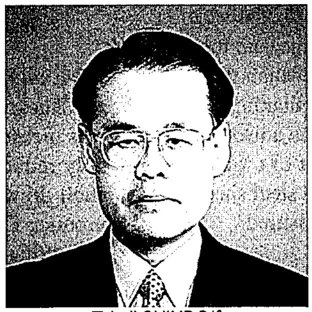
UDC 669 . 295 : 621 . 983

Square Shell Deep Drawability of Commercially Pure Titanium Sheet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Abstract

Uniaxial tensile tests and square shell deep drawing tests were carried out in order to investigate the formability of commercially pure titanium sheets. Materials used for experiments were 3 types of commercially pure titanium (JIS 1,2 class), SUS430, SUS304, and IF steel (Ti-added ultra low carbon steel). As the results, commercially pure titanium sheets have large difference of mechanical properties of 3 directions, but they show the best deep drawability among the four materials. Limiting drawing ratio (LDR) of commercially pure titanium sheets becomes 2.8, by both surface lubrication with polytetrafluoroethylene (Teflon) film, and highly exceeds that (2.33) of Ti-added ultra low carbon steel sheet by rust-preventive oil lubricant.

1. Introduction

It is reported that the most titanium applications in Japan are pure titanium sheets[1]. Improvement of the formability of pure titanium sheets is one of the keys to expanding the application of titanium. The formability of titanium sheets has been studied in terms of various forming techniques such as deep drawing[1-3], stretching[4-5], bending[6], and lubrication[7] during forming. Deep drawability is one of the indicators which are used to evaluate the formability. However, most previous studies have focused on experiments of the small cylindrical deep drawing having a diameter of 50 mm or less. So far it has been confirmed that pure titanium sheets have excellent cylindrical deep drawability as they have high r values[1-3].

However, since the shapes of practical parts such as automobile parts, bathtubs, and heat exchangers are complicated and are often polygons with corners, it is not easy to judge the formability of the material merely on the basis of the performance in cylindrical deep drawing which produces simple axisymmetric shapes. In addition, pure titanium sheets have low n values and tend to cause fusion with tools. With this background, we believe that square shell deep drawing, in which material draw-in is uneven and stretching of corner sections is involved, is more suitable for evaluating the formability of practical parts.

In this paper we discuss the results of a study on the mechanical properties of pure titanium sheet, Ti-added ultra low carbon steel (IF steel) sheet, SUS430 (18Cr) sheet, and SUS304 (18Cr-8Ni) sheet, on the basis of uniaxial tensile tests and square shell deep drawing tests.

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2. Experimental procedure

2.1 Test materials and methods of measuring mechanical properties

Tables 1 and 2 show the properties of test materials and composition of pure titanium sheet respectively. To examine the mechanical properties based on tensile tests, JIS No.5 test specimens were used in connection with yield strength (YS), tensile strength (TS), total elongation (TEl), and n values; JIS No.13A test specimens were used for testing r values. The respective mechanical properties in three directions, L, D, and C (at an angle of 0, 45, and 90 degrees to the rolling direction respectively) were measured. The measurement of n values was conducted in a range of 5-10%, lower than the 5-15% specified for mild steel sheets. In the case of pure titanium, the n values in the L direction only were measured since the anisotropy of this material is very large. Also in the measurement of r values, the range was reduced from the 15% specified for mild steel sheets, and the values at an elongation strain of 10% were measured.

2.2 Method of square shell deep drawing test

The square shell deep drawing test was conducted with a square punch having dimensions of 75 mm and 100 mm per side and square blanks. In this paper, the dimension of a side of the square of a punch is used to identify the type of drawing, for example, 75-mm square shell drawing. A double action hydraulic press with 780 kN for inner action and 490 kN for outer action was used as a forming test machine. Die dimensions include r_p or punch shoulder radius, r_{pc} or punch corner radius, and r_d or die shoulder radius. In the case of 75-mm square shell drawing, the dimensions are r_p = 5 mm, r_{pc} = 8 mm, and r_d = 5 mm. In the case of 100-mm square shell drawing, the dimensions are r_p = 8 mm, r_{pc} = 18 mm, and r_d = 5 mm. Polytetrafluorethylene (Teflon hereinafter) film having a thickness of 0.1 mm as lubricant was applied on both surfaces. Rust-preventive oil lubricant was also applied to the pure titanium sheet and the comparison material, Ti-added ultra low carbon steel (IF steel) sheet.

Limiting drawing ratio (LDR hereinafter), which is the length of the side of the largest blank drawable divided by the length of a side of the square punch, was used as a measure of drawability. The larger the LDR, the higher the drawability.

Table 1 Materials and their mechanical properties (average values in 3 directions)

Symbol	Material	Thickness (mm)	YS (MPa)	TS (MPa)	T.El (%)	U.El (%)	n value (5-10%)	r value (10%)
A	Titanium JIS class 1	0.65	230	316	47.8	14.0	0.16*	3.80
B	Titanium JIS class 1	0.95	227	297	51.9	15.2	0.17*	3.59
C	Titanium JIS class 2	0.60	309	367	42.1	9.7	0.15*	4.05
D	SUS430(18Cr)	0.60	335	479	29.5	18.3	0.19	1.14
E	SUS304(18Cr-8Ni)	0.80	290	654	64.9	>50	0.34	1.12
F	IF steel	0.80	144	302	48.7	28.9	0.29	1.99

* Value in the L direction (The values in the C and D directions were not computed since titanium has a low uniform elongation.)

Table 2 Composition of pure titanium sheets (wt%)

Symbol	Class	H	O	N	Fe	C
A	JIS class 1	0.002	0.06	0.01	0.03	0.01
B	JIS class 1	0.002	0.07	0.01	0.03	0.01
C	JIS class 2	0.001	0.10	0.04	0.05	0.01

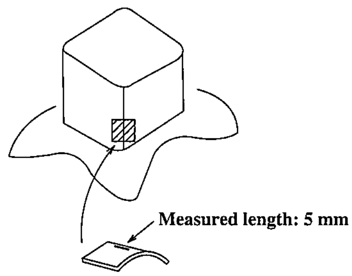


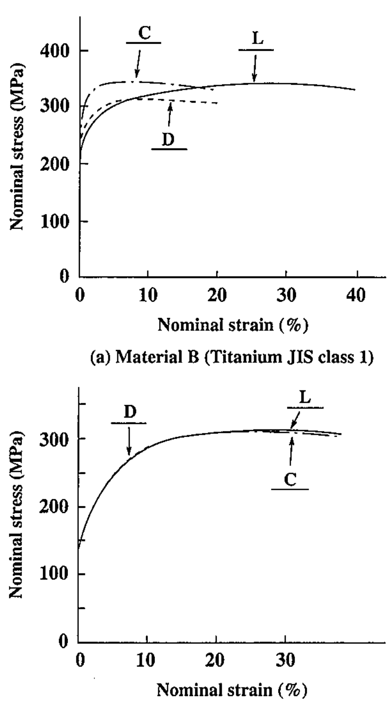
Fig. 1 Methods of cutting a 100-mm square shell sample and measuring surface roughness

2.3 Examination of square shells

Thickness distortion of a 100-mm square shell drawing sample was measured at the corner section where the thickness is remarkably reduced and breakage is most likely to take place by square shell drawing and at the middle point along the straight side of a product. **Fig. 1** shows a 100-mm square shell drawing sample taken by cutting the side wall portion near the die corner section and the method measuring of surface roughness.

3. Anisotropy of mechanical properties

The average values of the mechanical properties of materials measured in three directions are shown in Table 1. **Fig. 2** shows the nominal stress/nominal strain curves of pure titanium (material B) and IF steel (material F), representing the tested materials, on the basis of the uniaxial tensile tests. This figure shows that the nominal stress/nominal strain curve of pure titanium sheet in the rolling direction (L direction) is similar to that of IF steel. Pure titanium has a uniform elongation rate of about 29%. However, the rate is greatly reduced to about 10% at an angle of 45° (D direction) and about 7% at an angle of 90° (C direction), showing the material is highly aniso-



(b) Material F (IF steel)

Fig. 2 Relationship between nominal stress and nominal strain with direction of tension

tropic. The comparison material IF steel did not show such anisotropy. Though not shown in the figure, SUS304 and SUS430 did not show such anisotropy, either. The n values of pure titanium sheets, measured in the L direction, remained low on the order of 0.15-0.17. The r values were also anisotropic; the ranking of the values, from lowest to highest, was the L, D, and C directions.

4. Square shell deep drawability

Fig. 3 shows the relationship between the blank holding force and drawing ratio (the ratio of the length of a side of blank divided by the length of a side of punch) for both titanium JIS class 1 and class 2. The symbols used in the figure are ○ for formable, △ for wrinkle, and × for breakage. **Fig. 4** is a photo showing the LDR of the material B titanium JIS class 1 as a result of 75-mm square shell deep drawing, while **Table 3** lists LDRs resulting from 75-mm square shell deep drawing. **Fig. 5** shows the compared ranges of formability of different materials. It should be noted that IF steel with rust-preventive oil lubricant was employed for this comparison, because forming of cold-rolled steel sheet is not usually performed using Teflon.

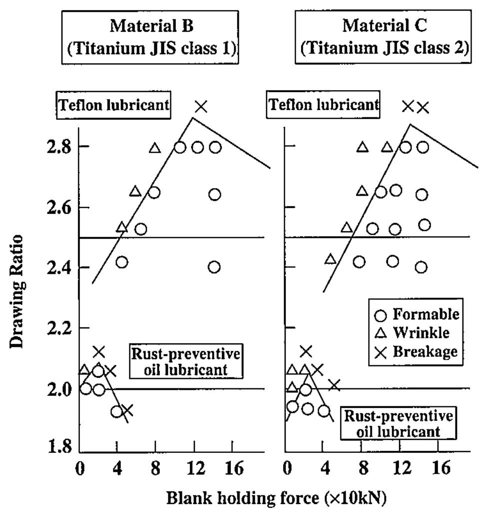


Fig. 3 Drawability limit depending on blank holding force (BHF) and drawing ratio (DR) in 75-mm square shell deep drawing (pure titanium)

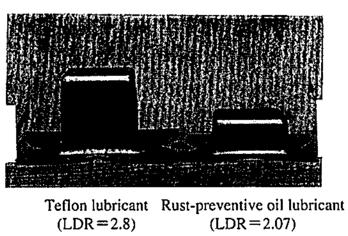


Fig. 4 Photo of square shells of LDR for different lubricants (pure titanium material B, 75-mm square shell drawing)

Table 3 Influence of lubricant on LDR of 75-mm square shell deep drawing

Symbol	Material	Thickness (mm)	Teflon lubricant on both surfaces	Rust-preventive oil lubricant
A	Titanium JIS class 1	0.65	2.8	2.07
B	Titanium JIS class 1	0.95	2.8	2.07
C	Titanium JIS class 2	0.60	2.8	2.07
D	SUS304	0.60	2.67	-
E	SUS430	0.80	2.27	-
F	IF steel	0.80	2.73	2.33

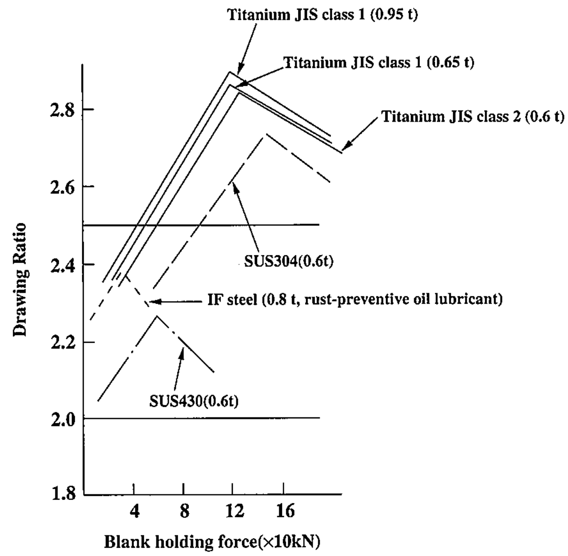


Fig. 5 Comparison of forming area of 75-mm square shell deep drawing (rust-preventive oil lubricant on IF steel and Teflon lubricant on other materials)

These results show that both pure titanium JIS class 1 and class 2 have favorable deep drawability as their LDRs reached 2.8 when drawing was performed using Teflon on both surfaces, which far exceeded the value of 2.67 of SUS304 under the same conditions and 2.33 of IF steel without using Teflon. In particular, as shown in Table 3, the LDR of pure titanium was higher than that of IF steel which was tested with Teflon lubricant. The drawability limit of pure titanium processed without applying Teflon on both surfaces but with rust-preventive oil lubricant was remarkably reduced. This applied to both JIS class 1 and JIS class 2 materials, suggesting the importance of lubrication in deep drawing of titanium sheets.

We also examined the thickness distribution and surface roughness to more clearly identify the square shell deep drawability of the materials. **Figs. 6 and 7** show the thickness strain distribution at the center point of the side wall and corner point of material B (titanium JIS class 1) and material F (IF steel) by100-mm square shell drawing. **Table 4** shows the thickness strain at corner and center points on the punch shoulder portion where the thickness reduces most of all. On the basis of these results, the thickness strain on the punch shoulder portion in the case of pure titanium clearly indicates that the reduction of the thickness at the wall center point is smaller than that at the corner point. By taking into consideration the fact that the thickness strain at the wall center point is almost the same as that at the corner point on the punch shoulder portion in the cases of IF steel and SUS430, the small n value of pure titanium and large anisotropy seems to affect the material.

Fig. 8 shows the surface roughness of both the corner point near the die shoulder radius of 100-mm square shell deep drawing and that of the raw material B before drawing for comparison. **Table 5** shows the calculated average roughness (Ra) of the raw materials and produced shells for materials B, D, and F. From these data, we found that the pure titanium shell using rust-preventive lubricant showed a lower lubrication effect since the surface roughness of the raw material used in the test this time was very low by nature and titanium easily caused fusion with the die, resulting in a small LDR value. On the other hand, in the case of drawing with Teflon applied

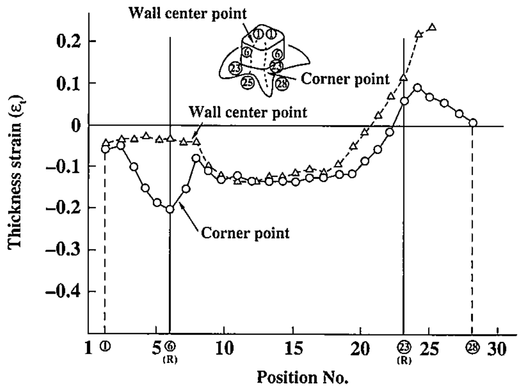


Fig. 6 Thickness strain distribution of 100-mm square shell (raw material B pure titanium, DR = 2.5)

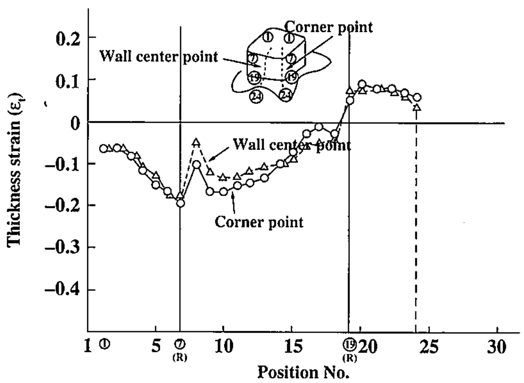


Fig. 7 Thickness strain distribution of 100-mm square shell (raw material F IF steel, DR = 2.3)

Table 4 Minimum thickness strain of punch shoulder portion in 100-mm square shell deep drawing

Symbol	Drawing ratio (DR)	Formed height (mm)	Corner	Wall center
A	2.5	90	–0.20	–0.05
B	2.5	90	–0.22	–0.06
E	2.3	70	–0.19	–0.18
F	2.3	70	–0.20	–0.22

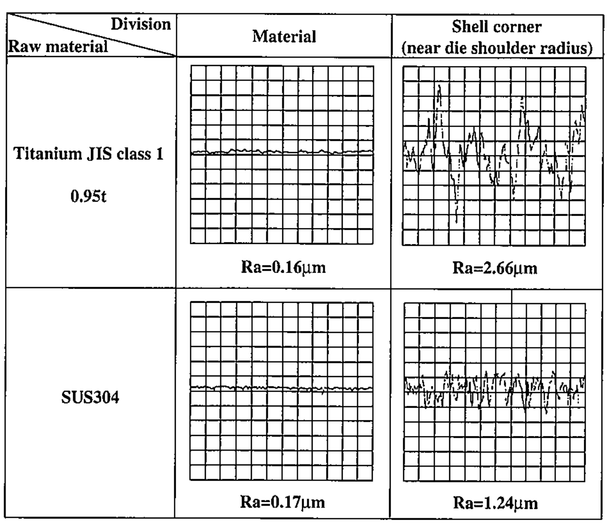


Fig. 8 Surface roughness of die radius portion of a 100-mm square shell and raw material

Table 5 Surface roughness (Ra) of raw material and of 100-mm square shell near die shoulder portion

Symbol	Drawing ratio (DR)	Surface roughness of raw material (Ra)	Surface roughness of square shell (Ra)
B	2.5	0.16 μm	2.66 μm
D	2.4	0.17 μm	1.24 μm
F	2.3	0.91 μm	1.79 μm

on both surfaces, the LDR value became large, presumably because pure titanium did not directly come in contact with the die, resulting in a high degree of lubrication. The surface roughness of the point near the die shoulder radius of a square shell became larger than that of the raw material. In particular, pure titanium showed a conspicuously large increase in surface roughness, resulting in remarkable surface roughening. This aspect also suggests that the drawability limit would lower without applying Teflon lubricant on both surfaces.

5. Conclusions

We examined the mechanical properties of pure titanium sheet, IF steel sheet, SUS430 sheet, and SUS304 sheet by conducting uniaxial tensile tests and square shell deep drawing tests. The following conclusions were drawn from the test results.

(1) The uniform elongation of pure titanium in the L direction is large, while that in the D direction and C direction is extremely small, indicating that the material is highly anisotropic. Austenitic SUS304 sheet, ferritic SUS430 sheet, and Ti-added ultra low carbon steel do not show this property.

(2) The LDR of pure titanium reached 2.8 when square shell deep drawing was conducted with Teflon lubricant applied on both surfaces, which far exceeded the value of 2.67 of SUS304 under the same conditions and 2.33 of Ti-added ultra low carbon steel (IF steel) without using Teflon. This fact proves that pure titanium has a good deep drawability. However, the drawability limit is remarkably reduced if drawing is done without Teflon. In short, lubrication is an important role in forming using pure titanium sheets.

(3) The reason for the above facts may be that the surface roughness of the pure titanium raw material is so small that the material is easily influenced by lubrication. In addition, it is considered that pure titanium is low in n value and very anisotropic, resulting in large fluctuations in thickness strain distribution between the corner points and wall center points of the square shells, which cannot be seen in the different materials such as IF steel.

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