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# Press Formability of Commercially Pure Titanium Sheets

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## Abstract

*This paper describes the press formability of commercially pure titanium sheets, for the use to require excellent workability. Titanium shows a peculiar characteristic which is caused by the structure of crystals, but by the contribution of slips and twinnings, it is easier to deform than the other hexiagonal close-packed lattice metals. When compared to a deep-drawing quality steel sheet, the tensile strength to total elongation balance is equal, the n value is small and the r value is large. It is thought that this is because slip systems for the dependence on deformation mode relating to flow stress and planar anisotropy relating to tensile properties are limited. Though it has a comparatively good stretchability regardless of poor ductility, a deep-drawability isn't as high as to be shown at the r value. The forming limit diagram and the stretchability in plane strain deformation are excellent in the transverse direction of the rolled sheet with r value's being high and are unrelated to the ductility characteristics. The mechanism is, it seems, the effects of slip and twinning. Regarding the press-formability of titanium sheets, it is important to study the effects of lubrication and die material, the use of the temperature and the speed during pressing, the press-forming system which suited the material, and the numerical simulation system of press-forming together with the constitutive equation and data base of material.*

## 1. Introduction

Titanium is the fourth most abundant metal element in the earth's crust, but owing to the difficulty to refine it, its wide use in daily commodities in an industrial scale has only begun lately. Although industrial production of titanium counts back only 20 to 30 years, its application is expanding widely thanks to its excellent material properties meeting the latest industrial and commercial requirements such as: a) light weight and high strength, and b) excellent corrosion resistance. **Table 1**[1] gives a historical overview of titanium applications in Japan. As is clear from the table, the application of titanium began with facilities for chemical industries and expanded then to the fields of electric equipment and seawater desalination plants. Most recently, its use in the form of sheet products is showing increases in

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**Table 1 Expansion of titanium applications in Japan**[1]

| Period | Market section and Technical trend | Typical applications |
|---|---|---|
| Mid/late 1950s | · Advent of industrial production<br>· Beginning of market development | Chemical industries (plant piping, heat exchangers) |
| 1960s | · High grade corrosion resistant material | Lining of reaction vessels and towers, heat exchanger tubes, piping |
| 1970s | · Electrodes for soda industry<br>· Air pollution problems | Electrodes, electrolytic cells<br>Flue gas desulfurization plants |
| Late 1970s to early 1980s | · Increase of power demands<br>· Seawater desalination plants | Condensers for power plants<br>Electrothermal tubes of seawater desalination facilities |
| Mid 1980s to present | · Building, marine and civil construction<br>· Daily and leisure commodities<br>· Cars, motorcycles | Roof lining of covered athletic fields, etc., building exterior panels<br>Table ware, eyeglass frames, golf clubs, plate heat exchangers<br>Auto engine parts, mufflers |

the fields such as building exterior finishing and other daily commodities. In these applications, the titanium materials are subjected to bending, drawing, and other working peculiar to light gauge sheet products. For this reason, high workability comparable to that of deep-drawing steel sheets or stainless steel sheets is often required of titanium materials.

In view of the situation, this paper focuses on an industrially pure titanium sheet (hereinafter called simply "pure titanium sheet") for press forming uses, overlooks its characteristics such as physical properties, work hardening behavior and plastic anisotropy and, finally, explains the relation between the material properties and press formability.

## 2. Material Properties of Pure Titanium Sheet

### 2.1 Physical Properties (see Table 2[2])

The melting point of titanium is 1,668°C, the highest among the metals listed in Table 2, and its density is 60% of that of steel and because its strength is nearly the same as that of steel, its specific strength is the highest among metal materials[3]. On the other hand, its thermal conductivity and electric conductivity are the lowest among generally used metal materials. The specific heat of titanium is nearly the same as those of iron and austenitic stainless steel but, because of its small density, it has a small heat capacity. Another characteristic of titanium is that its coefficient of linear expansion is as small as 2/3 that of iron and approximately half that of austenitic stainless steel.

### 2.2 Crystal Structure

The crystal structure of titanium is a close-packed hexagonal lattice and its characteristic plastic deformation behavior depends on this crystal structure. Its slip systems are {10$\bar{1}$0}<11$\bar{2}$0> (prismatic plane slip) and {1011}<11$\bar{2}$0> (pyramidal plane slip), and, as a special orientation, {0001}<11$\bar{2}$0> (basal plane slip) is also observed. The prismatic plane slip is predominant among them (see **Fig. 1**). Besides the above, twinning deformation is also observed at planes such as (1012) and (1021). The close-packed hexagonal lattice structure is considered to be less ductile than face-centered and body-centered cubic lattices because of fewer slip systems than the cubic lattices. But titanium, in which the contribution of slip and twinning deformation is large, is more easily deformed than Zn and Mg, the crystal structure of which is the same close-packed hexagonal lattice[3].

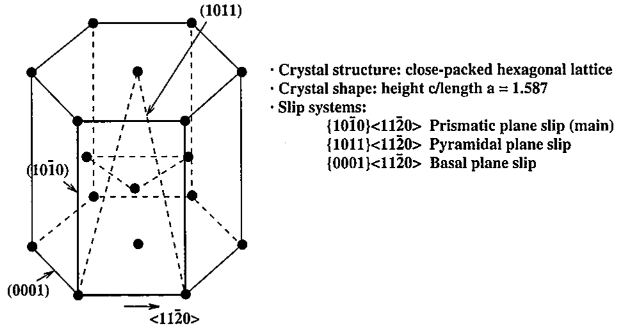

**Fig. 1 Crystal structure and slip systems of titanium**

**Table 2 Physical Properties of Metals and Alloys**[2]

| Material | Atomic weight | Melting point (°C) | Density (g/cm$^3$) | Thermal conductivity (cal/cm$^2$/s /°C/cm) | Specific heat (cal/g/°C) | Coefficient of linear expansion* (cm/cm/°C) |
|---|---|---|---|---|---|---|
| Alminum Al | 26.97 | 660 | 2.70 | 0.487 | 0.21 | $23.0 \times 10^{-6}$ |
| Titanium Ti | 47.90 | 1,668 | 4.51 | 0.041 | 0.12 | 8.4 |
| Iron Fe | 55.85 | 1,530 | 7.86 | 0.145 | 0.11 | 12.0 |
| Copper Cu | 63.57 | 1,083 | 8.93 | 0.923 | 0.09 | 16.8 |
| Titanium alloy Ti-6%Al-4%V | | 1,540-1,650 | 4.42 | 0.018 | 0.13 | 8.8 |
| 18%Cr-8%Ni stainless steel | | 1,400-1,427 | 8.03 | 0.039 | 0.12 | 16.5 |

* 0 - 100°C

### 2.3 Tensile Properties

2.3.1 Mean Planar Properties

**Table 3**[4,5] and **Fig. 2** show a comparison of pure titanium with SPCE (low carbon Al-killed cold-rolled steel sheet for deep drawing use) and SUS304 (18%Cr-8%Ni stainless steel sheet) in terms of tensile characteristics. The mean planar value $\bar{X}$ for each of the tensile characteristic figures was calculated by substituting the figures $X_0$, $X_{45}$ and $X_{90}$ in the 0°, 45° and 90° directions to the rolling direction in equation (1):

$$\bar{X} = (X_0 + 2X_{45} + X_{90})/4 \qquad \text{...... (1)}$$

The following conclusions are derived from the table and figure:

a) The Young's modulus E of pure titanium is about a half those of SPCE and SUS304.

**Table 3 Mechanical properties of typical metal sheets (0.8 mm thick, mean planar values)**[4,5]

| Materials | E$^{*1}$(GPa) | YS$^{*2}$(MPa) | TS(MPa) | El(%) | n-value | r-value |
|---|---|---|---|---|---|---|
| Pure titanium | 106 | 274 | 332 | 47.1 | 0.086 | 4.41 |
| SPCE | 206 | 169 | 300 | 49.4 | 0.224 | 1.54 |
| SUS304 | 200 | 241 | 605 | 65.4 | 0.433 | 0.84 |

*1 Young's modulus, *2 Yield strength

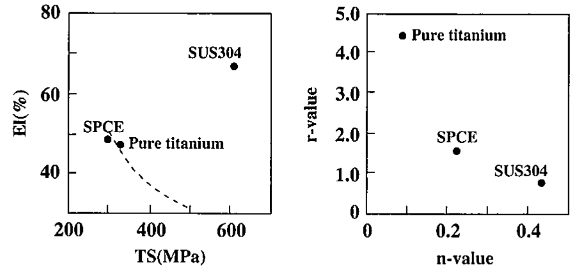

Fig. 2 TS-El balance and correspondence between n-value and r-value

b) Generally speaking, the larger the tensile strength TS of a metal material, the smaller its total elongation El tends to become (the tendency being called strength-ductility balance or TS-El balance). With respect to the TS-El balance, the pure titanium sheet is nearly in the same level as SPCE, but SUS304 is far above the level.

c) Regarding work hardening index (n-value) and plastic strain ratio (r-value), the n-value of pure titanium is smaller than that of SPCE, and its r-value larger. On the other hand, the n-value of SUS304 is larger than that of SPCE, and its r-value smaller. Thus, the n-value and r-value of SUS304 and pure titanium are in symmetric contrast with each other with respect to SPCE.

2.3.2 Work Hardening Property

When a pure titanium sheet is tensile-tested, the load hits a maximum point under a considerably lower strain than in the case of SPCE or SUS304, and then lowers towards rupture. In order to confirm if or not the tendency keeps under not only uniaxial tension (tension under stress in one direction) but also biaxial tension as in press forming, a normal tensile test (under uniaxial tension) and a hydraulic bulging test (under equi-biaxial tension) were conducted, and true stress $\sigma$ - logarithmic strain $\varepsilon$ diagrams were prepared as shown in **Fig. 3**[6]. (The method to prepare the $\sigma$-$\varepsilon$ diagrams under the equi-biaxial tension is explained in 3.1.1.) The diagrams show the following:

a) The work hardening of SUS304 continues up to $\varepsilon \geqq 0.40$ under both the uniaxial and equi-biaxial tensions.

b) In the case of pure titanium, while the uniaxial tension can be applied only up to $\varepsilon \fallingdotseq 0.10$, the equi-biaxial tension can be applied up to $\varepsilon \geqq 0.60$.

c) A similar tendency is observed with SPCE, but not as conspicuous as pure titanium.

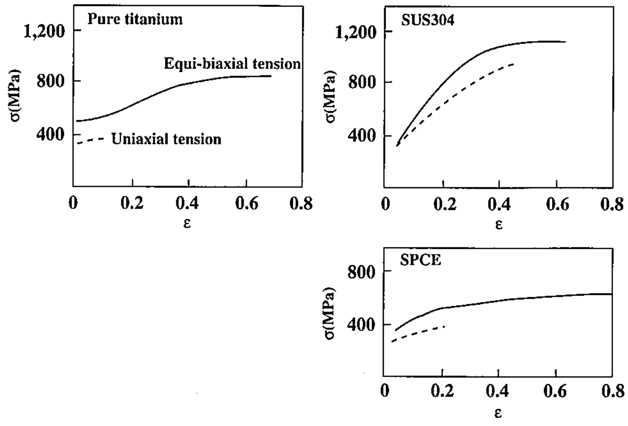

Fig. 3 Stress-strain curves under uniaxial and equi-biaxial tension[6]

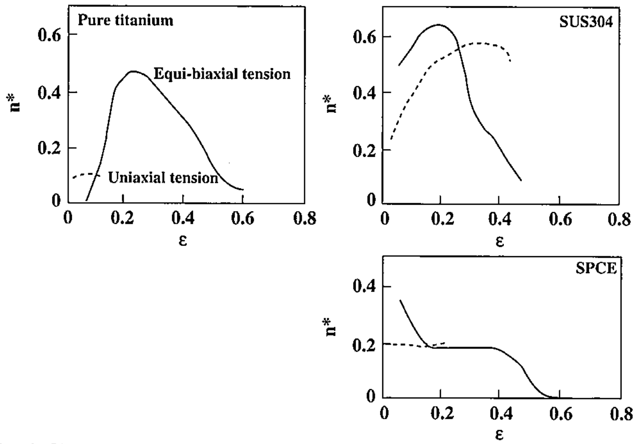

Fig. 4 Changes of instantaneous n-value (n*) under uniaxial and equi-biaxial tension[6]

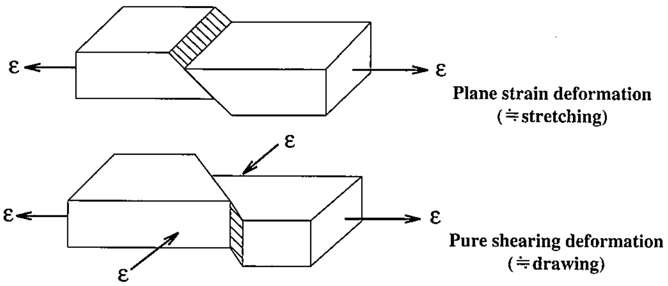

Fig. 5 Planes of maximum shearing stress under principal modes of deformation

Next, **Fig. 4**[6] shows the change of instantaneous n-value (n*) calculated from the $\sigma$-$\varepsilon$ diagrams under the uniaxial and equi-biaxial tensions using the equation below. In the case of pure titanium, while the value of n* under the equi-biaxial tension is small in a low strain range, it increases as strain increases and becomes larger than that of SPCE in the strain range of $\varepsilon = 0.20$ to $0.40$.

$$n^* = (\Delta\sigma/\sigma)/(\Delta\varepsilon/\varepsilon) \qquad \text{......} (2)$$

The work hardening behavior of pure titanium is significantly different depending on the mode of deformation as explained above, and the mechanism of this behavior is examined below. **Fig. 5** compares the plane of maximum shearing stress (the plane of a slip system that acts first when there is a slip system near it) under the plane strain tension and the same under the pure shearing, instead of the uniaxial and equi-biaxial tensions, respectively, for ease of explanation. The plane of maximum shearing strain is totally different under the two modes of deformation. The reason why the values of $\sigma$ and n* of pure titanium are significantly different under the uniaxial and equi-biaxial tensions in Figs. 3 and 4 is, therefore, probably that ease of deformation is very different depending on whether or not there is a slip system near the plane of maximum shearing stress.

2.3.3 Planar Anisotropy

Tensile characteristics in the 0°, 45° and 90° directions to the rolling direction were measured using samples of pure titanium prepared through different production conditions. **Fig. 6** shows the measuring results of typical pure titanium samples and a comparative SPCE sample. The following observations can be derived from the figure:

a) Total elongation El of the pure titanium samples is superior to that of SPCE in the 0° and 45° directions, but remarkably inferior in the 90° direction.

b) Uniform elongation u-El of pure titanium samples is superior to that of SPCE in the 0° direction, but many of them have uniform elongation far inferior in the 45° and 90° directions.

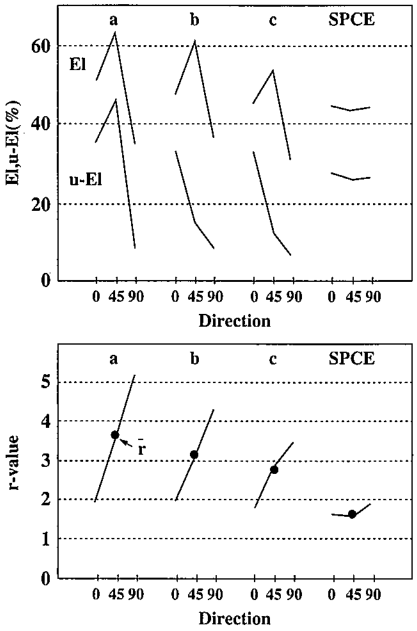

Fig. 6 **Planar anisotropy of tensile test values (0.5 mm thick, JIS No. 13 test pieces, tensile speed 10 mm/min)**

c) The r-value of the pure titanium samples is larger than that of SPCE.

d) Significant planar anisotropy is seen in each of the characteristic figures of the pure titanium samples: while the anisotropy pattern of El is an inverted V shape (45° > 0° > 90°), the lowest being in the 90° direction, that of r-value is linear, the largest being in the 90° direction, and that of u-El has either an inverted V or linear shape.

It is presumed that the reason why the tensile characteristics of pure titanium show remarkable planar anisotropy as shown above is that the crystal plane and orientation easily deformed plastically are limited differently depending on the crystal structure as explained with the examples of Fig. 5.

## 3. Press Formability of Pure Titanium

### 3.1 Axisymmetric Formability

3.1.1 Stretching

A stretch forming test using a spherical head punch 32 mm in diameter was carried out on sheet samples of various metals including copper, 7-3 brass, aluminum alloys of 2000 and 5000 series in addition to pure titanium, SPCE and SUS304. The relation of forming limit height to work hardening indices n and [n] under the uniaxial and equi-biaxial tensions, respectively, was investigated based on the results of the test. The values of the work hardening index under the uniaxial tension in different directions were calculated through application of the n-th power's hardening law to the true stress $\sigma$ - logarithmic strain $\varepsilon$ diagrams up to the maximum load point of a normal tensile test, and the mean planar value n of the work hardening index under the uniaxial tension was obtained using equation (1). The mean planar value [n] of the work hardening index under the equi-biaxial tension was calculated from the results of a hydraulic bulging test.

That is to say, the hydraulic pressure p up to the plastic instability point (maximum hydraulic pressure point) in a hydraulic pressure-forming height diagram, and the radius R of the curvature and sheet thickness t ($t_0$: initial thickness) near the apex were measured, and then the $\sigma$-$\varepsilon$ diagrams were obtained using equations (3) below. The index obtained through application of the n-th power's hardening law to the $\sigma$-$\varepsilon$ diagrams was used as the mean planar value [n]$^{5)}$.

$$\sigma = pR/(2t),\ \varepsilon = |\ln(t/t_0)| \qquad \ldots\ldots (3)$$

**Fig. 7**$^{6)}$ shows the relation of the forming limit height to n and [n]. From the figure it is understood that the correspondence between the forming height and n is not at all good in pure titanium, brass and other samples, but that the forming height and [n] linearly correspond well to each other in all the tested materials including pure titanium. The relation of the critical forming height to n and [n] was nearly the same as that shown in Fig. 7 in the case of a stretch test using a cylindrical punch. These results indicate the following:

a) Pure titanium has comparatively good stretchability despite its small n-value under the uniaxial tension.

b) The stretchability of pure titanium can be evaluated using the n-value ([n]) under the equi-biaxial tension.

3.1.2 Deep Drawing

Samples of 8 mild steel grades, SUS304, copper and aluminum alloys (2000 and 5000 series) in addition to pure titanium were deep-drawn using a cylindrical punch 32 mm in diameter. In order to prevent draw-out in any of the samples, the diameter of the blanks was 80 mm, a little larger than is required in drawing limit conditions. This means that the deep drawing work was done in rather a stretching condition. **Fig. 8**$^{5)}$ shows the relation between the limit forming height and mean planar r-value. As is clear from the figure, as far as the mild steels including SPCE and copper are concerned, the forming height is in a good linear correspondence to the r-value (mean planar value), but they do not correspond to each other when pure titanium and SUS304 are taken into consideration: the forming height of pure titanium (r-value > 4.0) is close to that of a mild steel having

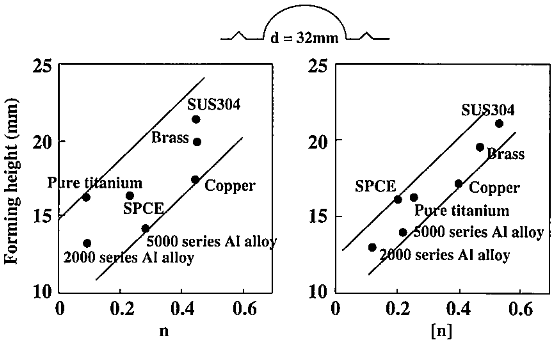

Fig. 7 **Relation of forming height of spherical head stretching with n and [n] (0.8 mm thick, punch diameter 32 mm, press lubricant oil applied to punch surface)**$^{6)}$

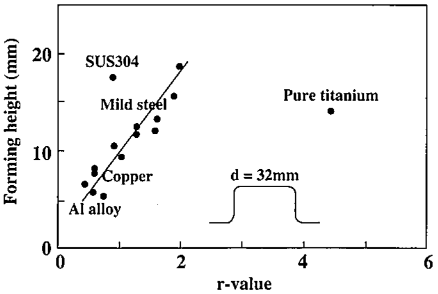

Fig. 8 **Relation between forming height of deep drawing and r-value (0.8 mm thick, blank diameter 80 mm, punch diameter 32 mm, rp = rd = 5 mm, press oil applied to both of sheet surfaces)**$^{5)}$

an r-value of 1.5 and thus its deep-drawability is not as high as is expected from its r-value, in contrast, SUS304 (r-value < 1.0) has the same level of deep-drawability as a mild steel having an r-value of 2.0.

(1) Correspondence between deep-drawability and r-value of pure titanium

1) Change of r-value depending on plastic deformation: The limit of deep drawing is determined by the force Pa in the influx direction imposed on the material at the shoulder of the punch (point a in **Fig. 9**) and the force Pb in the influx direction imposed on the material at the shrinking flange portion (point b in Fig. 9), and deep-drawability becomes better as Pa increases and Pb decreases. Further, according to R. Hill's theory of plastic anisotropy, Pa and Pb are affected by r-value and, the larger the r-value, the larger Pa becomes and the smaller Pb becomes (here, Pa is more affected by r-value than Pb)[7]. Both the conditions are satisfied in a material having a high r-value and, therefore, it is concluded that pure titanium has a good deep-drawability. On the other hand, r-value is known to change as a result of slip and rotation of crystal caused by plastic deformation and, when the deformation is large such as under deep drawing work, the effect cannot be neglected[8]. In consideration of this, when the relation between the r-values ($r_x$, $r_y$) in the directions in right angles to the influx direction and the plastic strain $\varepsilon_x$ is calculated under the assumptions that R. Hill's anisotropy coefficient (corresponding to r-value) of quadric yield surface changes depending on plastic deformation and that the change of the anisotropy coefficient occurs in a manner to minimize the plastic work, the results are that the increase of $\varepsilon_x$ causes $r_x$ to decrease in plane strain deformation (the change of $r_y$ is small) and that both $r_x$ and $r_y$ increase in drawing deformation. When these results are applied to the deep drawing of pure titanium, Pa decreases in the material at point a in Fig. 9 since $r_x$ decreases as a result of the plane strain deformation, and deep drawability is deteriorated in proportion. In the material at point b, Pb decreases as $r_x$ and $r_y$ increase as a result of the drawing deformation thereby improving deep drawability, but the influence of r-value on Pb is small. As stated above, in pure titanium having high r-value, the decrease in r-value caused by the forming work is suspected to be significant, and the deterioration of deep drawability also significant.

2) Effectiveness of mean planar values: This is presumably an issue as to how well the formability during an axisymmetric forming of a material can be evaluated using mean characteristic figures of the material, when the material is planar-anisotropic and its characteristics are not axisymmetric. The issue as to which material characteristic figures should be used for evaluating materials having, unlike mild steels, very large planar anisotropy such as pure titanium has to be clarified yet in the future.

3) Influence of friction: Friction conditions between the surfaces of the material to be formed and a metal die have a considerable influence on deep drawability. It is well known that, especially when a pure titanium sheet is deep-drawn using ordinary dies for a mild steel sheet, friction resistance increases and the forming limit is lowered. This can be considered to be the reason why the forming height and r-value in Fig. 8 did not correspond to each other. The problems related to the friction conditions of a pure titanium sheet will be discussed in section 4.2.

(2) Correspondence between deep-drawability and r-value of SUS304

The influence of the stretch forming factor and that of work-induced transformation characteristics possibly explain the reason why SUS304 demonstrated excellent deep-drawability in Fig. 8, not in correspondence to r-value. With respect to the former, the drawing work was not pure deep drawing but some factor of stretching was involved therein, as a result of setting the blank diameter a little larger than the figure according to the limit drawing condition in order to prevent the drawing-out from occurring in any of the materials. Further, n-value is suspected to have been involved as a new influencing factor in addition to r-value, as a consequence. With regard to the latter, it is suspected that deep-drawability was enhanced by the so-called work-induced transformation, in which austenite changed into martensite when SUS304 underwent the working. This is the phenomenon of material hardening as a result of martensite transformation. The amount of the hardening is influenced by the mode of deformation: the hardening is large in stretch deformation where the volume of material decreases; and the hardening is small in drawing deformation where the material volume increases[9]. It is suspected that the deformation mode-dependency of the amount of hardening contributed to the improvement of deep-drawability.

### 3.2 Non-axisymmetric Formability

#### 3.2.1 Forming Limit Strain

Rectangular sample blanks were stretched using a cylindrical punch 50 mm in diameter and 5 mm in corner radius under the condition outlined in **Fig. 10**. The width of the test pieces was changed and the longitudinal strain (the larger principal strain:$\varepsilon_{major}$) and transverse strain (the lesser principal strain:$\varepsilon_{minor}$) of the samples were measured at their fractured portions, and we described forming limit diagrams (FLDs) with $\varepsilon_{major}$ and $\varepsilon_{minor}$ plotted along the ordinate and abscissa, respectively. A scribed circle 5 mm in diameter was drawn on each of the samples for measuring the fracture strain. Since there were only a small number of measurement points (6 to 7 per test piece), rough forming limit lines were drawn linking the measurement points.

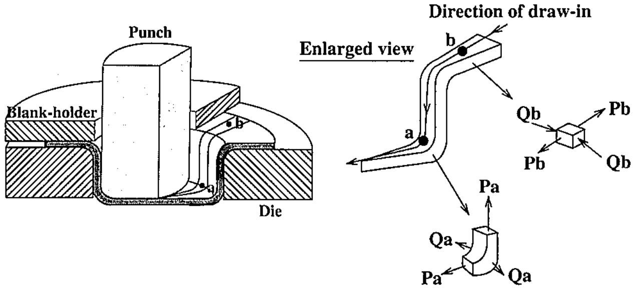

Fig. 9 Forces acting at portions a and b during deep drawing (a: plane strain deformation, b: tension-compression deformation)

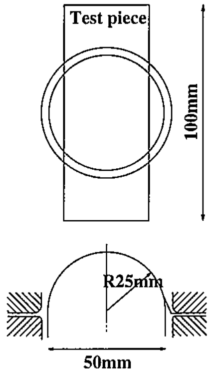

Fig. 10 Plane strain stretching test

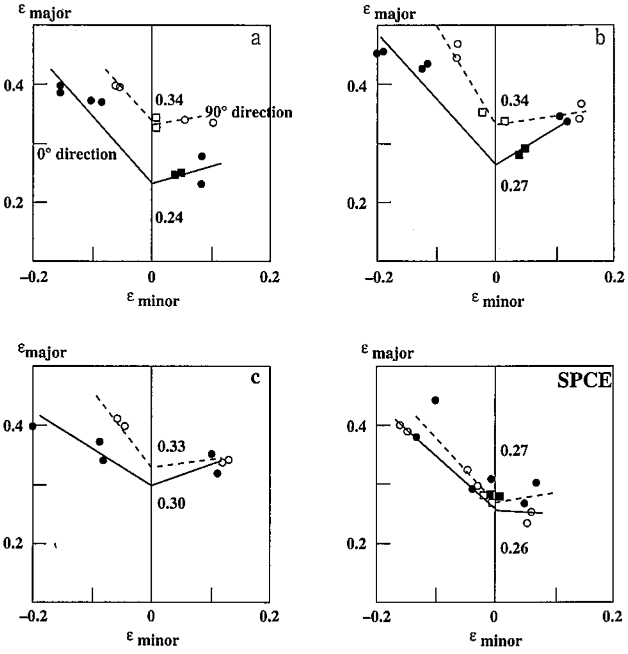

**Fig. 11 Forming limit strain diagrams**

**Fig. 11** shows the FLDs of the pure titanium and SPCE samples used for the examination of the planar anisotropy (in 2.3.3 above), wherein the length of the sample blanks was in 0° and 90° to the rolling direction. As is clear from the figure, forming limit strain takes a minimum value near a plane strain deformation range (along the ordinate). While in SPCE there is little difference of FLDs in the 0° and 90° directions, in pure titanium the forming limit strain in the 90° direction is much larger than that in the 0° direction. Since the FLD is considered to depend on ductility, when we compare the FLDs in Fig. 11 with the tensile characteristics in Fig. 6, it does not correspond at all to ductility characteristic figures, namely the planar anisotropy of total elongation El and uniform elongation u-El. In contrast, the FLD corresponds well to the plastic anisotropy of r-value. In fact, FLD is larger in the 90° direction where r-value is higher.

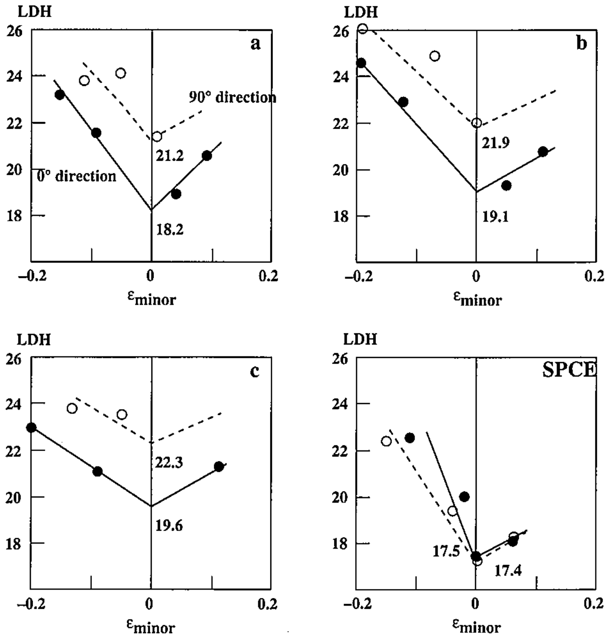

**Fig. 12 Forming limit height diagrams**

3.2.2 Plane Strain Stretching

Forming limit height was measured using the same tool and samples and under the same condition as the measurement of the FLDs. **Fig. 12** shows principal examples of forming limit height diagrams thus obtained, wherein limiting dome height (LDH), or the forming limit height, is plotted along the ordinate and transverse strain $\varepsilon_{minor}$ of the sample blanks along the abscissa. As is clear in the figure, the forming limit height of all the samples takes a minimum value near a plane strain deformation range (along the ordinate). It is also seen therein, that whereas the forming limit height LDH$_0$ of plane strain deformation of SPCE is nearly the same in the 0° and 90° directions, the same of pure titanium is higher in the 90° direction than in the 0° direction by 10% or so. When we compare the difference of LDH$_0$ in different directions with the tensile characteristics shown in Fig. 6, the LDH$_0$ does not correspond at all to ductility characteristic figures, namely the planar anisotropy of total elongation El and uniform elongation u-El, but it corresponds well to r-value, as was observed in the case of the FLDs in Fig. 11. In fact, the LDH$_0$ is larger in the 90° direction where r-value is higher.

3.2.3 Influence of r-value on Formability

Bending forming is a typical non-axisymmetric forming. There are study reports on the relation between bending limit and r-value of pure titanium and titanium alloys. In summary, they state (1) that, among different materials, the lower the mean planar r-value, the better the bendability, (2) but that, with regard to the correspondence to the planar anisotropy within a material, bendability is better in the 90° direction where r-value is higher (bending strain in the 90° direction is the largest). As stated above, the correspondence between bendability and r-value is reversed in (1) and (2). The mechanism in which slip deformation and twinning deformation affect bendability via the FLD is suspected to be one of the reasons for this[10)]. But how these factors affect the bendability under various modes of deformation and other details have not been made sufficiently clear yet. Therefore, more study in detail taking work hardening, deformation texture, etc. into consideration is required.

## 4. Problems to Be Studied in Future

Press forming consists of three elements: material, dies and forming conditions. Findings of past studies of the formability of pure titanium from the material property aspect can be summarized as follows: a) better drawability than expected, b) very large planar anisotropy, and c) non-correspondence between press formability and tensile test results. The fact that various practical improvements have been worked out in dies and forming conditions and implemented in the actual work fields of press forming of titanium materials indicates the importance of elementary technologies in these aspects. In this respect, the aspects to be studied for further expansion of titanium applications are outlined below.

### 4.1 Lubrication and Die Materials

It is well known that poor lubrication is one of the causes of forming defects in the deep drawing of pure titanium. For instance, when a pure titanium sheet coated with a low viscosity lubricant is clamped by plane vises made of SKD11 and subjected to a drawing test under a bearing load, there occurs a violent serration in the drawing load. This is presumably due to breakage of oxide films on the surfaces of pure titanium by the tensile deformation and subsequent sticking and slipping owing to the direct contact between exposed titanium metal surfaces and die materials caused by sliding movements. This is a seizure phenomenon caused by sliding and deformation among the surface oxide films, the work piece metal and the die material, and it seems to occur more prominently with pure titanium than other metals. The following countermeasures are practiced for preventing the phenomenon: a) use of a sticking-resistant lubricant; b) application of a resin film to prevent metal contact of pure titanium with die material; and c) use of a die material less adhesive to pure titanium$^{11)}$. However, the problems of poor lubrication, low efficiency of press forming work, wear of die materials, etc. have not been solved and, therefore, better methods are looked for.

### 4.2 Temperature, Forming Speed and Material Basis

In view of the comparatively low softening temperature of titanium, warm working at a temperature range of 200 to 300°C or so is sometimes practiced for its bending formation. Bendability of pure titanium, however, is known to deteriorate at 200 to 400°C owing, presumably, to temperature-dependency of twinning deformation$^{10)}$. Drawing work of titanium alloys taking advantage of their superplastic deformation behaviors at 500°C or above is also industrially practiced.

The above are all measures to make up for the poor ductility of titanium through improvement of forming conditions. However, since the change of material characteristics at high temperatures is strongly dependent on the materials of the work piece and the tools and the speed of deformation (or sliding), closer coordination between fundamental material studies and industrial practices is very important.

### 4.3 Study of Forming Systems Suitable for Titanium

Conventional press forming technologies have been worked out mainly on the basis of steel sheets and their applications to aluminum alloys and other non-ferrous materials have been expanded. The material forming system based on these technologies has its foundation on the economical efficiency of the material to be worked, forming facilities and productivity. However, when dealing with materials such as titanium, which is much different from conventional materials in deformation characteristics and material costs and regarding which only a small amount of data regarding forming and use are available, an elementary technology such as hydraulic forming capable of solving the problems of low material ductility and poor sliding property simultaneously is effective, although its productivity is not very high.

Further, when complicated work has to be done on a material whose deformation characteristics are not fully clarified like titanium, a forming simulation system to control and optimize the mutually influencing factors of material properties and forming conditions in an overall manner is a very powerful tool. In developing such a system, however, it is inappropriate to apply existing concepts and methods to materials having peculiar deformation characteristics and surface properties such as titanium without modifying them and, thus, it is necessary to study new constitutive equations of the materials and build up material databases$^{12)}$. These studied will largely contribute also to development of new titanium materials.

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