Deep Drawing of Circular Sheet Metals with Rubber Rings*
(2nd Report, The Case of Repeated Drawing Operations)

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The drawing limits of mild steel and aluminum sheets were examined for the case of repeated drawing operations in which the blank was deformed incrementally as the rubber ring was repeatedly loaded and unloaded. The drawing condition used was based on the optimum one for the first drawing operation clarified in our 1st report.

The obtained drawing ratio was 2 for mild steel, 3 for hard aluminum and 6 for half-hard and soft aluminum. When the work hardening of the blank was diminished by intermediate annealings, a maximum drawing ratio of 12 was achieved for soft aluminum.

The strain distribution, shape and surface roughness of drawn cups were also examined.

Furthermore, the relation between the height of the drawn cup and the number of drawing operations was discussed for the case of using either a vulcanized natural rubber or a polyurethane ring and was compared with the data reported by N. A. Maslennikov.

1. Introduction

According to the results obtained in the previous experiments(1) on the first drawing operation, the maximum drawing ratios achieved were 2.0 for soft aluminum and 1.8 for mild steel. Therefore, a certain number of drawing operations should be repeated continuously in order to obtain fully drawn cups with larger drawing ratios than above ones. For the blank materials having a small deformation resistance such as soft aluminum, a cup with a drawing ratio of about 5.0 can be completely drawn in ten drawing operations by using only one metal die throughout the process. On the other hand, there is also one of the serious problems in punchless drawing that the shape of the drawn cup is not always uniform. However, it is considered that the shape can be corrected if one redrawing or ironing with metal tools is adopted as an additional process. Considering these aspects, the punchless drawing process should be practically recommendable as a specialized technique for the comparatively low volume production rather than for the large quantity one.

In this paper, firstly, the drawing limits of mild steel and aluminum sheets were examined. The experiments were made on both cases of repeated drawing operations with and without intermediate annealings. As a result of experiments, a cup with a drawing ratio of 12.0 was obtained for soft aluminum. Secondly, the measurements were made of strain distribution, shape and surface roughness of drawn cups. Moreover, the difference in the height of drawn cups was compared between the polyurethane and the vulcanized natural rubber used as a ring. Finally, experimental results obtained in this investigation were compared with Maslennikov's ones(2) and through above comparisons, some problems which had been untouched until then were discussed.

2. Relationship between limiting drawing ratio and number of drawing operations

2.1 The case of repeated drawing operations without intermediate annealings

Three kinds of aluminum and mild steel sheets were used as the blank materials. The diameter of the blank was 120 mm for aluminum and 106 mm for mild steel. The drawing ratio is here defined as the diameter of the initial blank divided by the diameter of the die hole.

Figure 1 shows soft aluminum and mild steel cups at each stage in the repeated drawing opera-
The relationships between the ratio of the cup height to the die diameter, \( h/d_1 \), and the number of drawing operations, \( n \), are indicated in Fig. 2~Fig. 4. Figure 2 shows the result for the case where the drawing ratio is 3.0 for aluminum blanks and 2.65 for mild steel. It is seen from Fig. 2 that the height of aluminum cups increases in proportion to the number of drawing operations. Meanwhile, for mild steel, the rise of the curve becomes less steep after the third drawing operation. This means that a fully drawn cup can not be obtained in this case even if more drawing operations are repeated continuously. However, when the die of 50 mm in diameter (drawing ratio \( \beta = 2.1 \)) was used, a mild steel cup could be drawn completely in four or five drawing operations. It can be concluded from the above that the limiting drawing ratio is about 2.0 for the mild steel blank of 0.8 mm in thickness.

The results on the aluminum cups will be shown below for the case of reducing the die hole diameter in order. Figure 3 shows the result for a die diameter \( d_1 = 30 \) mm \( (\beta = 4.0) \). It is found that the height of the cup hardly increases after the first drawing operation for hard aluminum. However, for the cases of soft and half-hard aluminums, the
height increases in proportion to the number of drawing operations and the drawing is completed, in both cases, at the seventh drawing operation.

The result for the die diameter of 20 mm (β = 6.0) is indicated in Fig. 4. The increase in the height of the cup at each drawing operation is also shown in Fig. 4 together with the relation between the value of $h/d_1$ and the number of drawing operations. The deformation of the soft and half-hard blanks continues to increase without stopping through the drawing process. By repeating these drawing operations a soft aluminum cup could be fully drawn in fifty-five drawing operations. On the other hand, for half-hard aluminum, a fairly wide flange portion remained at that time. Moreover, for soft aluminum, the repeated drawing operations were carried out using a die of diameter 15 mm (β = 8.0). In this case, however, the deformation of the blank stopped at last after ten drawing operations.

It can be concluded from the results that the limiting drawing ratio obtained by the repeated drawing operations without intermediate annealings is about 3.0 for hard aluminum and about 6.0 for half-hard and soft aluminums. Soft aluminum cups having various drawing ratios are shown in Fig. 5 as examples of the products drawn without intermediate annealings. The height of the cup with a drawing ratio of 6.0, which is shown at the extreme right in Fig. 5, is about 140 mm ($h/d_1=7.0$).

2.2 The case of repeated drawing operations with intermediate annealings

If the work hardening of the blank materials can be diminished by intermediate annealings, a cup will be obtained which has a greater drawing ratio than the cup drawn without intermediate annealings. From this point of view, it is examined with soft aluminum how a high cup can be obtained by this process. Intermediate annealings, which were performed at 360°C for 30 min., were repeated every time the magnitude of the increase in the height of the cup became less than 1 mm in each drawing operation.

The relationship between $h/d_1$ and $n$ is shown in Fig. 6 for a die with an internal diameter of 15 mm.

Fig. 5 Soft aluminum cups drawn without intermediate annealings

Fig. 6 Relationship between ratio of cup height to die diameter and number of drawing operations with intermediate annealings
It is found from this figure that intermediate annealings have extremely great effects on the increase of the cup height. It should be also noticed that the height of a fully drawn cup and the number of drawing operations required change widely depending on the dimension of the ring and the applied load. Namely, as the applied compressive load increases, the deformation of the blank also becomes larger in each drawing operation and consequently, the number of drawing operations drops. On the other hand, a meridian tension acting on the cup surface at the die profile and the side wall, which results from the polyurethane being forced into the die opening, increases as the internal diameter of the ring decreases. Hence, in such a case, the sheet metal at these portions is subjected to a large elongation in the meridian direction and the height of the cup increases.

A photograph of the cups corresponding to each curve shown in Fig. 6 is given in Fig. 7. Their height is 200 mm \((h/d_1=13.4)\) for the highest cup, 158 mm \((h/d_1=10.6)\) for the middle one and 132 mm \((h/d_1=8.8)\) for the lowest one. The numbers of annealings performed in order to obtain the above cups were 19, 16 and 11 respectively.

Figure 8 shows the relationship between the value of \(h/d_1\) and the number of drawing operations for the die hole diameter of 10 mm \((\beta=12.0)\). In this case, the thickness of the blank was reduced from 1.0 mm to 0.5 mm because it was impossible to make the drawing progress due to the extremely great drawing ratio. Figure 9 shows a cup with a drawing ratio of 12.0 and the crack which occurred at the flange (see Fig. 17 in the first report). The crack shown in Fig. 9, which is one of the fatal defects in this process, tends to occur under a high compression ratio of the ring. Therefore, in order to avoid the occurrence of the crack, the drawing operations should be repeated under a rather low compression ratio.

3. Strain distribution in the drawn cup

Figure 10 shows the metal flow in the soft aluminum cup with a drawing ratio of 4.0. Strain distributions for the mild steel cup after the third drawing operation are shown in Fig. 11. The measurement of strains was made at the angles of 0°, 45° and 90° to the rolling direction of the sheet. The radial, thickness and circumferential strains are expressed by \(\varepsilon_r\), \(\varepsilon_t\) and \(\varepsilon_\theta\) respectively.

The thickness strains of soft aluminum cups drawn
without intermediate annealings are also shown in Fig. 12. It can be seen from the above two figures that the sheet thickness of a drawn cup increases in all portions except the bottom. The thinning at the bottom portion becomes remarkable as the die hole diameter decreases. As described in the first report, it depends on only the drawing condition in the first drawing operation whether the thickness increases or decreases in this portion. A cup without thinning in all portions, therefore, can be easily obtained by adopting the adequate condition in the first drawing. Figure 13 shows a cross-section of the cups drawn from mild steel and soft aluminum blanks. The numbers along the cup wall indicate the percentage thickness strain in each location.

Vickers hardness was also measured for a soft aluminum cup with a drawing ratio of 4.0. The result of the measurement is shown in Fig. 14. It is clear from comparison with the initial hardness of the blank that the hardness scarcely changed in the bottom portion.

4. Shape and surface roughness of a drawn cup

The serious problems related to a cup drawn by this process are that the shape at the bottom is rather variable, and also so-called nodes as shown in Fig. 15 remain at the side wall portion.

The nodes appeared when aluminum blanks were drawn under an extremely high applied load using a polyurethane ring with a larger internal diameter than that of the die. The number of the nodes corresponds to that of the repeated drawing operations. It can be considered that these nodes occurred because the ring covered only the flange portion at the early stage of each drawing and as a result, the part of the blank at the die profile portion could not deform along the die profile. Therefore, it is especially important in order to obtain a cup without nodes to use a ring with almost the same internal diameter as the die hole diameter.

The shape of the cup at the bottom portion is decided by the drawing condition adopted in the first
drawing operation and therefore it varies widely from nearly flat to hemisphere. In order to discuss this variation of the shape, the relation between the height of the cup and the contraction at the periphery of the blank was calculated. In the calculation, the radius at the bottom of a drawn cup was assumed to be 5 mm and 20 mm (hemisphere), which corresponded to the punch profile radius in the conventional deep drawing with metal tools. Figure 16 shows the results of the calculation and the measurement. It is clear from Fig. 16 that the shape of the bottom gradually becomes hemispherical as the internal diameter of the ring decreases.

Figure 17 shows the surface roughness measured along the side wall portion of soft aluminum cups drawn without intermediate annealings. The surface roughness varies in the range of 1～6 μ, although it has a tendency to increase slightly as the distance from the bottom of the cup increases. The correlation is not especially recognized between the surface roughness and the drawing ratio. On the other hand, the surface roughness of a cup drawn with intermediate annealings increased to the range of 3～17 μ.

![Fig. 14 Hardness distribution of drawn cup](image1)

![Fig. 15 Nodes appearing at side wall of drawn cup](image2)

![Fig. 16 Relationship between ratio of cup height to die diameter and contraction at periphery of blank](image3)
5. Considerations

The relationship between the number of drawing operations and the deformation of the blank was examined for the cases of using polyurethane and vulcanized natural rubber as a ring. The natural rubber had a JIS hardness of 85, which was almost same as the hardness of the polyurethane ring used in this experiment. The dimensions of the die and ring and the condition of lubrication were also kept constant in both cases. In Fig. 18, if the curve reaches the horizontal $D/d_i = 1.0$, it means that the blank has been completely drawn, where $D$ is the current diameter of the periphery of the blank. It is clear from Fig. 18 that the deformation of the blank proceeds much more efficiently for polyurethane than for natural rubber and also this tendency becomes remarkable as the applied load increases.

The minimum number of drawing operations required for obtaining fully drawn cups is compared between polyurethane and natural rubber rings. Figure 19 gives the result for the case that the intermediate annealing was not performed. When the drawing ratio is less than about 3.5, the vulcanized natural rubber is also practical enough for use, but for a larger drawing ratio than the above one, the use of polyurethane is more efficient. It should be also emphasized that a cup with a drawing ratio below 5.0 can be obtained in ten drawing operations.

Finally, comparison is made of the results obtained in our experiment with the Maslennikov’s one. In
both experiments, the drawing conditions were almost same except the differences in the ring thickness and lubricants (see Table 1). Figure 20 shows the relation between $D/d_1$ and $n$. It is seen from Fig. 20 that there is a fairly large difference in the deformation of the blank. Namely, for the case of the applied load below 35 tons, the number of drawing operations required to draw a cup completely is much larger in our experiment than in Maslennikov's one. However, it should be noticed that a fully drawn cup can be obtained, also in our experiment, in ten drawing operations if the drawings are repeated under an applied load above 40 tons. The number of drawing operations required, for example, was 6 under an applied load of 50 tons.

6. Conclusions

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

(1) The limiting drawing ratios obtained in the repeated drawing operations without intermediate annealings are about 2.0 for mild steel, 3.0 for hard aluminum and 6.0 for half-hard and soft aluminums.

(2) A remarkable drawing ratio of 12.0 was achieved for soft aluminum when the work hardening of the blank was diminished by intermediate annealings.

(3) The height of a fully drawn cup and the number of drawing operations required change widely depending on the dimension of the ring and the applied load.

(4) The decrease in thickness is scarcely recognized in all portions of a drawn cup.

(5) The nodes at the side wall of a drawn cup tend to occur under an extremely large compression ratio of the ring. The occurrence of them, however, can be prevented by using a ring with nearly the same internal diameter as the die hole diameter.

(6) The use of a polyurethane ring is much more efficient than that of a vulcanized natural rubber.

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