An Experimental Study of the Punchless Drawing Utilizing Lateral Fluid Pressure

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An experimental study has been made to clarify the drawing characteristics in the new deep drawing utilizing lateral fluid pressure, and to examine the possibility of its punchless drawing. In this new deep drawing, the lateral fluid pressure acting on the perimeter of a blank causes the reduction of punch force. In the drawing process under a constant lateral fluid pressure, punch pressure increased to a maximum and then decreased with increasing depth of drawing. This maximum value decreased linearly with increasing lateral fluid pressure, and approached to zero. The punchless drawing became feasible under a limited tool condition.

1. Introduction

In a conventional drawing method, the drawing ratio in a single drawing is limited to about 2.2 to 2.5 for ductile materials. Recently, the deep drawing method utilizing lateral fluid pressure in which the drawing ratio is improved remerkably, was presented.[1), 2)] In this new drawing method, the lateral fluid pressure acts on the perimeter of a blank to force it inward, and the center of the blank is pushed into a die by a punch. However, the detailed information on this drawing method was not reported, and it seems that the deformation process was not analyzed. The authors have clarified the deformation process of the deep drawing utilizing lateral fluid pressure by experimental and theoretical analysis. In this paper, the drawing characteristics in this deep drawing for aluminum sheets are reported and its punchless drawing is proposed.

2. Experimental Procedure

2.1 Experimental apparatus

Photograph 1 and Fig. 1 show the total view of experimental apparatus and the diagram of its main equipment, respectively. This apparatus is equipped with a lateral pressure system and a punch pressure system, which are fluid pressure systems to produce drawing force. The main equipment consists of many parts; a plunger (7) is that to produce high pressure in the lateral pressure system, and a intermediate cylinder ⑧ is that to separate the punch pressure system from the lateral pressure system. A hold-down cylinder ④ plays the roles of punch guide, blank holding and fluid seal. And a stop ring ⑤ determines the effective clearance between the hold-down cylinder and a die ③.

The lateral fluid pressure acting on the perimeter of a blank and punch pressure were produced with a universal testing machine of 50-tons capacity (B) and a hand pump (C), respectively (see Photo. 1). The maximum fluid pressure obtained in the

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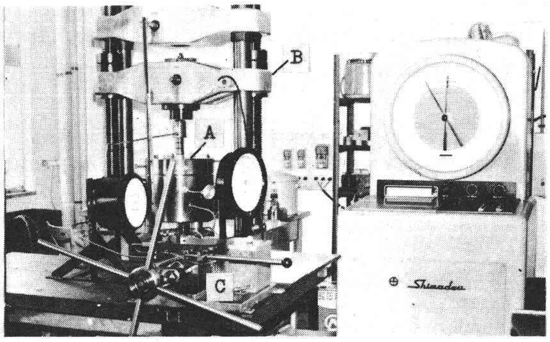
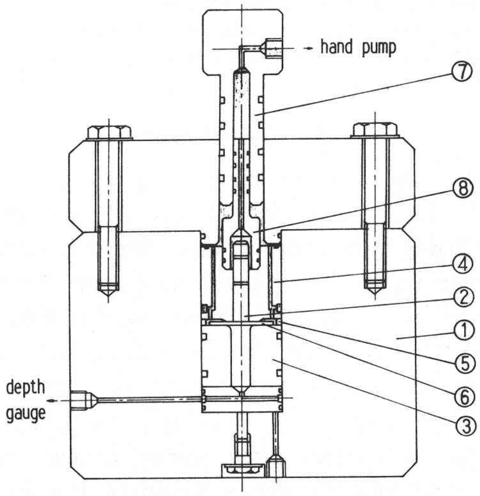


Photo. 1 Total view of experimental apparatus (A : main equipment, B : 50 t universal testing machine, C : hand pump).



①chamber ②punch ③die ④hold-down cylinder

⑤stop ring ⑥blank ⑦plunger ⑧intermediate cylinder

Fig. 1 Diagram of main equipment.

lateral pressure system of this apparatus was 500 MPa (about 5000 kgf/cm^2).

2.2 Drawing operation

A blank ⑥ was set as shown in Fig. 1 and its both surfaces were coated with a tallow lubricant. Pressing down the plunger ⑦ with the universal testing machine, the fluid pressure in the lateral pressure system was raised. The pressurized liquid forced down the hold-down cylinder ④, which caused the protrusion on its bottom to penetrate the blank slightly. And as the lateral fluid pressure was raised to 20 MPa (about 200 kgf/cm^2), a good fluid seal was formed (see Fig. 2).

After the fluid pressure in the lateral pressure system had been raised to a set value p_s, a punch ② was forced down by pressurizing the liquid in the punch pressure system with the hand pump. In the punchless drawing, the fluid pressure in the lateral pressure system was adjusted to draw a blank into the die throughout its drawing process.

2.3 Tool and specimen

Table 1 shows the dimensions of tools used for the cup drawing in this experiment. The height of the protrusion of the hold-down cylinder h and the height of the stop ring H were determined experimentaly by considering the initial clearance c_0 $(= H - t_0)$ and the initial depth of the penetration b_0 $(= h - c_0)$ shown in Fig. 2, where t_0 is the initial thickness of a blank. The initial depth of penetration b_0 should be minimized to

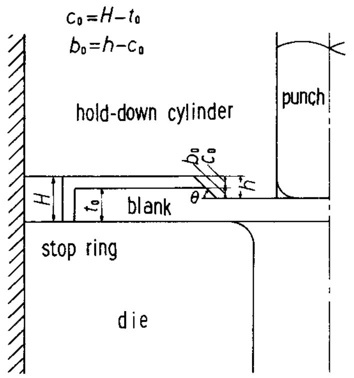


Fig. 2 Initial depth of penetration b_0 and initial clearance c_0.

Table 1 Main dimensions of tools.

Punch		Diameter d_p [mm]	Punch radius ρ_p [mm]	
	P-1	15.0	2.0	
	P-2**	10.0		
Die		Die radius ρ_d [mm]	Die throat diameter d_d [mm]	
	D-1	2.5	16.9 (t_0 = 0.8)	
	D-2		18.7 (t_0 = 1.5)	
	D-3*	1.0	16.9	
	D-4*	3.0		
	D-5*	4.0		
	D-6**	2.0	11.9 (t_0 = 0.8)	
Hold-down cylinder		Protrusion***		
		Diameter d_h [mm]	Height h [mm]	Taper angle θ [deg.]
	H-1	26.0	0.1	7.0
	H-2*	30.0		
	H-3**	21.0		
Stop ring		Height H [mm]		
	R-1	0.85 (t_0 = 0.8)		
	R-2	1.60 (t_0 = 1.5)		

* Tool used only for punchless drawing (H-2 is used only for D-5)
** Tool used for punch diameter d_p = 10 mm
*** See Fig. 2

Table 2 Mechanical properties of specimens.

Specimen		Tensile strength	Elongation	Work hardning exponent
Material	Thickness of sheet t_0 [mm]	[MPa]	e_f [%]	n
A1050P–O	0.8	80	50	0.28
	1.5	78	52	0.27
A1050P–H12	0.8	107	16	0.10

reduce the ironing between the die and the protrusion of hold-down cylinder as far as a good fluid seal can be formed. Some initial clearance c_0 was necessary to reduce the friction between the blank and tools and to prevent the non-axisymmetric deformation of the blank. In this experiment, b_0 = 0.05 mm, c_0 = 0.05 mm for a 0.8 mm thick blank and b_0 = 0.1 mm, c_0 = 0.1 mm for a 1.5 mm thick blank were adopted.

For the specimens, soft aluminum sheet of A1050P–O and 1/4 hard aluminum sheet of A1050P–H12 were used, and their mechanical properties are shown in Table 2. The diameter of the blank was 60 mm except for a special case. Therefore, drawing ratios DR (defined as the ratio of the blank diameter d_0 to the punch diameter d_p) were 4 and 6 for the punch diameters of 15 mm and 10 mm, respectively.

3. Results and Consideration

3.1 Drawing characteristics

(1) Minimum lateral fluid pressure required to draw a blank without fracture

Figure 3 shows the minimum lateral fluid pressure $p_{s\cdot min}$ required to draw the blanks having various diameters with a 15 mm diameter punch without fracture. For

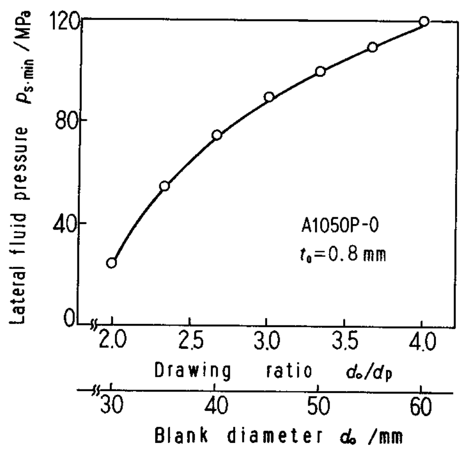


Fig. 3 Relation between minimum lateral fluid pressure $p_{s\cdot min}$ required to draw a blank without fracture and drawing ratio d_0/d_p

the 0.8 mm thick sheet of A1050P–O, as shown in this figure, $p_{s\cdot min}$ increases with increasing drawing ratio and the value of $p_{s\cdot min}$ for a drawing ratio of 4 is 120 MPa (about 1200 kgf/cm^2). For the 1.5 mm thich sheet of A1050P–O and the 0.8 mm thick sheet of A1050P–H12, the values of $p_{s\cdot min}$ for the same drawing ratio were 120 MPa and 140 MPa (about 1400 kgf/cm^2), respectively.

As shown in this figure, drawing ratios up to 4 are obtained for the 15 mm diameter punch. Photo. 2 (a) shows the cup drawn with the drawing ratio of 4. Furthermore, a drawing ratio of 6 is obtained for a 10 mm diameter punch as shown in Photo. 2 (b). These drawing ratios are much larger than the maximum drawing ratio obtained in a conventional deep drawing method, which suggests that the lateral fluid pressure takes charge of the majority of the work required to draw a blank.

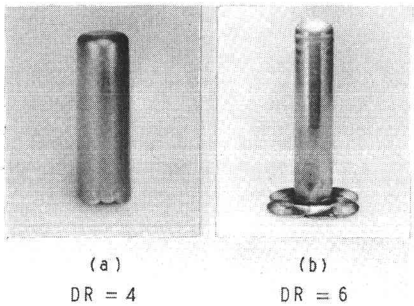


Photo. 2 Cups drawn by the deep drawing utilizing lateral fluid pressure.

(2) Curve of p_p–S and curve of $p_{p\cdot max}$–p_s

The drawing characteristics of this drawing method are represented by the curves of p_p–S shown in Fig. 4 ~ 6. These curves show the variation of punch pressure p_p against depth of drawing S (i.e. punch stroke) for different set values of lateral fluid pressure p_s.

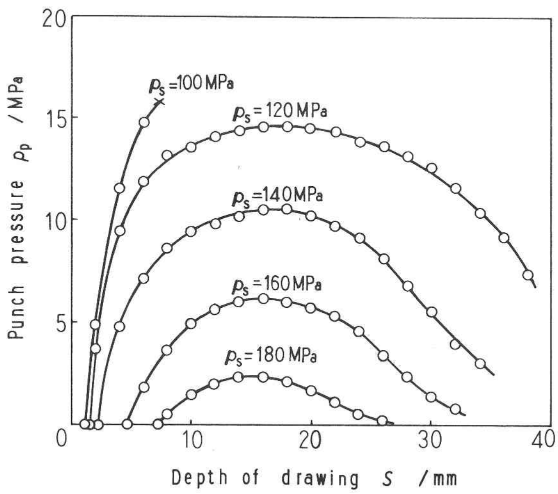


Fig. 4 Curves of punch pressure p_p – depth of drawing S for different lateral fluid pressures p_s .(A1050P–O, t_0 = 0.8 mm, d_p = 15 mm).

Figure 4 shows the curves of p_p–S for the 0.8 mm thick sheet of A1050P–O drawn with the 15 mm diameter punch (DR = 4). As shown in this figure, when the lateral fluid pressure p_s rises to a set value, some drawing deformation has already proceeded in spite of $p_p = 0$, and that deformation increases with increasing p_s. In every curve of p_p–S, the value of p_p increases to a maximum and then decreases slowly with increasing S, and every value of S corresponding to each maximum value of p_p is about 15 mm. The maximum punch pressure $p_{p \cdot max}$ decreases with increasing p_s.

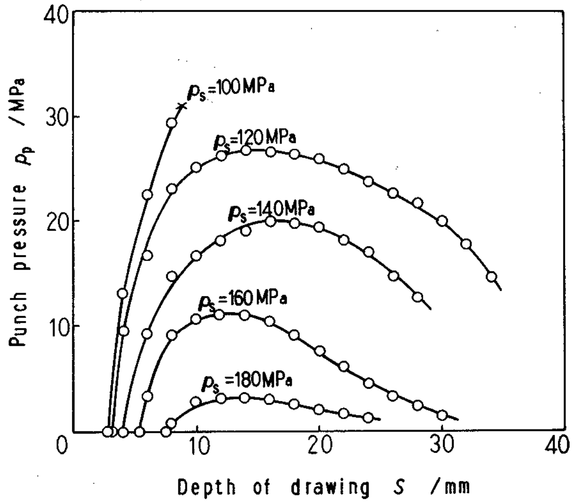


Fig. 5 Curves of punch pressure p_p – depth of drawing S for different lateral fluid pressures p_s. (A1050P–O, t_0 = 1.5 mm, d_p = 15 mm)

For the 0.8 mm thick sheet of A1050P–H12, every curve of p_p–S rose rapidly to a peak and then descended, and every value of S corresponding to each peak was about 7.5 mm. And every value of $p_{p \cdot max}$ for each lateral fluid pressure p_s was 6 ~ 8 MPa (about 60 ~ 80 kgf/cm^2) higher than that for A1050P–O. Fig. 5 shows the curves of p_p–S for the 1.5 mm thick sheet of A1050P–O. These curves have the same tendency as those for the 0.8 mm thick sheet.

Figure 6 shows the curves of p_p–S for the 0.8 mm thick sheet of A1050P–O drawn with the 10 mm diameter punch (DR = 6). These curves have the same tendency as those shown in Fig. 4, but the value of $p_{s \cdot min}$ is 220 MPa (about 2200 kgf/cm^2), which is almost doubled. And every value of S corresponding to the peak of each curve is about 22 mm.

Figure 7 shows the relation between the maximum punch pressure $p_{p \cdot max}$ and the lateral fluid pressure p_s for the 0.8 mm (Fig. 4) and 1.5 mm (Fig. 5) thick sheets of A1050P–O drawn with the 15 mm diameter punch (DR = 4). In either sheet, $p_{p \cdot max}$ decreases linearly to zero with increasing p_s as shown in this figure. For p_s below 180 MPa (about 1800 kgf/cm^2), the value of $p_{p \cdot max}$ for the 1.5 mm thick sheet is higher than that for the 0.8 mm thick sheet, and the difference between them decreases with increasing p_s. The value of p_s corresponding to $p_{p \cdot max}$ = 0 is equivalent to the maximum value of the lateral fluid pressure which varies with increasing depth of drawing in the punchless drawing described later in sect. 3.3, and so its experimental values are

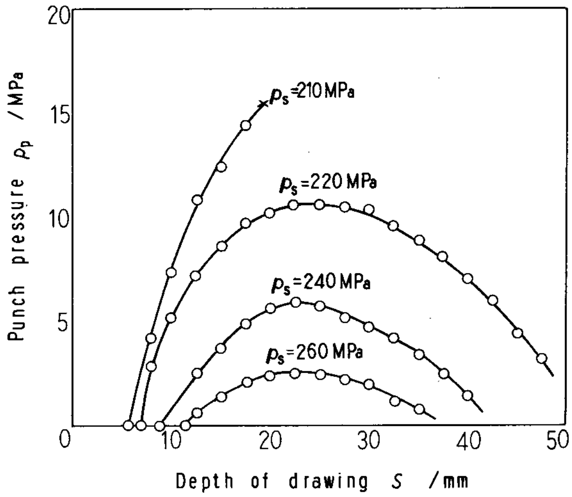


Fig. 6 Curves of punch pressure p_p – depth of drawing S for different lateral fluid pressures p_s. (A1050P–O, t_0 = 0.8 mm, dp = 10 mm)

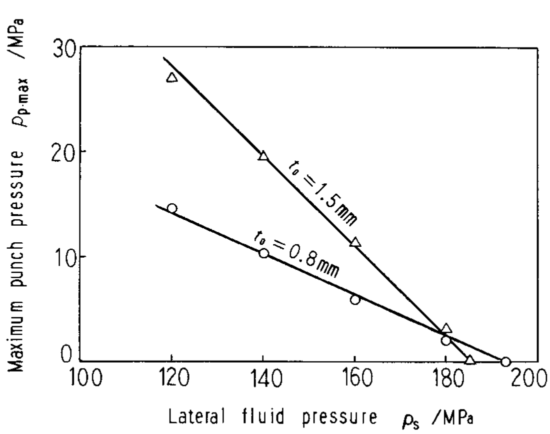


Fig. 7 Relation between the maximum value of punch pressure $p_{p \cdot max}$ in p_p–S curve and lateral fluid pressure p_s.

protted on the horizontal axis.

As shown in Fig. 4 ~ 7, the drawing characteristics of this drawing method are given as the relation between the depth of drawing, the punch pressure, and the lateral fluid pressure. However, the punch pressure and the lateral fluid pressure act on different surfaces so that it is difficult to estimate the degrees of contribution of these pressures to the drawing deformation. This problem was solved by introducing the idea of the drawing force defined by authers, which will be described in subsequent paper.

(3) Variation of thickness

To research the effect of the lateral fluid pressure p_s on the thickness of cylindrical cups, the thickness of the half-drawn cups of A1050P–O (t_0 = 0.8 mm) was measured. The thickness of the inner annular zone of the cup flange was reduced by 0.05 mm corresponding to b_0 (see Fig. 2) by the penetration of the protrusion of hold-down cylinder at the beginning of the drawing operation, and then that was unchanged during the drawing process. The thickness of the rim of the cup flange increased by 0.05 mm corresponding to c_0 in early stage of the drawing operation, and then that was unchanged during the drawing process. The thickness of the cup flange increased with increasing distance from the axis of the die, which suggested the existance of the slight clearance between the upper surface of the cup flange and the bottom of the hold-down cylinder.

The thickness of the part bended on the die shoulder increased gradually from that of the inner annular zone of the cup flange to that of the cup wall. And its increment increased with increasing lateral fluid pressure p_s, which is caused by the decrease of the tensile stress in meridian direction induced by the reduction of punch force. The thickness on the profile radius of the cup decreased, and its decrement decreased with increasing lateral fluid pressure p_s.

3.2 Process of drawing deformation

From the experimental results obtained, the process of the drawing deformation is considered as follows.

Figure 8 presents the schematic diagram to explain that process. Fig. 8 (a) shows the state just before loading, in which the protrusion of hold-down cylinder ④ is in contact with a blank ⑥. Pressurizing the liquid in the lateral pressure system shown by dark shading, the hold-down cylinder ④ is in contact with a blank ⑥. Pressurizing the liquid in the lateral pressure system shown by dark shading, the hold-down cylinder is pressed down, which causes its protrusion to penetrate the blank slightly. When the hold-down cylinder comes in contact with the stop ring ⑤ as shown in Fig. 8 (b), its downward movement is stopped, before which the seal in the lateral pressure system has been completed. The depth of penetration and the clearance shown in this figure cor-

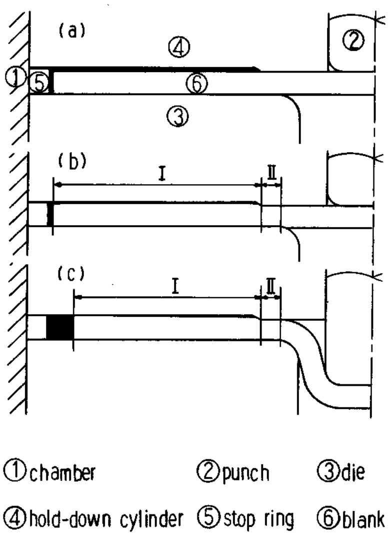


Fig. 8 Schematic diagram of deep drawing process.

respond to b_0 and c_0 shown in Fig. 2, respectively. The pressurized liquid in the lateral pressure system is sealed at the region **II** where the blank is penetrated by the protrution of hold-down cylinder. In outer region **I**, the fluid pressure being equal to the lateral fluid pressure is applied to the upper and lower surfaces of the blank.

Pressing down the punch ② after raising the lateral fluid pressure to a setting value, the blank is drawn into the die ③ with the slight ironing forced by the tapered surface of the protrusion of hold-down cylinder. As the deformation proceeds, the thickness of the outer annular zone of the cup flange increases to the height of stop ring H (see Table 1) as shown in Fig. 8 (c). However, the thickness is not permitted to increase above H by that force pressing down the hold-down cylinder which arises on account of the difference between the areas of its upper and lower surfaces applying fluid pressure.

From the observation of the surfaces of half-drawn cups, the lubrication between the cup flange and tools is considered as follows. In the region **I**, lubricant is kept between the blank and the tools, and the state of fluid lubrication persists throughout the drawing process. On the other hand, the region **II** at which the pressurized liquid is sealed is in the state of boundary lubrication and forced lubrication is expected by wedge action.[3]

3.3 Punchless drawing

As described in sect. **3.1** (2), under higher lateral fluid pressure p_s, the drawing deformation proceeded considerably before applying punch pressure and besides the maximum punch pressure $p_{p\cdot max}$ was reduced remarkably. Therefore, it was considered that aluminum blank may be able to be drawn without punch under a limited tool condition. And so the possibility of the punchless drawing was pursued in this investigation.

The experimental equipment and its individual tools used in the punchless drawing were shown in Fig. 1 and Table 1. For the specimen, the 0.8 mm thick sheet of A1050P −O was used. In the punchless drawing, a blank was drawn into the die by only the lateral fluid pressure applied to its perimeter. The setting of a blank and the fluid seal in punchless drawing were as same as those in the drawing using lateral fluid pressure with punch.

Photograph 3 shows the shape of the cups drawn in the punchless drawing with the dies having various die radii. For a die radius ρ_d = 3.0 mm, the cup has perfectly cylindrical wall at all times as shown in Photo. 3 (b). By magnifying the vertical section of the cup with projecter, it was clarified that the blank was deformed along the die profile as if punch was used.

For a smaller die radius, ρ_d = 1.0 mm, the cup is hollowed at four portions of its wall by buckling as shown in Photo. 3 (a). And, for a larger die radius, ρ_d = 4.0 mm, the cup is wrinkled at the part bended on the die shoulder as shown in Photo. 3 (c). And each non-axisymmetric deformation represents the typical deformation in the punchless drawing with the die having insufficient or excessive die radius. For a die radius, ρ_d = 2.5 mm, which was used in the drawing using lateral fluid pressure with punch, the cup had perfectly cylindrical wall in most cases but sometimes the cup was hollowed at its wall by buckling. Therefore, it seems that this die radius is slightly

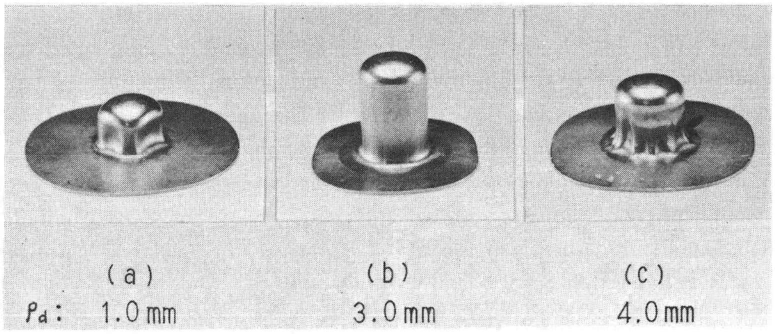


Photo. 3 Shape of cups drawn by punchless drawing.

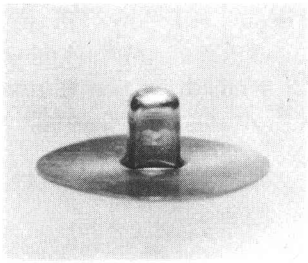


Photo. 4 A cup drawn by punchless rectangular drawing.

smaller than the optimum value.

Photograph 4 shows an example of the application of this punchless drawing to rectangular drawing.

4. Conclusion

In this study, the drawing characteristics of the deep drawing utilizing lateral fluid pressure applied to the perimeter of a blank for the reduction of punch force were clarified experimentaly for aluminum sheets, and the possibility of its punchless drawing was examined.

The results obtained for the soft aluminum sheet of A1050P–O may be summarized as follows.

(1) Drawing ratios of 4 and 6 are obtained for the punch diameters of 15 mm and 10 mm, respectively, which suggests that the lateral fluid pressure contributes to the drawing deformation remarkably.

(2) In the drawing process under a constant lateral fluid pressure, some deformation proceeds by the lateral fluid pressure bellow a set value before applying the punch pressure, and that deformation increases with increasing set value of lateral fluid pressure. The punch pressure increases to a miximum value and then decreases with increasing depth of drawing.

(3) The maximum punch pressure $p_{p \cdot max}$ decreases linearly to nearly zero with increasing set value of lateral fluid pressure. Except for high lateral fluid pressure,

$p_{p \cdot max}$ for the 1.5 mm thick sheet is higher than that for the 0.8 mm thick sheet, and the difference between them decreases with increasing set value of lateral fluid pressure.

(4) The punchless drawing becomes feasible for the 0.8 mm thick sheet by using the die having a die radius of 3.0 mm, and the cup has perfectly cylinderical wall. For the die having insufficient die radius, the cup is hollowed at its wall by buckling. And for the die having excessive die radius, the cup is wrinkled at the part bended on the die shoulder.

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