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Formability of pure titanium sheets

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1. INTRODUCTION

Due to its lightweight and high specific strength, commercially pure titanium (CP Ti) has been a potential material for structural components, and attracts much attention form the electronics industry. The principal manufacturing process of CP Ti has been press forming because of its competitive productivity and performance. Among the fabrication processes of press forming, stamping of CP Ti sheets is especially important for the production of thin-walled structural components used in the electronics products, such as the cover cases of notebook, mobile phone, etc. Although the CP Ti usually exhibits limited ductility at the room temperature due to its hexagonal close-packed (HCP) structure, and the mechanical properties can be improved at elevated temperatures, a manufacturing process at room temperature is always desired for cost-effective reason. However, most research of CP Ti is focused on material science [1-4], and the literature regarding formability of stamping CP Ti sheets is not profound.

In the present study, the formability of stamping CP Ti sheets was investigated using the experimental approach. The mechanical properties of CP Ti sheets at various temperatures ranging from room temperature to 300^{o} C were obtained from experimental results. In addition, the important forming characteristics of CP Ti sheets, such as forming limit, springback, and limiting drawing ratio, were also examined by experiments.

2. MECHANICAL PROPERTIES TESTS AT VARIOUS TEMPERATURES

The stress-strain relations are the fundamental information for the study of formability of a sheet metal. Since CP Ti bears the hexagonal close-packed (HCP) atomic structure, the formability is limited at room temperature and can be improved at elevated forming temperature. In the present study, tensile tests were performed at various temperatures ranging from room temperature to 300^{o}C and under different strain rates of 0.1, 0.01, 0.001, and 0.0001 /sec. The tensile test specimens made of JIS Grade 1 CP Ti sheets of 0.5 mm thickness were prepared according to the ASTM standards. The specimens were cut along planes coinciding with the rolling direction (0^{o}), and at angles of 45^{o} and 90^{o} to the rolling direction. The specimens were wire cut to avoid burrs along the edge.

In order to perform tensile tests at elevated temperatures, a heating furnace was mounted on the MTS810 test machine. The specimens were heated to 100^{o}C, 200^{o}C, and 300^{o}C before the tensile tests were performed. During tests, the temperature of specimen was kept constant until the specimen was stretched to failure.

The stress–strain relations for CP Ti sheets at room temperature obtained from specimens in the three different orientations is shown in Fig. 1. The anisotropic behavior is observed in Fig. 1. It is seen in Fig. 1 that the 0^o specimen has highest yield strength and largest elongation than the specimens in the other two directions, and the difference in elongation is more significant. It is also observed that the 0^o specimen works harden most among the specimens in the three directions. These results are consistent with those obtained by Ishiyama *et. al.*[5]. They found that the slip deformation occurs in both 0^o and 90^o directions in the beginning stage of stretch of specimens. During further deformation stage, the twining deformation increases faster in the 0o direction and produces higher resistance against slip of dislocations, resulting in higher yield strength, work hardening, and elongation. Figure 2 shows the original and deformed specimens in the three directions. It is noticed in Fig. 2 that the 0^o specimen undergoes uniform deformation before fracture, while the 90^o specimen displays an obvious necking, and the deformation mode of 45^o specimen lies between those other two modes.

In order to examine the effect of strain-rate on the deformation of CP Ti sheets, the tensile tests were also performed at room temperature under different ram speeds, equivalent to engineering strain-rates of 0.1, 0.01, 0.001, and 0.0001, respectively. The stress-strain relations at various strain-rates for the 0^o specimen are shown in Fig. 3. A significant drop of stress-strain curves from strain-rate 0.01 to 0.001 is noticed in Fig. 3, and the curves become close to each other afterwards. The same trends are also observed in the tensile tests for 45^o and 90^o specimens. It indicates that a stable stress-strain relations for CP Ti sheets can be obtained under the strain-rates smaller than 0.001.

The stress-strain relations of CP Ti sheets at various temperatures ranging from room temperature to 300^oC for the specimen of 0^o direction are shown in Fig. 4. The relations shown in Fig. 4 are obtained from the tests performed at strain-rate of 0.001. It is seen in Fig. 4 that the CP Ti sheet exhibits better formability at elevated temperatures. The stress-strain curves get lower proportionally to the increase of testing temperature. It is to be noted in Fig. 4 that the elongation of the specimen does not increase from room temperature to 100^oC as expected, on the contrary, the elongation becomes smaller when the specimen is heated up to 100^oC. However, the elongation gets larger at temperatures higher than 100^oC. The smaller elongation at 100^oC is quite unusual. But this phenomenon only happens to the 0^o specimen. For 45^o and 90^o specimens, the elongation continuously increases as the testing temperature gets elevated. It is also observed in Fig. 4 that the yield stress and elongation of 0^o specimen at room temperature are 350 MPa and 34%, respectively. It implies that forming of CP Ti sheets at room temperature is feasible for relatively shallow products from formability point of view. This makes it possible to manufacture electronics components using CP Ti sheets.

Another index for anisotropy is the plastic strain ratio, r-value, which is defined as the ratio of plastic strain in the transverse direction to that in the thickness direction in a uniaxial tensile test. In the present study, the r-value was obtained from tensile tests for specimens of 0^o, 45^o, and 90^o directions at room temperature. The r-values measured from specimens stretched to 20% are 4.2, 2.2, and 2.1 for 0^o, 45^o, and 90^o specimens, respectively. Since the higher r-value indicates better drawability, it shows that CP Ti sheets hears better deep drawing quality in the rolling direction than the other two directions. Also the anisotropy of CP Ti sheets was concluded form the significant different r-values.

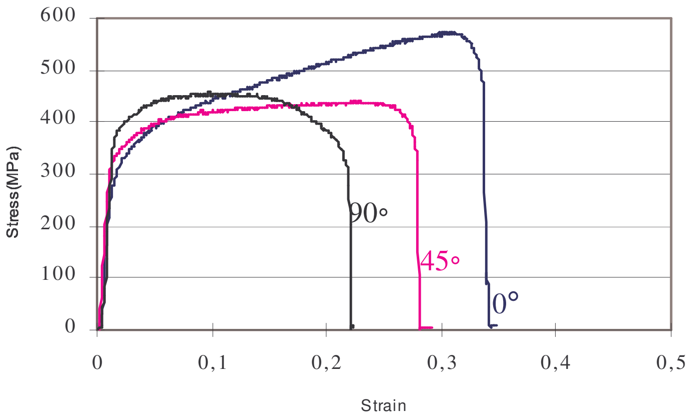

Fig. 1. True stress-strain relations at room temperatureobtained from specimens in the three directions

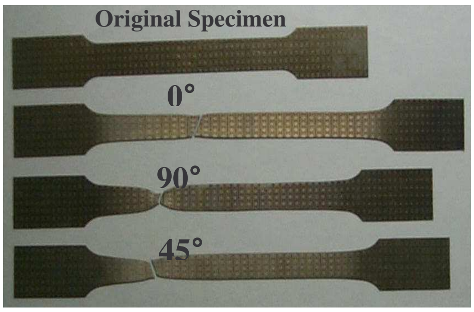

Fig. 2. Orginal and deformed specimens in the three directions

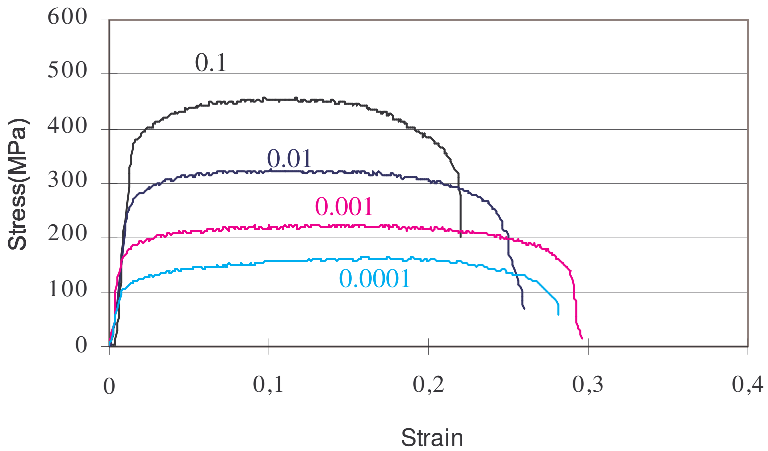

Fig. 3. Stress-strain relations at various strain-rates for 0° specimen at room temperature

3. STAMPING FORMABILITY OF CP TI SHEETS

In addition to the basic mechanical properties, the stamping formability of CP Ti sheets was also examined. In the present study, the forming limit tests at room temperature, and the

V-bend tests and circular cup drawing tests at various temperatures were performed. These tests represent the forming properties of a sheet metal in a stamping process.

3.1 Forming Limit Tests

Since Keeler [6] introduced the concept of the forming limit diagram (FLD) in 1963, it has been a widely accepted criterion for fracture prediction in the sheet-metal forming. To determine a FLD, stretching tests were performed for sheet-metal specimens of different widths using a semi-spherical punch. The specimens were first electrochemically etched with circular grids that would be deformed into ellipses after being stretched. The engineering strains measured in the major- and minor- axes of the ellipse are termed the major strain and minor strain, respectively. They are also the principal strains on the plane where the strains are measured.

In the present study, rectangular specimens having the same length of 100mm, but with different widths ranging from 10 to 100 mm in an increment of 10 mm, were tested. Similar to the tensile tests, the CP Ti sheet was cut at three orientations to the rolling direction, i.e., 0^o, 45^o, and 90^o, for each size of specimen. During the tests, specimens clamped at periphery were stretched to failure over a 78mm semi-spherical punch. The engineering major- and minor-strains measured in the location closest to the fracture for each specimen were recorded. The major- and minor-strains were plotted against one another with the major strain as the ordinate, and the curve fitted into the strain-points was defined as the forming limit curve. The diagram showing this forming limit curve is called the forming limit diagram. The FLD is a very useful criterion for the prediction of the occurrence of fracture in a stamping process.

According to the previous analysis, CP Ti sheet could be formed at room temperature. In order to further confirm its feasibility, the forming limit tests were performed at room temperature. Figure 5 shows the forming limit curves obtained from the test results. It is seen in Fig. 5 that the major strain at the lowest point of the curve, which is also the plane strain deformation mode, is 0.33. Compared with cold-rolled steels or stainless steels, this value is a little lower. However, for stamping of shallow products, the forming limit curve shown in Fig. 5 may indicate that forming at room temperature is possible.

3.2 V-Bend Tests

Since CP Ti has a lower value of elastic modulus than that of steel, springback could be much significant in a bending process. In the present study, the V-bend tests were performed to examine the springback property of CP Ti sheets at various forming temperatures. The tooling used in the V-bend tests is shown in Fig. 6. It can be seen in Fig. 6 that the lower die has an opening angle of $90^{o.}$ In order to study the effect of punch radius on the springback, the tooling sets with punch radii from 0.5 mm to 5.0 mm, in an increment of 0.5mm, were prepared. The CP Ti sheets with a thickness of 0.5 mm, a length of 60 mm, and a width of 15 mm were used as specimens. For tests at elevated temperatures, both tooling and specimens were enclosed in a heating furnace. The bending tests were conducted at room temperature, 100^oC, 200^oC, and 300^oC, respectively. After bending tests, the angles of bent specimens were measured by a CMM, and the springback angles were calculated.

Figures 7 and 8 show the relationships between springback and punch radius at room temperature and 300^oC, respectively. It is seen in both figures that the springback decreases for smaller punch radii regardless of temperature change. The smaller punch radius causes larger plastic deformation at the bend, and hence reduces the effect of springback. It is also noted in both Fig. 7 and Fig. 8 that negative values of springback occur for smaller punch radii.

This is because that the sheet on the straight sides of v-shape is deformed into an arc at the beginning of bending process, and the load applied to flatten the arc at the end of bending process results in a complex stress distribution that causes the negative value of springback [7]. Comparing both figures, it is observed that the springback decreases as the forming temperature increases regardless of the punch radius. It indicates that CP Ti sheets not only have better formability but also exhibits less springback at higher forming temperatures.

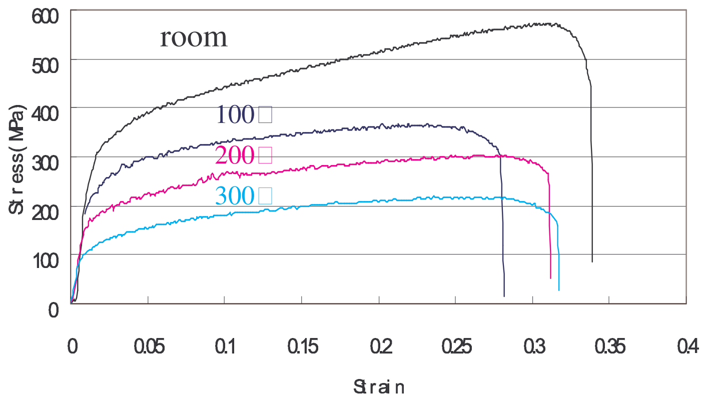

Fig. 4. True stress-strain relations at various temperatures for 0° specimen

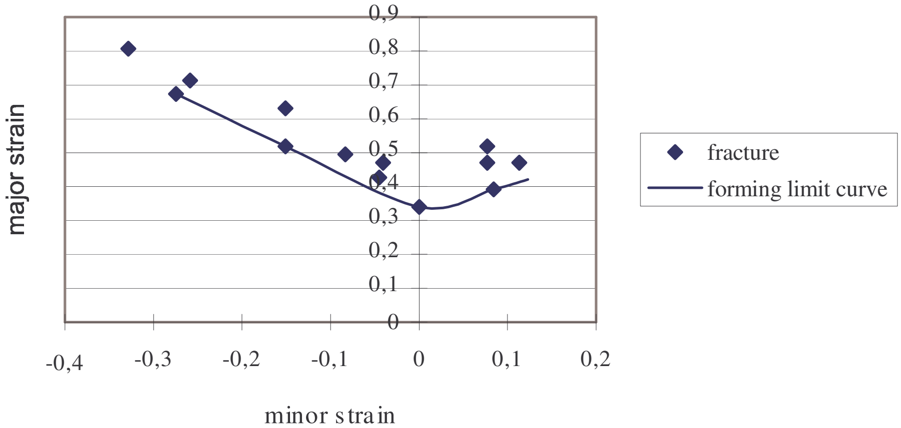

Fig. 5. Forming limit curve at room temperature

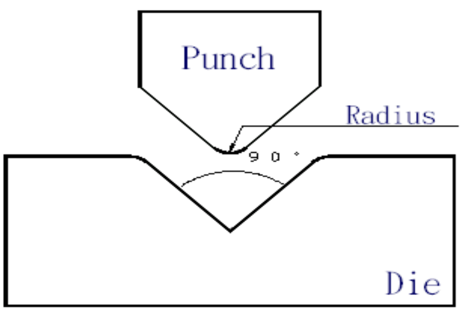

Fig. 6. Tooling used in the V-bend tests.

It is known that the springback is affected by both the elastic modulus and the yield stress of the material. Since the elastic modulus does not vary too much with the change of temperature, and the yield stress of CP Ti sheets decreases with the increase of temperature, the decrease of springback at higher forming temperatures is due to the lower yield stress of CP Ti at elevated temperatures.

3.3 Circular Cup Drawing Tests

The limiting drawing ratio (LDR), which is defined as the ratio of the largest diameter of circular blank (Do) to the punch diameter (Dp) in a successful circular cup drawing process, is a popular index for the formability of sheet metal. A larger value of LDR implies a larger drawing depth, that is, a better formability. In the present study, the punch and die shown in Fig. 9 were used for the circular cup drawing tests. Tests were performed at room temperature, 100°C, and 200°C. The heating apparatus used in the tensile tests was adopted for the tests at elevated temperatures. In order to obtain a successful drawing process, the blank size and blank holder force were adaptively adjusted to eliminate the defects such as fracture and wrinkle. Since the punch diameter is 35 mm, the blank diameter is increased in an increment of 3.5 mm from 70 mm to the largest possible diameter for the convenience of calculating the LDR. MoS_2 was used as lubricant in all circular cup drawing tests conducted in the present study, and the drawing speed is 0.2 mm/sec.

Figure 10 shows the drawn cups at various temperatures. It is clearly seen in Fig. 10 that the drawing depth increases as the increase of forming temperature. It is also to be noted in this figure that the earing shapes of the drawn cup formed at various temperature are quite different. The earing phenomenon becomes significant at higher forming temperature. The values of LDR, drawing depth, and related process parameters are listed in Table 1 for the tests conducted at various temperatures. It is noticed in Table 1 that all values increase as the forming temperature increases. However, the increase of LDR and drawing depth is not so significant in the range from room temperature to 100°C, but gets larger from 100°C to 200°C. It is also noted in Table 1 that a larger blank holder force is required for the larger blank size to be successfully drawn at higher temperature. The value of LDR of CP Ti sheets is 2.2 at room temperature, which also indicates that stamping of CP Ti sheets at room temperature is feasible.

Table 1
Test results of circular cup drawing.

Temperature	Blank Diameter	LDR	Blank-Holder Force	Drawing Depth
Room Temperature	77 mm	2.2	2.75 KN	20 mm
100℃	84 mm	2.4	3.5 KN	29 mm
200℃	101.5 mm	2.9	4.0 KN	40 mm

4. CONCLUDING REMARKS

The formability of stamping CP Ti sheets at various forming temperatures was investigated in the present study by conducting various experiments. The mechanical properties of the CP Ti sheets at various temperatures were first examined, and the stress-strain relations obtained from the experiments indicate that CP Ti sheets have higher yield stress and smaller elongation at room temperature, but proportionally decrease in yield stress and increase in elongation when the sheet is heated to a elevated temperature up to 300°C. It is to be noted

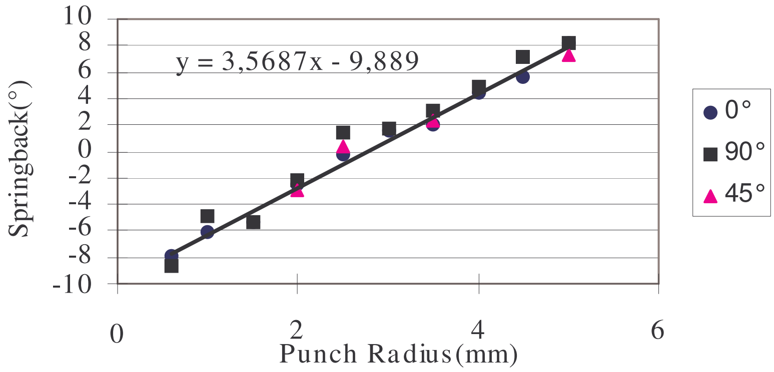

Fig. 7. Relations between springback and punch radius at room temperature for specimens of three directions

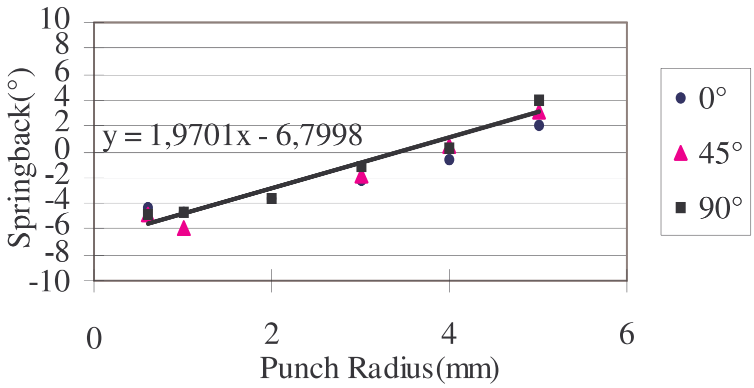

Fig. 8. Relations between springback and punch radius at 300℃ for specimens of three directions

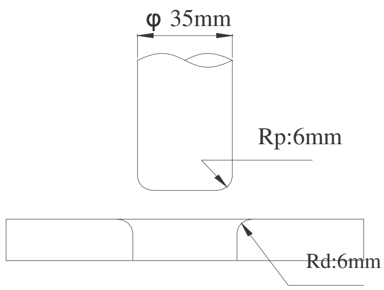

Fig. 9. Punch and die used in circular cup drawing tests

that the stress-strain relations obtained from the tensile tests at room temperature indicates that the CP Ti sheet could be formed into shallow components at room temperature, although the yield stress is a little bit higher. The forming limit diagram of CP Ti sheets obtained at room temperature is not so high as those of cold rolled steels, but the minimum major strain of 0.33 also provides an optimum possibility for CP Ti sheets to be formed at room temperature.

Fig. 10. Drawn cups at various forming temperatures

The circular cup drawing tests reveals that the CP Ti sheet has a LDR value of 2.2 at room temperature, and a successfully drawn cup with a depth of 20mm confirms that the CP Ti sheet can be formed at room temperature. However, the high r-values obtained from the tensile tests and the earing phenomenon displays in the drawn circular cups indicates that the CP Ti sheet bears significant anisotropy in plane that could also affect the formability of drawing deep cups.

The strain-rate effect on the stress-strain relations at room temperature was also investigated. The experimental results show that the stress-strain relations become stable when the strain-rate is smaller than 0.001. In the V-bend tests, the experimental results reveal an important information that the springback can be reduced at elevated forming temperatures. Also the springback could be reduced if a smaller punch radius is used to form the parts. The experimental results obtained in the present study provide the fundamentals for the stamping die design of forming CP Ti sheets.

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