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Forming Pressure Control in First Stage Drawing and Re-drawing of Cylindrical Shells with Rubber Die*

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The effect of forming pressure upon the contact state between a punch and a formed cup, the forming rate of the side wall, and the decrease of the metal thickness at the punch profile portion are clarified for the cases of the first stage drawing and the re-drawing with rubber die.

The relation between the forming limit and the pressure path is also discussed. The adoption of the S character type pressure path makes the drawing possible, even when the drawing can not be performed successfully under the constant or the linearly increased pressure path.

Moreover, forming conditions under which the total drawing ratio increases are clarified. A product with total drawing ratio of 5.38 can be obtained by using a spherical head punch for the first stage drawing and a flat head punch and a spherical head collar for the re-drawing.

1. Introduction

In the deep drawing of sheet metals, it is essentially important to repress the thinning of a metal at the punch profile portion by reducing the additional resistances due to the friction at the interface between tools and a metal, bending and unbending at the die profile portion. In the ordinary drawing method using a metal punch and die, the effects of these factors on the forming limit of a cup have been investigated in detail, since the factors related to the resistances can be treated separately.

On the other hand, in the deep drawing (1)~(4) with rubber die, the profile of the forming radius portion varies with the applied forming pressure. Consequently, the additional resistances mentioned above and the contact length between a punch and a cup wall change also according to the magnitude of the forming pressure. Therefore, in order to obtain a cup having a large drawing ratio, it is extremely important how to control the forming pressure during the process of the deep drawing.

Hitherto, many investigations were made of the deep drawing method employing a resilient material such as rubber or hydraulic fluid as a die. However, there have been few reports in which the pres-

sure control in the drawing process, i.e. the pressure path, is discussed in detail and systematically. Namely, the relation between the pressure path and the forming limit has been briefly discussed for the hydroforming (5) but it has been only shown for the rubber-pads drawing (6) that the forming pressure should be increased gradually as the punch stroke increases.

Another feature of the deep drawing with rubber die is that the concentration of the axial tensile stress at the punch profile portion can be relaxed by the frictional force generated between the side wall of a formed cup and a punch. When the forming pressure is high, the frictional effect contributes to the improvement of the limiting drawing ratio, but at the same time, the inconvenience occurs that the frictional resistance at the flange portion also increases. Then, if it is possible to make use of only the frictional effect at the side wall portion, it is expected that the limiting drawing ratio becomes larger. When the redrawing is carried out using rubber die, it is considered that the almost same condition as mentioned above can be realized. The methods of re-drawing (7)~(11) reported hitherto fall into three main groups: (i) direct re-drawing (ii) reverse re-drawing with metal tools, and (iii) re-drawing using metal tools with fluid pressure. However, the total drawing ratio obtained by these methods is about 3.5. Therefore, it is considered that there are some problems to be examined with respect to the improvement of the total drawing ratio.

From the above mentioned point of view, in this paper, the forming pressure control is mainly investigated for the first stage drawing and the re-drawing with rubber die. Firstly, in order to clarify the effect of the forming pressure on the deformation behavior of the sheet metal, the deep drawing is performed with various constant pressure paths. The de-

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crease of metal thickness at punch profile portion, the movement of the contact point of a formed cup and a punch, and the forming limit are examined. Secondly, on the basis of these data, the pressure path by which a cup having large drawing ratio can be obtained is discussed and the S character-type pressure path is proposed as the most effective ones. Finally, the re-drawing of the cup drawn by the first stage drawing with rubber die is executed. The effect of pressure path and tool shape on the forming limit is examined experimentally, and then the forming condition to improve the total drawing ratio is clarified.

2. Experimental condition and procedure

2.1 Experimental condition

The materials used in this experiment are cold rolled steel plate (SPCE) and soft aluminium plate (Al-0). The mechanical properties of them are listed in Table 1.

The experimental condition and the dimensions of the tool used are shown in Table 2. The experimental apparatus for re-drawing is shown in Fig.1. The collar ④ is not used for the first stage drawing.

2.2 Experimental procedure

The drawing is performed with various pressure paths up to the pressure of 800 kg/cm². Taking out the product in various stages of drawing, the deformation process is observed and especially the decrease of the metal thickness at the punch profile portion and the variation of the point at which a punch and a formed cup begin to contact are measured. The boundary of contact between a punch and a cup is obtained by measuring the contact mark as shown in Fig.2 with the height gauge. A fracture or a wrinkle of the cup is detected by a change in the rubber pressure-stroke dia-

Table 1 Mechanical properties of materials

	SPCE		Al-0
	First stage drawing	Redrawing	
Tensile strength, kg/cm ²	32.4	30.4	8.7
Total elongation, %	42.1	48.3	32.5
F, kg/cm ²	57.2	53.9	18.3
n	0.224	0.232	0.236
r value	1.43	1.96	0.69

Table 2 Experimental condition

Punch	First stage drawing, mm	Flat	diameter: 25, 25.4, 27, 30 ; profile radius: 4
	(Collar for redrawing)	Spherical	diameter: 25, 25.4, 27
	Redrawing, mm	Flat	diameter: 13, 14, 16, 17, 18, 20 ; profile radius: 3
		Spherical	diameter: 16
Die	Material	Vulcanized natural rubber (60 in JIS hardness)	
	Dimensions, mm	diameter: 70 ; thickness: 10 (10 pads)	
Blank	Material	SPCE, Al-0	
	Dimensions, mm	diameter: 60, 63, 65, 67, 70 ; thickness: 0.6, 0.8, 1.0	
Lubricant		Johnson wax #150 (Both sides of blank except contact surface with punch head)	
Drawing speed, mm/s		0.2~0.5	

gram drawn on the X-Y recorder.

3. Effect of forming pressure on deformation behavior of cup in first stage drawing

3.1 Development of thickness strain

Figure 3 shows the development of thickness strain ϵ_t of the cup drawn under the constant pressure with stroke $\bar{h}$. It is obvious from Fig.3 that ϵ_t is affected considerably by forming pressure $\bar{p}$. When the forming pressure is low, the decrease of the thickness is concentrated at the punch profile portion and, if the drawing proceeds, a fracture occurs at that portion. On the other hand, under the high forming pressure, the decrease of thickness at the punch profile portion scarcely grows in the stage after the cup wall is formed. It is also seen that the thickness strain has a tendency to propagate from the punch pro-

- ① Load cell for detecting mean rubber pressure
- ② Retainer, ③ Rubber pads
- ④ Collar for re-drawing, ⑤ Blank holder
- ⑥ Punch, ⑦ Die cushion pin
- ⑧ Load cell for detecting punch force

Fig.1 Experimental apparatus for first stage drawing and re-drawing

Fig.2 Contact portion with rubber

file portion to the side wall. This tendency is one of the special merits in this forming method. From the thickness strain distribution shown in Fig.3, it is considered that a cup can be safely drawn as the forming pressure increases.

3.2 Decrease of thickness at punch profile portion and variation of point of contact between punch and formed cup

In the following, paying attention to the minimum thickness at the punch profile portion, the effect of forming pressure and drawing ratio on the minimum thickness and the variation of point of contact between a punch and a formed cup are examined.

The tendency of the decrease of thickness at the punch profile portion in the drawing process is classified into three cases as shown in Fig.4, according to the forming pressure and the drawing ratio ($\beta = R_0/R_2$).

(a) In the case that drawing ratio is small ($\beta \leq 2.4$), the thickness decreases slightly in the beginning of drawing but thereafter it scarcely changes. The effect of forming pressure on the decrease of thickness is not remarkable.

(b) In the case that drawing ratio is medium ($\beta = 2.6$), it is seen that either the thickness is kept almost constant or it decreases rapidly after a certain stroke and then a fracture occurs.

(c) In the case that drawing ratio is large ($\beta \geq 2.8$), metal thickness continues to decrease invariably and a fracture occurs.

Then, the reason is examined from the

Fig.3 Development of thickness strain ϵ_t for first stage drawing

contact state between a punch and a formed cup why the development of the decrease of thickness depends on the forming pressure as shown in Fig.4(b).

Figure 5 shows the relation between the contact length ($R - y_0$), as shown in Fig.2, between a punch and a formed cup and the minimum thickness at the punch profile portion. In the early stage of the forming, in other words, the stage before the blank contacts entirely with the punch profile portion, the rate of decrease of thickness is affected by drawing ratio and metal thickness but is scarcely affected by forming pressure. However, after the side wall portion is formed (angle of contact between formed cup and punch $\varphi_1 = 90^\circ$), the effect of pressure on the decrease of thickness becomes remarkable and when the side wall portion is scarcely formed, a fracture occurs. Therefore, in the deep drawing with rubber die, whether the drawing is possible or a fracture occurs is considered to be closely related to the rate of forming of the side wall portion.

3.3 Analytical consideration of profile and stress at forming radius portion

Fig.4 Variation of minimum thickness at punch profile portion with punch stroke h (R_2 : punch radius)

Fig.5 Relation between decrease of minimum thickness at punch profile portion and contact length ($R - y_0$)

Figure 6 shows the effect of the forming pressure on the movement of the contact point (that is, the variation of contact length). The curves in Fig.6 indicate the value obtained from the analysis. The analysis treated in this paper differs from the previous one⁽⁴⁾ in that the work hardening of the material is taken into consideration ($\sigma_{eq} = F \varepsilon_{eq}^n$) and that the more suitable values are used as the coefficient of friction⁽¹²⁾ ($\mu_m = 0.08$ between metals, and $\mu_R = 0.01$ between rubber and metal). It is found from Fig.6 that the lower the forming pressure, the smaller the rate of forming of the side wall portion.

Figure 7 shows the variation of meridian stress during the drawing process. The following value is adopted as σ_R in the ordinate. Before the side wall portion is formed ($\varphi < 90^\circ$), the value at the boundary between punch profile portion and forming radius portion ($\sigma_R = \sigma_d$). After the side wall portion is formed ($\varphi = 90^\circ$), the value at the boundary between punch profile portion and side wall portion. In the latter, σ_R is calculated by using the initial value of σ_d at the boundary between the side wall and the forming radius portions and by considering the frictional effect at the side wall portion. It is seen that, in the stage before the value of R/R_2 reaches 1.1~1.4, σ_R increases as forming pressure increases but, in the range exceeding the above, σ_R decreases rapidly as the forming

pressure increases.

On the other hand, under low forming pressure, the rate of forming of the side wall portion is small and also the frictional effect at the side wall portion is small, so that meridian stress σ_R becomes large in comparison with the case of high forming pressure. Consequently, the decrease of thickness continues to develop and a fracture occurs.

4. Pressure path and forming limit

4.1 The cases of constant pressure path and linearly increased pressure path

In the deep drawing, the forming limit is determined by the appearance of a fracture and a wrinkle of the cup. Then, the effect of forming pressure on the forming limit is examined under various drawing conditions. Figure 8 shows the forming limit for SPCE in the case of the constant pressure path and the linearly increased pressure path (initial pressure 200 kg/cm²). It is seen from Fig.8 that, when the metal thickness is same [cf. (a), (b)], according as the drawing ratio increases, and also when the drawing ratio is same [cf. (a), (c), (d)], according as the thickness increases, the fracture limit extends to a higher pressure range and consequently the forming region decreases.

On the other hand, the limit of wrinkle appears in a comparatively low pressure range. When the metal thickness is same, the pressure at the upper limit of wrinkle decreases slightly according as the drawing ratio increases. However, the effect of thickness on the wrinkle limit

Fig.6 Variation of contact length ($h-y_0$) with punch stroke h

Fig.7 Effect of forming pressure on meridian stress σ_R

Fig.8 Forming limit for first stage drawing under constant pressure path and linearly increased pressure path (SPCE)

is not so remarkable.

As is seen in Fig.8(b) and (c), if the fracture limit extends to a high pressure range, it is difficult to draw a cup completely by the pressure path such as a constant one or a linearly increased one. For this case, it is effective to adopt the so-called S character type pressure path described later. But, when the forming region exists as shown in Fig.8(a) and (d), it is confirmed experimentally that any pressure path may be adopted if it passes the upside of the fracture limit curve. Here, it is stated in addition that there is a possibility of drawing under the linearly increased pressure path, even if the drawing is impossible under the constant pressure path.

4.2 Proposition of S character type pressure path

Considering from the above described tendency of the thickness decrease at the punch profile portion, in order to prevent

[Broken line corresponds to forming limit shown in Fig.8(b)]

Fig.9 S character type pressure path

an occurrence of the fracture of a cup, it is necessary to form the side wall portion without decreasing the metal thickness in the stage after the metal contacts the punch profile portion. In other words, at a certain stage in the drawing process, if the forming radius portion can be converted momentarily to the side wall portion without decreasing the thickness, thereafter, the thinning of the metal at the punch profile portion is fairly restrained by the frictional effect at the side wall portion.

In order to realize the above described idea, it is considered that the adoption of the so-called S character type pressure path shown in Fig.9 is very effective.

4.2.1 Deformation process of cup

Figure 10 shows the drawing process of a cup in the S character type pressure path. As the pressure is low in the early stage of drawing, the forming radius portion is kept fairly large. When the pressure is suddenly increased, the forming radius becomes small and at the same time the side wall portion is formed. Moreover, at this time, the blank holder is slightly moved upwards by the mechanism of the press used, so that the forming radius portion can be converted to the side wall portion without increasing the tensile force acting on the metal at the punch profile portion.

Figure 11 shows the variation of the minimum metal thickness at the punch profile portion and the contact point between a punch and a formed cup. In the stage at which the forming pressure is increased rapidly, it is seen that the side wall portion is also rapidly formed, though the metal thickness decreases slightly. There-

Fig.10 Drawing process of cup in S character type pressure path

after, since the drawing proceeds under high pressure, the metal thickness decreases scarcely and the side wall portion increases in proportion to the punch stroke.

4.2.2 Consideration on S character type pressure path

Figure 12 shows the initial pressure p_0 and the time t_0/R_2 in which the pressure rises rapidly in the S character type pressure path. The broken line shown in Fig. 12 indicates the forming limit in the constant pressure path. It is found from Fig. 12 that the S character type pressure path should be selected so as to raise the pressure just before the line representing the

Fig. 11 Variation of minimum thickness and contact length in S character type pressure path

Fig. 12 Initial forming pressure p_0 and punch stroke h_0 at which forming pressure increases rapidly

wrinkle limit for the constant pressure path. In this case, it is feared that a fracture may occur since the S character type pressure path crosses the fracture limit for the constant pressure path. But, as shown in Fig. 10, the fairly large part of the forming radius portion is already converted to the side wall portion at an intersection (7). In the stage after the side wall of a cup is formed, the tensile force acting at the punch profile portion is relieved by the frictional effect at the side wall portion. Therefore, the decrease of the metal thickness is not so much developed, and the fracture of a cup can be prevented.

The frictional effect at the interface between a punch and the side wall of a formed cup can be estimated quantitatively by the following equation.

$$\frac{\sigma - \sigma_s}{p} = \frac{K_2 \{(\mu_m \pm \mu_R) \pm \mu_R (t_0/R_2)\} H}{(t_0/R_2) \{1 + (t_0/2R_2)\} R_2}$$

where, σ : meridian stress at the side wall of a formed cup

σ_s : meridian stress at the boundary between the side wall and forming radius portion

p : average forming pressure

$K_2 = 0.8$, ratio of the pressure acting at the side wall to the average forming pressure

t_0 : thickness of blank

Fig. 13 Frictional effect at side wall portion

Fig. 14 Re-drawing process of Cup (SPCE)

R_2 : punch radius

H : length of the side wall measured from the boundary between the side wall and the forming radius portion

The plus sign in the above equation corresponds to the case that the forming pressure rapidly rises and the minus sign to the case of constant pressure path. Figure 13 shows the result of calculation using a more suitable value ⁽¹²⁾ of μ_R than one used in the previous paper ⁽⁴⁾. It is obvious that the meridian stress at the side wall of a cup decreases in proportion to the length of the cup wall and that the rate of decrease of the stress becomes large as the relative punch radius R_2/t_0 increases.

5. Re-drawing with rubber die

5.1 Experimental apparatus

The apparatus shown in Fig.1 is used in the experiment. The collar ④ is put on the punch ⑥ and the cup obtained by the first stage drawing is put on them. Therefore, re-drawing process is different from the first stage drawing in that the rubber pressure acts only on the formed cup contacting the punch and the collar profile portion. In other words, the frictional resistance on the flange portion

Fig.15 Development of thickness strain for re-drawing

A : Point of minimum thickness
appeared in re-drawn cup

B : Point of minimum thickness
in first stage cup

Fig.16 Thickness decrease
at point of A and B

does not exist, which is one of the largest resistance components in the first stage drawing. Therefore, in the re-drawing with rubber die, only the frictional effect at the side wall portion can be utilized effectively.

5.2 Deformation process and general tendency of thickness strain distribution

Figure 14 shows the deformation process of a cup in the re-drawing. Figure 15 shows the development of the thickness strain distribution with an increase of the punch stroke Δ . The general tendency of the thickness strain distribution is almost same as that of the first stage drawing shown in Fig.3. The point of minimum thickness (B) which appears at the punch profile portion of a cup in the first stage drawing is moved to the side wall portion in the re-drawing but this point still corresponds to that of minimum thickness. Figure 16 shows the comparison of the development of thickness strain at the points B and A, where A is the point of the minimum thickness appearing newly at the punch profile portion of the re-drawn cup. It is seen that the decrease of thickness at B is larger than that at A. Therefore, whether the re-drawing is successful or not depends on the development of thickness decrease at B in the first stage drawing.

6. Effect of pressure path on forming limit for re-drawing

As in the first stage drawing, the forming limit in the re-drawing is also

Fig.17 Forming limit for re-drawing under constant pressure path and linearly increased pressure path (SPCE)

strongly affected by the forming conditions such as the pressure path and the drawing ratio.

Figure 17 shows the forming limit in the re-drawing using a flat head punch and a collar. The shadowed portions A and B in Fig.17 indicate the forming region. The portion A is for the constant pressure path and B for the linearly increased pres-

Fig.18 Cups not re-drawn successfully

sure path. Moreover, the portion C exists, in which the cup obtained by the first stage drawing can not be re-drawn as shown in Fig.18(a), because the forming pressure is too small.

The general tendency seen in Fig.17 is as follows. The redrawing becomes possible by the adoption of the linearly increased pressure path, even if the redrawing is impossible with the constant pressure path. When the total drawing ratio β^* is same, the portions A, B and C appear on the higher side of the pressure as the metal thickness increases. When the first stage drawing ratio β is kept constant, the portions A and B become narrow as the redrawing ratio β' becomes large. Furthermore, if the total drawing ratio β^* is same, the larger the first stage drawing ratio β , the easier the redrawing.

Figures 18(b) and (c) show the wrinkles observed in the redrawing.

In order to consider the above described relation between the forming limit and the drawing ratio, the development of the thickness strain with the punch stroke r' is examined under various drawing ratios. Figure 19 shows the thickness strain distribution of the redrawn cup. When the

Fig.19 Effect of first stage drawing ratio β and re-drawing ratio β' on thickness strain distribution

redrawing ratio is small ($\beta'=1.50$), the point of the minimum thickness in the first stage cup is still that of minimum thickness in the redrawing. But a thickness strain at this point does not develop during the redrawing. When β' is large, a thickness strain at the side wall which corresponds to the point of the minimum thickness in the first stage drawing, de-

velops rapidly at the final stage of the redrawing. This tendency becomes remarkable as β' increases. Therefore, it is considered that a fracture comes to occur at the side wall portion of a redrawn cup as β' approaches the limiting value. When β' exceeds the limiting redrawing ratio, a thickness decrease at the punch profile portion continues to develop and a fracture occurs at that portion.

If the total drawing ratio is kept constant [Fig.19(c) and (d)], the following are seen. When β is large and β' is small, [(d)], the thickness decrease at the punch profile and the side wall portions stops during the redrawing process. But, when β is small and β' is large, [(c)], the thickness at the punch profile portion continues to decrease and results in a fracture. Therefore, in order to improve the total drawing ratio, it is necessary to make β as large as possible. This tendency is similar to the result⁽¹⁰⁾ of redrawing with metal tools.

7. Effect of tool shape on forming limit for re-drawing

Fig.20 Effect of tool shape on forming limit for re-drawing (Marks are same to those shown in Fig.17)

Figure 20 shows the effect of

Fig.21 Effect of tool shape on thickness strain distribution

the shape of the punch and the collar on the forming limit for redrawing. From comparison of Fig.20 and Fig.17(f), it is found that the forming region (shadowed portions A and B) differs according to the combination of the punch and the collar. When the spherical head punch is used in the redrawing, the cup is sheared at the collar edge in the early stage of forming, because the head portion of the cup is pressed against the collar edge by rubber. Therefore, the redrawing is possible only with the linearly increased pressure path.

On the other hand, if the flat head punch is used, the forming region exists in both cases of the constant pressure path and the linearly increased one. Referring to Fig.20(b) and Fig.17(f) in detail, it is found that the forming region B is larger in the former than in the latter. Since the punch used for the redrawing is same in both cases, the difference in the forming limit is considered to be due to the shape of the punch in the first stage drawing or the collar in the redrawing.

Then, the difference in the forming limits mentioned above is discussed on the basis of the thickness strain distribution. Figure 21 shows the thickness strain distribution of redrawn cups ($\beta'=1.69$) obtained by the linearly increased pressure path. The first stage cup ($\beta=2.59$) is obtained by the S character type pressure path. Figure 21(a) and (b) correspond to Fig.20(b) and Fig.17(f), respectively. It can be concluded from Fig.21 that the development of the thickness strain is different depending on the shape of the collar for the redrawing. Namely, as is seen in Fig.21(a) and (c), if the spherical head collar is used, a thickness strain scarcely develops regardless of the shape of the punch for the first stage drawing. On the other hand, when the flat head collar is used, the thickness at the side wall portion decreases rapidly in the lat-

Fig.22 Effect of punch shape on forming limit for first stage drawing ($\beta=2.64$, $t_0=1.0 \text{ mm}$, SPCE)

ter stage of the redrawing, and therefore the danger of a fracture at the side wall portion increases. From this fact, it can be understood that many points representing the fracture at the side wall portion appear in the neighbourhood of the forming region B, as shown in Fig.17(f).

8. Forming condition to improve total drawing ratio

The forming condition to improve the total drawing ratio β^* is discussed on the basis of the results obtained above. The factors considered here are the pressure path, the drawing ratio β , β' and the shape of tools.

In the first stage drawing, it is necessary to obtain a cup having as large drawing ratio as possible. As pressure path for this purpose, the S character type one is considered most desirable. Figure 22 shows the effect of the shape of the punch on the forming limit for the first stage drawing. It is seen from Fig. 22 that the forming region (shadowed portions A and B) is wider for the spherical head punch than for the flat head one. Therefore, it is obvious that the drawing can be easily performed if the spherical head punch is used.

In the case of re-drawing, it is desirable to adopt the forming condition stated in the following. Considering the extent of the forming region shown in Fig. 17, it is suitable to draw in the linearly increased pressure path. The forming re-

Fig.23 Difference in profile at forming radius portion depending on shape of collar

Fig.24 Effect of collar shape on meridian stress σ_d at boundary between forming radius and side wall portion

gion for the redrawing widens by the use of the punch with flat head. Moreover, it is desirable to use a collar with spherical head, since the decrease of the metal thickness may be restrained. Figure 23 shows the comparison of the profile at the forming radius portion in the cases of using the collar with a flat and a spherical head. It is seen that the profile at the forming radius portion changes largely according to the shape of the collar, and that the radius of curvature at the forming radius portion becomes large if the spherical head collar is used. Figure 24 shows the calculated result of the meridional stress σ_m at the boundary between the forming radius portion and the side wall of a formed cup. It is seen that the value of σ_m for the spherical head collar is slightly smaller than that for the flat head collar.

Under the forming conditions described above, the steel cup with total drawing ratio β^* of 5.38 is obtained, as shown in Fig. 25(a). The drawing ratio in the first stage is 2.80 and the redrawing ratio is 1.92. Figure 25(b) shows a cup with $\beta^*=4.38$, obtained by the first drawing and the redrawing in the constant pressure path. Figure 25(c) shows a soft aluminium cup of $\beta^*=4.12$.

9. Conclusions

The following is a summary of the points clarified in this investigation.

(1) The forming pressure has significant effects upon the development of thickness decrease of a formed cup and the rate of formation of the side wall portion.

(2) When the forming pressure is low, the rate of formation of the side wall portion is small and the decrease of metal thickness concentrates at the punch profile portion. By contrast, when the forming pressure is high, the concentration of the thickness strain is restrained due to the so-called frictional effect at the side wall portion. Therefore, the fracture of a cup is apt to occur under rather low pressure than under high pressure.

(3) The fracture limit extends to the higher side of the pressure as the drawing ratio increases and also as the metal thickness increases. A fracture occurs at the early stage of the drawing as the forming pressure becomes high.

(4) A difference in the fracture limits between the constant pressure path and the linearly increased one is hardly recognized. Since the fracture limit appears generally on the lower side of the pressure, the forming region exists on the higher side.

(5) In the case where the fracture limit appears on a comparatively low side of pressure, the drawing is possible by adopting either the constant pressure path or the linearly increased one, if they pass the pressure range above the fracture limits. In the case where the fracture limit extends to the higher side of pressure, it is very effective to adopt the S character type pressure path. However, in both cases, it is necessary to increase the forming pressure in order to prevent the occurrence of a wrinkle in the final stage of the drawing.

(6) The point of the minimum thickness in the redrawn cup corresponds to that in the cup obtained by the first stage drawing.

(7) The forming region for the redrawing in the constant pressure path is determined mainly by the fracture at the punch profile portion and the wrinkle at the forming radius portion or the collar profile portion. In the linearly increased pressure path, the forming region is determined by the fracture at the side wall portion and the wrinkle at the forming radius portion.

(8) Unlike the case of the first stage drawing, the forming region in the redrawing exists between the lower limit of fracture and the upper limit of wrinkle. On the lower side of wrinkle limit, there is a pressure range in which the redrawing does not proceed at all. Moreover, the redrawing can be easily performed as the metal thickness increases.

(9) The redrawing becomes possible in the linearly increased pressure path, even if it is impossible in the constant pressure one. But, when the fracture limit and the wrinkle limit for the constant pressure path intersect, the redrawing is impossible even in the linearly increased pressure path.

(10) In order to improve the total drawing ratio, it is important to make the drawing ratio in the first stage as large as possible. It is also effective to use a spherical head punch for the first stage drawing, and to adopt the combination of a flat head punch and a spherical head collar for the redrawing. By using these tools, a steel cup with a total drawing ratio 5.38 can be obtained.

Fig. 25 Cups obtained by re-drawing

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