A and C in the figure, become strong. Sheet A approaches rotational symmetry, but sheet C still remains strongly orientated as shown symbol B. These variations of the texture correspond approximately to their r -value changes.

6.3 r -value change of pure-sheared sheet

Figure 8 shows the change of r value with the equivalent strain ϵ_{eq} by pure shear. The equivalent strain is calculated assuming isotropic Mises' material; that is, $\epsilon_{eq} = -2/\sqrt{3} \cdot \ln(b/b_0)$, where $\ln(b/b_0)$ is the width strain. For the assessment of T_{max} , the average r value should be noted⁽⁷⁾. The $\bar{r}$ values in all drawing directions of sheet A increase with prestraining at the early stage, and then decrease more or less. However, the change is relatively small, and the $\bar{r}$ value ranges between 1.5 and 2.0. The r value in sheet C changes with the drawing direction. The $\bar{r}$ values in all cases, however, decrease together from 3.5 to 1.5–2.5.

The equivalent strain at the flange when the drawing load reaches maximum in the deep-drawing

Fig. 8 Change of r value with pure shear

Fig. 9 {0002} pole figure of pure-sheared sheet ($\varepsilon_{eq} = 0.166$)

process was about 0.15 in the drawing ratio $B_0 \div 2.0$. The $\bar{r}$ value at $\varepsilon_{eq} = 0.15$ ranges between 1.5 and 2.5 in both sheet A and sheet C in Fig. 8. These r -value changes can explain the experimental result that the T_{max} of sheet A was almost the same as that of sheet C.

6.4 Texture of pure-sheared sheet

Figure 9 shows the {0002} pole figure of the pure-sheared sheet at $\varepsilon_{eq} = 0.166$. In sheet A, the strong band of reflection can be always observed perpendicular to the drawing direction (DD). This corresponds to the fact that the r values perpendicular to the DD at $\varepsilon_{eq} = 0.166$ are smallest in all cases, as shown in Fig. 8(a) ~ (c). The pole figure of Fig. 9(d) shows that the {0002} distribution slightly varies comparing with that

of the original sheet of Fig. 7(c). This explains the monotonous change of the r value in Fig. 8(d). The pole figures of Figs. 9(e) and (f) varied markedly from Fig. 7(c). Thus the rapid changes of the r value in Figs. 8(e) and (f) can be understood. The pole figure of Fig. 9(f) also has the strong band against DD as shown in pure-sheared sheet A. Then, the same change of r value as in sheet A is shown. Such a change of r value as this should be attributed to the crystal rotation, the theoretical analysis of which remains for the future.

7. Conclusions

The effects of the r value on the deep-drawability of commercially pure titanium sheets was investigated in detail. Lower and higher r -value sheets were self-made, and the effects of the r value on the limiting drawing ratio LDR, the fracture strength, T_{cr} , and the maximum drawing load, T_{max} , were examined. The following were clarified.

(1) The LDR correlates positively with the $\bar{r}$ value, but the rate of increase $\Delta LDR / \Delta \bar{r}$ is smaller than that of mild steel sheets and almost equal to that of commercially pure aluminum sheets.

(2) The T_{cr} correlates positively to the $\bar{r}$ value, but the value $\Delta T_{cr} / \Delta \bar{r}$ is small. The T_{max} remains almost constant, irrespective of the $\bar{r}$ value. These can be connected with the result of (1), and the situation is similar to that for mild steel sheets and different from that of aluminum sheets.

(3) The relations in (2) can be explained by the $\bar{r}$ -value changes of sheets equibiaxially tensioned and pure-sheared, which resemble the strain paths of the fracture site at the punch profile and flange respectively.

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