Analysis of Square Cup Deep-Drawing Test of Pure Titanium

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Abstract. The prediction of formability of titanium is more difficult than steels since its strong anisotropy. If computer simulation can estimate the formability of titanium, we can select the optimal forming conditions. The purpose of this study was to acquire knowledge for the formability prediction by the computer simulation of the square cup deep-drawing of pure titanium. In this paper, the results of FEM analysis of pure titanium were compared with the experimental results to examine the analysis validity. We analyzed the formability of deep-drawing square cup of titanium by the FEM using solid elements. Compared the analysis results with the experimental results such as the forming shape, the punch load, and the thickness, the validity was confirmed. Further, through analyzing the change of the thickness around the forming corner, it was confirmed that the thickness increased to its maximum value during forming process at the stroke of 35mm more than the maximum stroke.

1. Introduction

Titanium is abundant in the earth. It is the fourth in abundance next to aluminum, iron, and nickel in the earth's metal elements. Titanium is superior in strength and hardness compared to iron. Titanium is lighter than iron. The mass density is about 57% of iron. The crystal structure of α titanium is an hcp structure. Slip system of hcp structure is three and it is less than the bcc structure such as iron and the fcc structure such as aluminum. Due to this fact, the anisotropic parameter r value is large and changes greatly even in-plane of titanium sheets. From this reason, the prediction of formability of titanium is more difficult.

Computer simulation on the titanium forming process was less reported compared with the steels and aluminum. Particularly, the studies on the formability of the square cup deep-drawing of titanium are few. Ohwue et al. [1] applied finite element analysis (FEM) simulation using full model of circular titanium blanks. The occurrence of earrings in circular-shell deep-drawing tests for two different types of crystal materials titanium was investigated. On the other hand, in the sheet metal forming simulation, the studies of optimum process design are energetically carried out. Kitayama et al. [2] applied their proposed optimization algorithm to the optimal variable blank holder force trajectory for the square cup deep-drawing. The objective is taken as the minimization of the deviation of the whole thickness.

If computer simulation can estimate the formability of titanium, we can use better forming conditions to improve the formability. The purpose of this study was to acquire knowledge for the formability prediction by the computer simulation of the square cup deep-drawing of pure titanium.
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2. Analysis Model and Analysis Conditions
Using the dynamic explicit method elastic-plastic FEM program LS-DYNA, 3-dimensional analysis of a square cup deep-drawing was carried out. A square cup deep-drawing test for pure titanium was performed. The specimen is JIS H 4600 TP340C with a heat treatment (pure titanium JIS2 species). Basically the analysis condition is set to be the same as this used in the deep drawing test.

The dimensions of tools are shown in Fig. 1(a). At the corner, the clearance between the die and the punch is designed to have the maximum value of 0.7 mm. The amount of maximum punch stroke is 65.5 mm. The stroke speed is 5,000 mm/s that is faster than real speed to save the calculation time of the dynamic explicit FEM. The blank holding force is 10 kN and the die is fixed. The tools are modeled as rigid bodies. The mesh size is from 0.2 mm to 5.0 mm.

The workpiece is shown in Fig. 1(b). The workpiece sheet thickness is 0.477 mm and diameter \( \phi \) is 100 mm. Values of the material parameters used in the calculation are listed in Table 1. The mechanical properties, the relationship between stress and plastic strain obtained from the results of the tensile test.

The solid element with the reduced integration is selected to model the titanium blank. Three elements with the size of 0.16mm in the thickness direction are employed. The element size in the plane of blank is 0.5 mm. Hill’s quadratic anisotropic yield function(1948) is used. We used solid element to consider the thickness contact force changes when the plate thickness increases and decreases in the forming process.

Coulomb friction for contacts between titanium blank and working tools: punch, die and blank holder was assumed to be 0.2 in the simulation.

![Figure 1. (a) Geometory of Tools. (b) Setting blank sheet along the rolling direction.](image)

| Young's modulus | \( r_0 \) | \( r_{45} \) | \( r_{90} \) | Yield stress | Poisson's ratio | Mass density |
|-----------------|----------|-----------|-----------|--------------|---------------|-------------|
| 108.5 GPa       | 1.89     | 3.72      | 3.18      | 250 MPa      | 0.34          | 4.50 \times 10^{-9} ton/mm³ |
3. Analysis results

3.1. Punch load and forming shape

The relationship between punch load and punch stroke are shown in Fig. 2. The punch load increases linearly when the punch stroke is less than 10 mm, and reached the first peak when the punch stroke is about 15 mm. Then the punch load decreases gradually at the stroke of about 35 mm. Again, it is increasing until reaching the second peak at the stroke of about 40 mm, and it drops to zero at the final stroke. The result has good agreement with the experimental result.

About the formed shape, the comparison between the analysis results and the experimental results are shown in Fig. 3. The formed shapes at the punch strokes of 20.5 mm, 40.5 mm and 65.5 mm punch are respectively shown in Fig. 3(a), (b) and (c) from the top view or the side view. With increasing the punch stroke, the earing occurred in the corner portion. That qualitatively matched with experiment. It can be seen that the second peak of the punch load corresponds to the certain amount earing in the corner portion.

Figure 2. The relationship between punch load and stroke.

(a)20.5 mm (b)40.5 mm (c)65.5 mm

Figure 3. Comparison between simulation(left) and experiments(right).

3.2. Thickness distribution

Fig. 4 shows the relationship between the thickness and the travel distance from the center of cup along the section at the punch stroke of 20.5 mm. Fig. 4 compares the computed thickness distributions with experimental results along the rolling direction (0 degree, Fig. 4 left) and along the 45 degree from the rolling direction (Fig. 4 right). Along both the rolling direction and 45 degree from rolling direction, the thickness in the bottom of the cup remains nearly the initial thickness. Along the rolling direction, the vertical wall thickness reduced, and the blank thickness increased toward the outer periphery. On the other hand, along the 45 degree from the rolling direction the vertical wall thickness reduced similarly with that in the rolling direction, but the thickness remains nearly the initial thickness toward the outer periphery.
Fig. 5 shows the relationship between the thickness and the travel distance from the center of cup along the section at the punch stroke of 40.5 mm. The vertical wall thickness along the rolling direction changes greatly. The experimental results show that the vertical wall thickness decreased and increased toward the outer along the 45 degree direction from the rolling direction. On the other hand, the computed results show that the vertical wall thickness increased toward outer part.

Then, Fig. 6 shows the thickness distribution of the vertical wall at the punch stroke 65.5 mm. Fig. 7 shows the history of thickness at the maximum thickness element. It can be seen that the thickness increases at the flange corner and decreases after passing through the die radius.

4. Conclusions
In this study, we analyzed the formability of deep-drawing square cup of titanium by the FEM using solid elements. By comparing the analysis results with the experimental results of the forming shape, the punch load, and the thickness, the validity was confirmed. Further, through analyzing the changing history of the thickness around the formed corner, it was confirmed that the maximum thickness occurred during forming process at the stroke of 35mm more than the maximum stroke.

References
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