

Study on micro extra deep drawing process with ultrahigh fluid pressure and press motion controls

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Abstract. A novel micro extra deep drawing process with ultrahigh fluid pressure and press motion controls are developed. A space between the blank and 1st punch is made by the press motion at the 2nd drawing stage and the ultrahigh pressure is applied so as to be disappeared this space. It can enhance a material flow into the die cavity because the ultrahigh pressure acts on the blank at side wall. In addition, a friction holding effect occurs, which prevents the thickness reduction at punch shoulder and side wall. Due to these mechanisms, the micro cup with aspect ratio of 2.0 can be successfully fabricated by micro extra deep drawing in FE simulation, although it cannot be fabricated by conventional micro deep drawing and micro hydromechanical deep drawing.

1. Introduction

Extra deep drawing has been developed as the special forming technique to fabricate the parts with high aspect ratio. It uses several forming principles such as, multi steps [1], counter and radial pressures [2], flange pressing [3], local heating and cooling [4], and super plasticity [5]. These technologies can achieve the high formability respectively. If these technologies can be scaled down to micro scale, it is useful to fabricate micro parts with high aspect ratio. However, when the dimension of part is scale down, there are several problems in micro scale to fabricate the micro parts with high aspect ratio using conventional micro deep drawing. It is difficult to fabricate the tiny tools and handle the tiny workpiece. The increase of friction force and the decrease of strength and ductility are resulted with scaling down to micro scale because of the tribological and grain size effects [6, 7]. These size effects cause the low formability in micro forming. Due to these difficulties in micro scale, no micro extra deep drawn cup except for micro cup with diameter of 0.5 mm and aspect ratio of 1.1 using micro redrawing process has been reported [8]. Thus, it is difficult to fabricate the micro parts with high aspect ratio using conventional micro forming techniques.

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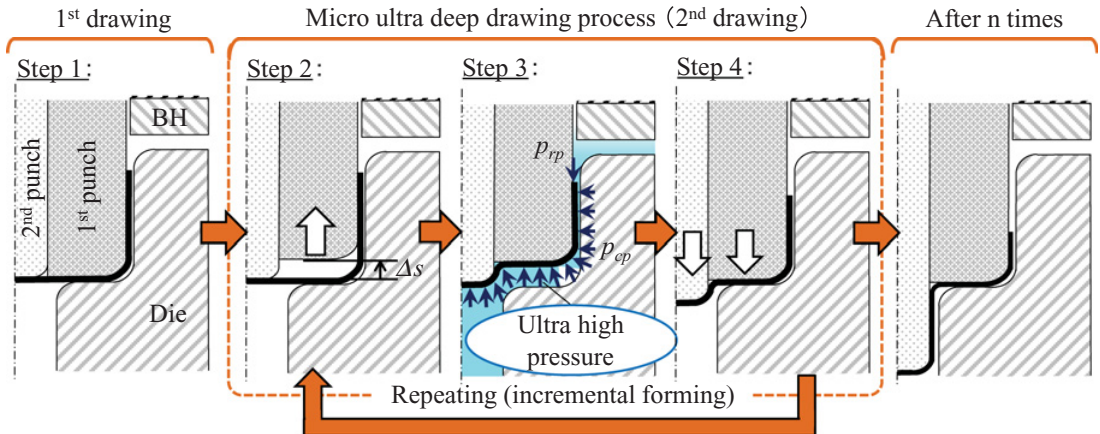


Figure 1. Forming process of micro extra deep drawing.

In conventional deep drawing, the blank is deformed by pulling force of the punch. The blank is subjected to the tensile stress during forming process and fracture occurs when the tensile stress reaches the tensile strength at punch shoulder part. Therefore, there is a limitation to improve the formability using conventional techniques. On the other hand, in extra deep drawing using flange pressing and aided friction force [9], the blank was deformed by the compression force. The compression force induces the material flow into the die cavity and deforms the blank without the tensile stress. Therefore, the fracture does not occur and the forming limit can be significantly improved. To use this forming deep drawing mechanism in micro scale, we propose and develop a novel micro extra deep drawing process using ultrahigh pressure and press motion controls. Using the micro extra deep drawing, the micro cup with large aspect ratio is fabricated and its forming mechanism is investigated using finite element (FE) simulation.

2. Micro extra deep drawing process

Figure 1 shows the micro extra deep drawing process. The newly proposed process is performed at the 2nd drawing stage. The 2nd punch is inside of the 1st punch to perform the 1st and 2nd drawings at the same axis. At stage 1, the 1st drawing is performed. At stage 2, the 1st punch is lifted up and the space is made between the 1st drawing and blank. At stage 3, the ultrahigh pressure is applied so as to be disappeared the space between the 1st punch and blank. At this stage, the blank flows into the inside and fits the punches. At stage 4, the 1st and 2nd punches go down. The blank thickness can be controlled by pressing force in this stage. These stages 2, 3 and 4 are regarded as 1 cycle and the long micro cup can be drawn by continuing several cycles.

3. FE simulation

The numerical analysis was carried out with an explicit dynamic FE code, LS-DYNA ver.971. The stainless steel foil (SUS304-H) of $50\ \mu\text{m}$ thickness was employed for FEM. For the mechanical properties, the young's modulus $E = 197\text{GPa}$ and yield stress $\sigma_y = 589\text{MPa}$ are used and a real stress-strain curve obtained by tensile test was input into FEM directly as shown in Fig. 2. The tooling dimensions used in micro extra deep drawing is listed in Table 1. The drawing ratios for 1st, 2nd drawing and total drawing ratio are $DR_1 = 1.8$, $DR_2 = 2.1$ and $DR = 3.8$, respectively. The blank was

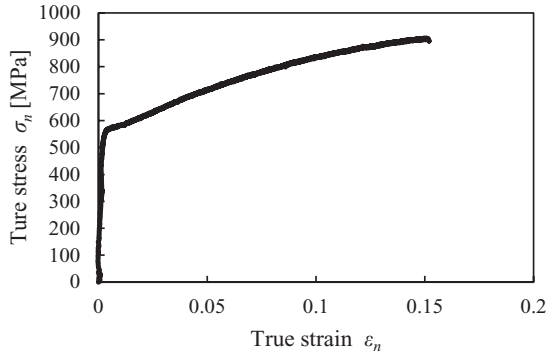


Figure 2. Stress strain curve of used material (SUS304).

Table 1. Tooling dimensions for micro extra deep drawing.

Initial blank diameter D_0 [mm]		1.700
Drawing punch	1st punch diameter D_{p1} [mm]	0.944
	2nd punch diameter D_{p2} [mm]	0.444
	1st punch corner radius r_{p1} [mm]	0.160
	2nd punch corner radius r_{p2} [mm]	0.120
Drawing die	1st die diameter D_{d1} [mm]	1.000
	2nd die diameter D_{d2} [mm]	0.500
	1st die corner radius r_{d1} [mm]	0.200
	2nd die corner radius r_{d2} [mm]	0.100
Clearance $C(=1.4t)$ [mm]		0.028

Table 2. Forming parameters for each forming method.

	Constant gap h [mm]	1st punch displacement Δs [mm]	Counter and radial pressure p_{rp}, p_{cp} [MPa]
Micro deep drawing	0.022	–	–
Micro hydromechanical deep drawing	0.022	–	$p_{rp} = p_{cp} = 100$
Micro extra deep drawing	–	0.03	$p_{rp} = p_{cp} = 100$

modeled as the solid of isotropic elastoplastic, and the tools were modeled as the shell of rigid body. The static and kinetic friction coefficients were set at $\mu_s = 0.20$, $\mu_d = 0.15$ between the blank and 1st and 2nd punches, and $\mu_s = 0.005$, $\mu_d = 0.003$ between the blank and die, respectively. To compare the formability, not only micro extra deep drawing but also the conventional micro deep drawing and micro hydromechanical deep drawing were carried out. In micro deep drawing and micro hydromechanical deep drawing, the constant gap method was adopted. The forming parameters, constant gap h , punch displacement Δs , counter pressure p_{cp} and radial pressures p_{rp} , were listed in Table 2.

4. Results and discussion

4.1 Drawn cups

Figure 3 shows the blank and cup shapes at the each stage of micro extra deep drawing. Through the 1st and the 2nd drawings, the micro cup with total drawing ratio of 3.8 can successfully be fabricated by micro extra deep drawing. Figure 4 shows the appearance of micro cups drawn by different forming methods. For the 2nd drawing of micro deep drawing and micro hydromechanical deep drawing, the local thinning occurs at 2nd punch shoulder and the micro cup cannot be drawn. On the other hand, the long micro cup with aspect ratio of 2.0 can be successfully drawn in micro extra deep drawing. It

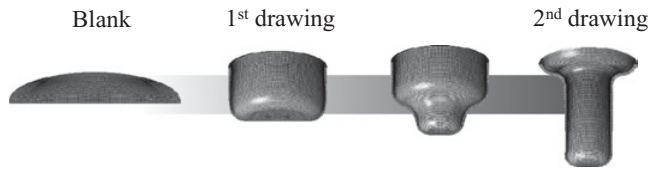


Figure 3. Blank and cup shapes at each stage of micro extra deep drawing.

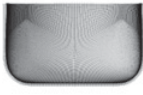
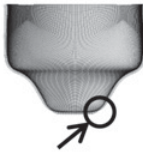

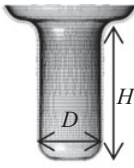
1 st drawing	2 nd drawing		
Micro deep drawing	Micro deep drawing	Micro hydromechanical deep drawing	Micro extra deep drawing
 Aspect ratio $H/D=0.6$	 Fracture	 Fracture	 Aspect ratio $H/D=2.0$

Figure 4. Appearance of micro cups drawn by different forming methods.

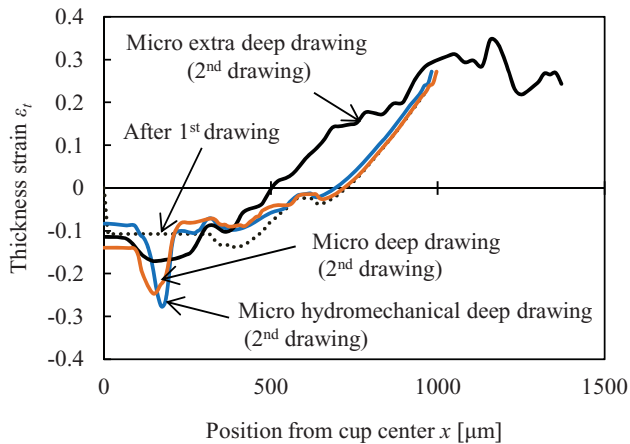


Figure 5. Comparison of thickness strain distribution for each forming method.

is because the thickness reduction at 2nd punch is prevented in micro extra deep drawing although the thickness significantly decreases at the 2nd punch shoulder in conventional micro deep drawing and micro hydromechanical deep drawing as shown in Fig. 5. It was found that micro extra deep drawing can fabricate the micro cup with longer aspect ratio than conventional micro redrawing [8].

4.2 Material flow in micro extra deep drawing

Figure 6 shows the material flow of blank by applying the ultrahigh pressure in micro extra deep drawing. By applying the ultrahigh pressure to the space between the blank and 1st punch, the blank at

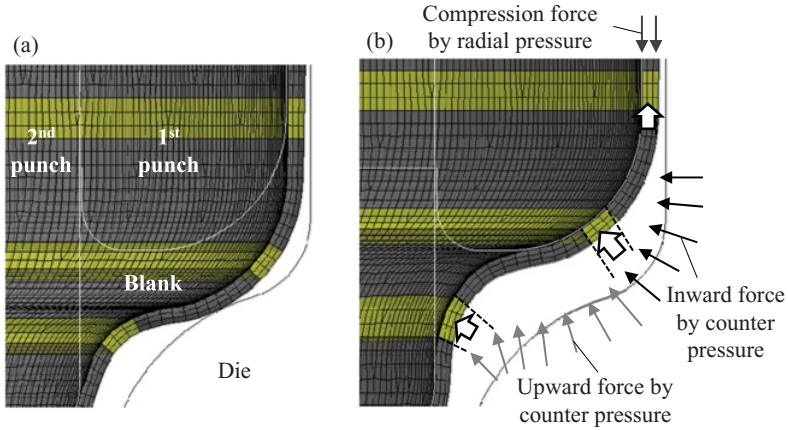


Figure 6. Material flow of the blank (a) before and (b) after applying the ultrahigh pressure.

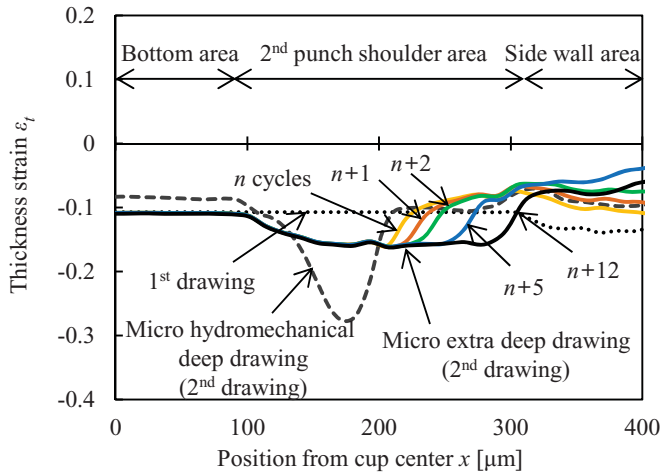


Figure 7. Change of thickness strain distribution near 2nd punch shoulder part in micro extra deep drawing process.

side wall of 2nd punch and flange area flow into the inside. It shows that the application of ultrahigh pressure can enhance the material flow by an inward force by counter pressure. In contrast, at the side wall of 1st punch, the blank goes up by an upward force by counter pressure. It prevents the material flow at side wall of 1st punch unlike at flange area. These material flows are related with the upward force by counter pressure, inward force by counter pressure, and compression force by radial pressure. These forces can be varied by changing the pressurization, tooling dimension, and the 1st punch displacement. By adjusting these parameters, the appreciate material flow can be obtained.

4.3 Friction holding effect in micro extra deep drawing

Figure 7 shows the change of thickness distribution near the 2nd punch shoulder during micro extra deep drawing process. The thickness decreases at the blank which does not contact with the 2nd punch. However, after the blank contacts with the 2nd punch, the thickness does not decrease. This behavior is called as the friction holding effect [2]. On the other hand, in micro hydromechanical deep drawing,

the thickness significantly decreases at the 2nd punch shoulder. It seems that the friction holding force at 2nd punch shoulder is not enough to prevent the thickness reduction. In the 2nd drawing of micro hydromechanical deep drawing, the friction holding force occurs not only at the 2nd punch shoulder but also the 1st punch shoulder. It increases the drawing resistance at flange area. In addition, the blank is deformed by the pulling force of punch in micro hydromechanical deep drawing. The blank at punch shoulder is subjected to the applied force during the forming process. Therefore, the applied force to blank becomes high and the fracture occurs. On the other hand, in micro extra deep drawing the blank is deformed by ultrahigh pressure which enhances the material flow. Therefore, the applied force to blank can be reduced. It is because that the friction holding effect can be obtained in micro extra deep drawing.

5. Conclusion

The objective of this research is to develop the micro extra deep drawing process using ultrahigh pressure and press motion controls to fabricate the long micro cup. In micro extra deep drawing, the space is made between the blank and the 1st punch by press motion control, and the blank is deformed by applying the ultrahigh pressure toward the space. It can enhance the material flow into the inside because the ultrahigh pressure acts on the blank at side wall. Moreover, the friction holding effect can be obtained, which prevents the thickness reduction at punch shoulder and side wall. Due to these forming mechanisms, the micro extra deep drawing can successfully fabricate the micro cup with the aspect ratio of 2.0 in FE simulation. It was shown that the micro extra deep drawing can exceed the aspect ratio of micro cup drawn by conventional micro redrawing.

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