Effect of counter punch on formability in two-step compression forming for producing extremely deep cup

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Abstract. This paper presents two-step compression forming with a counter punch for producing an extremely deep cup with good shape accuracy. In the proposed method, the bottom shape is formed in the first step of the boss forming, and then the side wall is formed in the second step of the flange compression. The influence of the counter punch position in the boss forming was investigated to improve the shape accuracy of the bottom portion in this study. Appropriate counter punch position was predicted in finite element method (FEM) analysis. When the counter punch position was not appropriate, the forming defects, which were the local thinning and the backflow of the material, occurred. Based on the FEM result, the experiments were carried out. The experimental result agreed with the analysis result, and a deep cup with good shape accuracy was successfully formed under the optimum condition.

Introduction

Deep cup-shaped parts made from sheet metal are generally used for various industrial fields such as automobiles, household electronics, precision equipment, and so on. For example, battery cases for electric vehicles are conventionally produced by multi-step deep drawing from sheet metal [1]. This is because the productivity of deep drawing is high compared to the other methods such as spinning [2]. The deep case is formed gradually by multi-step deep drawing because the material could fracture at the punch shoulder portion due to tensile force if the deep cup is attempted to be formed by single-step deep drawing.

To further reduce the processing time, a reduction in the number of steps in the deep-drawing process has been tackled by various methods. It is possible to reduce the drawing stage by optimizing the punch, die, and blank shape [1]. The use of the blank with localized hard portions that contact the punch shoulder is effective in preventing crack occurrence [3,4], but the blank with localized hard portions needs to be formed as a pre-process. Incremental forming in the deep drawing was proposed to reduce the frictional force between the die and the blank holder [5,6]. However, these methods need the press machine with motion controllable, or specialized equipment.

Authors propose a flange compression forming method to form an extremely deep cup by only one process with simple tools and a conventional press machine [7-9]. In the proposed method, the sheet does not fracture with the effect of hydrostatic pressure because the sheet is stretched by compression in the thickness direction. However, there remains the problem of low shape accuracy at the cup bottom. In this study, we propose two-step compression forming with a counter punch to produce an extremely deep cup with good shape accuracy. Appropriate forming conditions were investigated, and the effectiveness of the proposed method was verified by a series of finite element method (FEM) analyses and experiments.

Two-step Compression Forming

Fig. 1 shows the schematic illustration of two-step compression forming for producing the extremely deep cup. A punch with a pin, a die, and a counter punch are used. In the first step of boss forming, the bottom portion of the cup is formed. The center portion of the blank is compressed between the pin and the counter punch until the clearance between the punch and the die at the side is equal to the initial blank thickness as shown in Fig. 1 (b). In the second step of flange compression, the side wall of the cup is formed. In this step, the counter punch is removed, and then the material is extruded from the clearance c_{pd} between the pin and the die by compressing the flange portion between the punch and the die as shown in Fig. 1 (b).

Pin length l_p is geometrically determined based on the previous study [8]. Fig. 2 shows a schematic illustration of the boss forming at the beginning and end. l_p should be larger than the total value of the initial blank thickness t_0, the die corner radius r_{cd}, and the pin corner radius r_{cp} for forming the side wall with uniform thickness. This is because the clearance c_{pd} between the pin and the die changes at the initial stage of the flange compression if l_p is smaller than the total value of t_0, r_{cd}, and r_{cp}, and then the side wall thickness becomes thick near the bottom portion. However, the local thinning appeared at the portion that contacts the pin shoulder during the boss forming when l_p is too long. Therefore, l_p was determined by the following equation in this study.

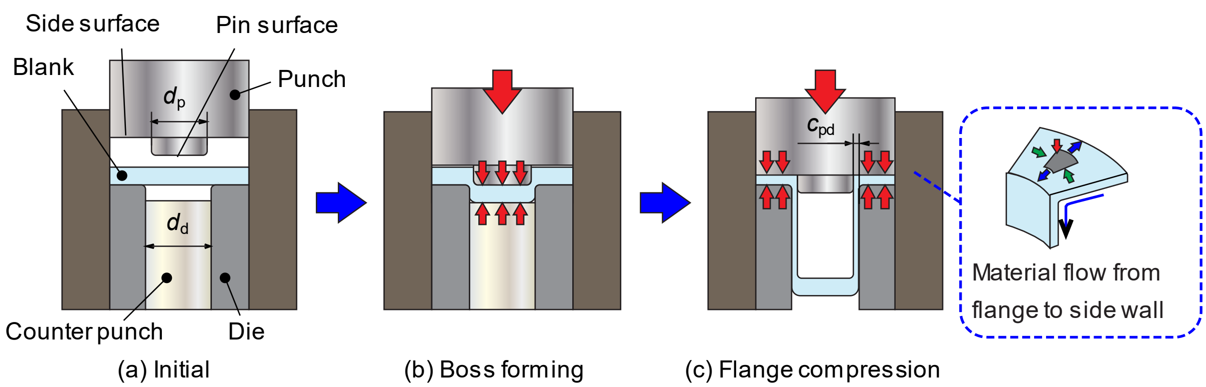

Fig. 1. Schematic illustration of two-step compression forming for producing extremely deep cup.

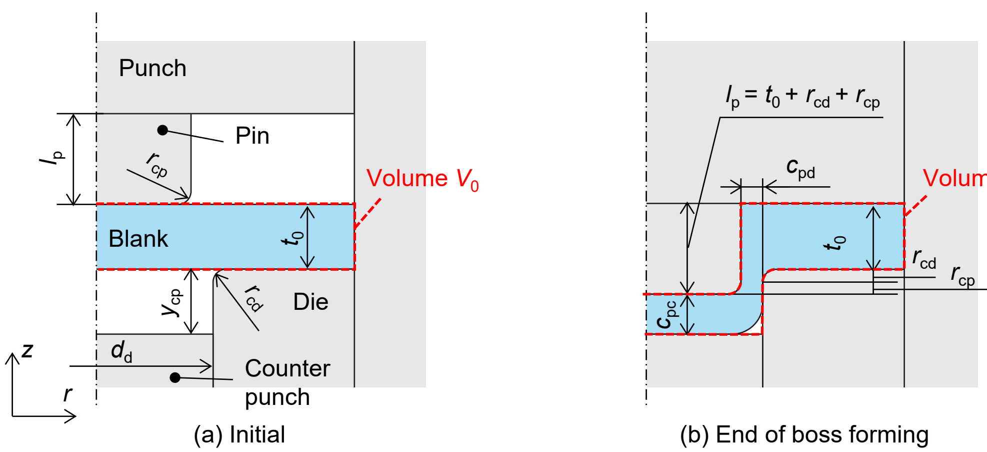

Fig. 2. Schematic illustration of the boss forming at the beginning and end.

$$l_{\mathrm{p}} = t_0 + r_{\mathrm{d}} + r_{\mathrm{p}} \tag{1}$$

The clearance c_{pc} between the pin and the counter punch at the end of the boss forming, which becomes the target bottom thickness t_{bt} of the formed cup, could be important. This is because the volume V_1 of the space enclosed by the punch, die, and counterpunch at the end of the boss forming changes with c_{pc} as shown in Fig. 2 (b). V_1 must be larger than the initial volume V_0 of the blank. If V_1 is smaller than V_0 due to small c_{pc}, excessive load could be applied to the device because the material cannot escape from the space in the device. Therefore, c_{pc}, when V_1 is equal to V_0, is considered to be the limit clearance c_{pcl}. When V_1 is equal to V_0, the following equation is obtained.

$$\pi\left(\frac{d_{\mathrm{d}}}{2}\right)^2 c_{\mathrm{pcl}} + V_{\mathrm{a}} + V_{\mathrm{b}} = \pi\left(\frac{d_{\mathrm{p}}}{2}\right)^2 t_0 \tag{2}$$

where t_0 is the initial blank thickness, and d_{d} and d_{p} are the diameters of the die and the punch pin. V_{a} and V_{b} were calculated by the following equations.

$$V_{\mathrm{a}} = \pi\left(\frac{d_{\mathrm{d}}}{2}\right)^2 r_{\mathrm{cp}} - \int_0^{r_{\mathrm{cp}}} \pi\left(\sqrt{r_{\mathrm{cp}}^2 - \left(z - r_{\mathrm{cp}}^2\right)^2} + \frac{d_{\mathrm{p}}}{2} - r_{\mathrm{cp}}\right)^2 dz \tag{3}$$

$$V_{\mathrm{b}} = -\pi\left(\frac{d_{\mathrm{p}}}{2}\right)^2 r_{\mathrm{cd}} + \int_0^{r_{\mathrm{cp}}} \pi\left(-\sqrt{r_{\mathrm{cd}}^2 - z^2} + \frac{d_{\mathrm{d}}}{2} + r_{\mathrm{cd}}\right)^2 dz \tag{4}$$

Therefore, c_{pcl} was obtained from Eq. 2, 3, and 4 as follows.

$$c_{\mathrm{pcl}} = \left(\frac{d_{\mathrm{p}}}{d_{\mathrm{d}}}\right)^2 t_0 - \frac{4(V_{\mathrm{a}} + V_{\mathrm{b}})}{\pi d_{\mathrm{d}}^2} \tag{5}$$

On the other hand, local thinning could appear if c_{pc} is too large. Therefore, an optimum value of c_{pc} was investigated for each pin and the die shoulder corner radius r_{cp} and r_{cd} to form a deep cup with good shape accuracy in this study. The optimum value of c_{pc} was predicted by FEM analysis for the boss forming. The optimum c_{pc}, which was predicted by FEM analysis, was verified by the experiment.

Material and Methods

An elastic-plastic analysis was carried out by using commercial code "Elfen" produced by Rockfield Software Ltd., Swansea, UK. Table 1 shows the analysis conditions. The analysis was conducted for the first step of the boss forming in order to predict the optimum value of the clearance c_{pc} between the pin and the counter punch at the end of the boss forming. The model is two-dimensional with axisymmetry. An explicit scheme was adopted. Three-node triangular elements and an adaptive remeshing scheme were applied. The von Mises yield criterion was selected. The blank was an elasto-plastic body, and a stress-strain curve of aluminum alloy 1100-O was applied to the blank. The stress-strain curve for the analysis was obtained by approximating the stress-strain curve in the tensile test according to Voce's law. The punch, the die, the counter

Table 1. FEM analysis conditions.

Blank	Material	Aluminum alloy 1100-O σ=90 - (90 - 35)e$^{-50\varepsilon}$ according to Voce's law
	Diameter d_0 [mm]	24
	Thickness t_0 [mm]	3
Punch	Material	Rigid body
	Pin diameter d_p [mm]	9.0
	Pin shoulder corner radius r_{cp} [mm]	0.2 ~ 1.0
	Pin length l_p [mm]	$t_0 + r_{cp} + r_{cd}$
Die	Material	Rigid body
	Diameter d_d [mm]	11.0
	Shoulder Corner radius r_{cd} [mm]	0.2 ~ 1.0
Counter punch	Material	Rigid body
	Diameter d_c [mm]	11
Clearance between pin and die c_{pd} [mm]		1.0
Clearance between pin and counter punch at end of boss forming c_{pc} [mm]		1.5 ~ 3.0
Friction coefficient μ		0.1

Table 2. Experimental conditions.

Punch pin shoulder corner radius r_{cp} [mm]	0.6
Die shoulder Corner radius r_{cd} [mm]	0.2
Clearance between pin and counter punch at end of boss forming c_{pc} [mm]	1.9, 2.2, 2.5
Lubricant	White petrolatum (Petrolatum HG, Taiyo Pharmaceutical Co. Ltd., Tokyo, Japan) on both sides of blank

punch, and the container were rigid bodies. The clearance c_{pc} between the pin and the counter punch at the end of the boss forming, the pin, and the die corner radius r_{cp} and r_{cd} were changed as the forming parameters. The local thinning ratio γ was calculated by the following equation to evaluate the local thinning of the formed cup.

$$\gamma = \frac{t_{st} - t_{min}}{t_{st}} \quad (6)$$

t_{st} is the target side wall thickness, which is equal to the clearance c_{pd} between the pin and the die, and t_{min} is the minimum wall thickness.

An experiment was carried out by using the device shown in Fig. 1. A universal testing machine (Autograph AG-300kNXplus, Shimadzu Corporation, Kyoto, Japan) was used for pressing the punch. Table 2 shows the experimental conditions. The other conditions for the experiment were the same as that for the analysis shown in Table 1. In the experiment, the deep cups were formed by conducting the first and the second steps, which are the boss forming and the flange compression. The pin and the die shoulder corner radius r_{cp} and r_{cd} were set to 0.6 and 0.2 mm, and the influence of the clearance c_{pc} between the pin and the counter punch at the end of the boss forming was investigated. In the second step, the flange was compressed until the punch load achieved 200 kN. The distribution of the cup diameter D from the bottom in the height direction

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was measured to evaluate the shape accuracy of the cup. The radius R of the cup was obtained by dividing D by 2.

Influence of Clearance c_{pc} between Pin and Counter Punch on Formability in FEM Analysis
Fig. 3 shows the influence of the clearance c_{pc} between the pin and the counter punch at the end of the boss forming when the pin and the die corner radius r_{cp} and r_{cd} were 0.6 and 0.2 mm. In this condition, the limit clearance c_{pcl} is 1.7 mm according to Eq. 5. The boss without any defects was formed under the condition of c_{pc} = 1.9 mm, while any defects, which were the backflow and the local thinning, occurred when c_{pc} was too small or large.

When the clearance c_{pc} was 1.6 mm, which was smaller than the limit clearance c_{pcl}, the backflow of the material occurred as shown in Fig. 3 (a). This is because the space between the pin and the counter punch is small compared to the initial volume of the blank under the pin. Fig. 4 shows the relationship between punch stroke S and punch load P. Under conditions where c_{pc}

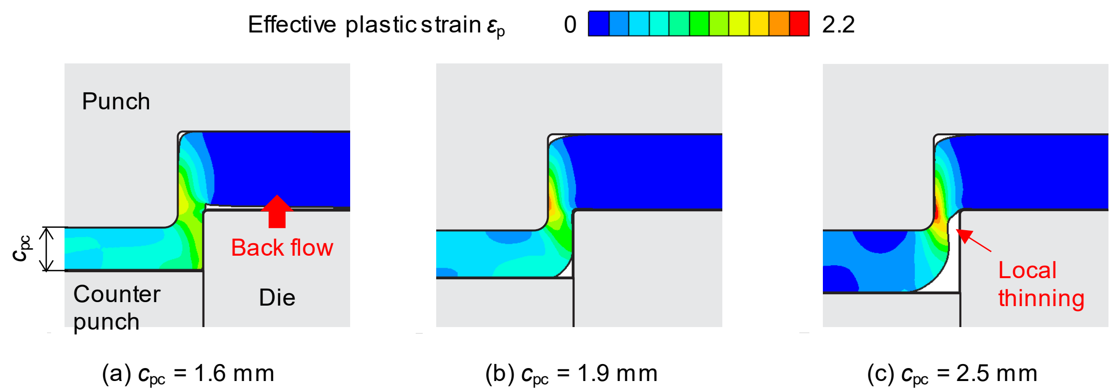

Fig. 3. Influence of clearance c_{pc} between pin and counter punch at the end of boss forming (Pin shoulder corner radius r_{cp} = 0.6 mm, die shoulder corner radius r_{cd} = 0.2 mm).

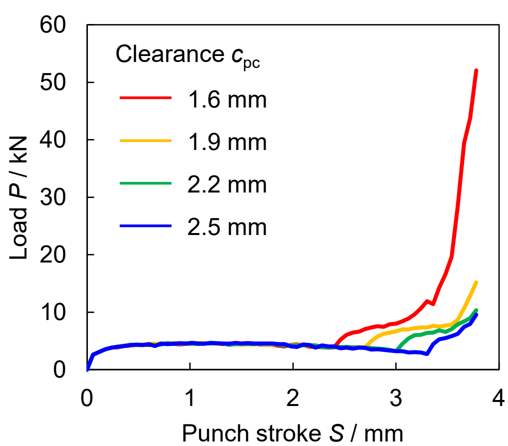

Fig. 4. Relationship between punch stroke S and punch load P (Pin shoulder corner radius r_{cp} = 0.6 mm, die shoulder corner radius r_{cd} = 0.2 mm).

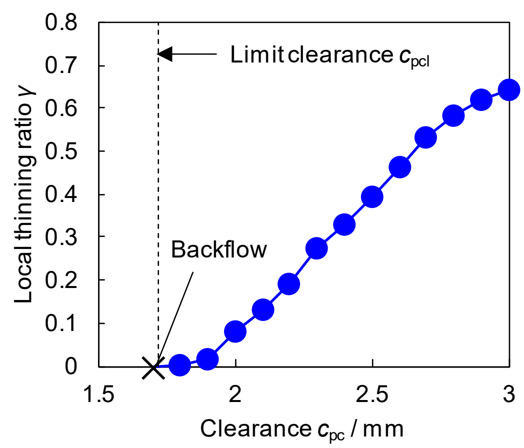

Fig. 5. Influence of clearance c_{pc} between pin and counter punch on local thinning ratio γ (Pin shoulder corner radius r_{cp} = 0.6 mm, die shoulder corner radius r_{cd} = 0.2 mm).

was 1.6 mm with the backflow occurring, P increased rapidly at the end of boss forming. This is because the space surrounded by the punch, die, and counterpunch was filled with material, but the material could not escape from the die. c_{pc}, where the backflow occurred, should not be selected because the large load may cause tool rupture.

When the clearance c_{pc} was too large such as c_{pc} = 2.5 mm, the local thinning appeared at the portion near the pin shoulder as shown in Fig. 3 (c). The local thinning should be suppressed because the local thinning causes the material's fracture. Fig. 5 shows the influence of c_{pc} on the local thinning ratio γ. γ was 0 under the condition of c_{pc} = 1.8 mm, and γ increased with the increase in c_{pc}. When the material did not contact the counter punch under the condition of c_{pc} = 3 mm, γ was 0.64. Therefore, the local thinning was prevented by compressive stress from the counter punch.

Influence of Shoulder Corner Radius r_{cd} and r_{cp} of Die and Punch on Appropriate Clearance c_{pc} between Pin and Counter Punch in FEM Analysis

The appropriate value of the clearance c_{pc} between the pin and the counter punch could change with the die and the pin shoulder corner radius r_{cd} and r_{cp} because the pin length l_p changes with r_{cd} and r_{cp} according to Eq. 1. Therefore, the influence of c_{pc} on the local thinning ratio γ was investigated for each r_{cd} and r_{cp} as shown in Fig. 6. The limit clearance c_{pcl}, which was calculated by Eq. 5, was also shown in Fig. 6. c_{pcl} decreases with the increase in r_{cd} or r_{cp} because the volume V_1 of the space enclosed by the punch, die and counterpunch at the end of boss forming increases with the increase in r_{cd} or r_{cp}.

Fig. 6 (a) shows the influence of the clearance c_{pc} and the die shoulder corner radius r_{cd} on the local thinning ratio γ when r_{cp} was 0.6 mm. γ decreased with the decrease in c_{pc} and the backflow occurred when c_{pc} was near the limit clearance c_{pcl} in the case that r_{cd} was 0.2 mm. However, γ increased with the increase in r_{cd}, and there was no c_{pc} for preventing the local thinning when r_{cd} was too large. This is considered to be because the pin length l_p is needed to increase with r_{cd}. When l_p is large, the pin is pressed deeper into the blank, and then the local thinning easily occurs in the boss forming. Under the condition that r_{cd} was 0.8 and 1.0 mm, the backflow occurred with the local thinning when c_{pc} was small. For this reason, c_{pc} of which the backflow occurred did not

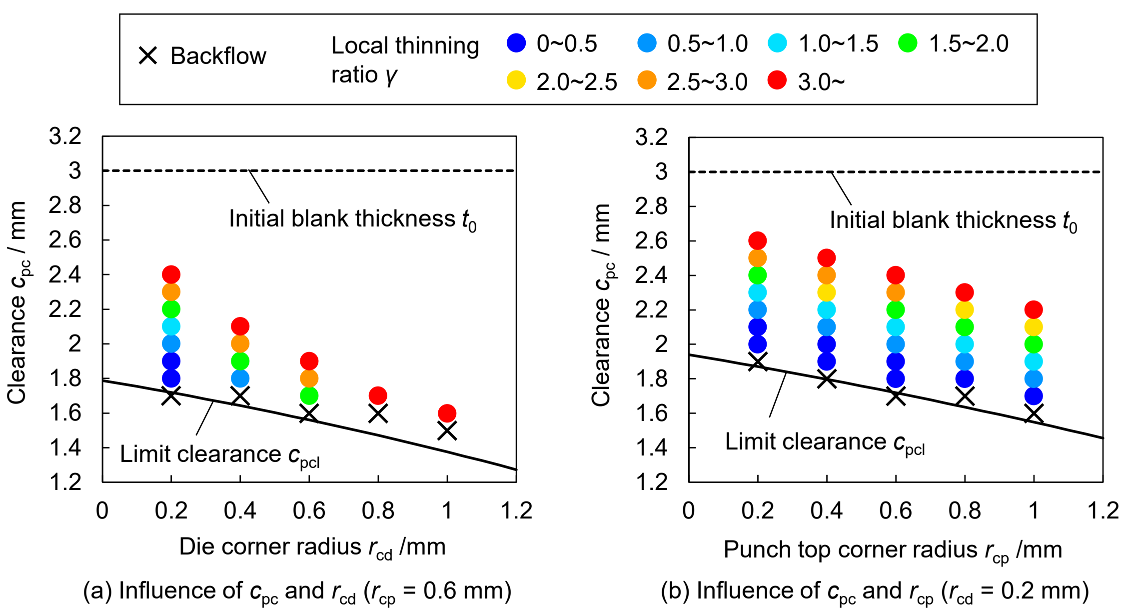

Fig. 6. Influence of clearance c_{pc} between pin and counter punch, die shoulder corner radius r_{cd}, and pin shoulder corner radius r_{cp} on the local thinning ratio γ.

agree with c_{pcl} under the condition that r_{cd} was 0.8 and 1.0 mm. From the above result, r_{cd} should be small to prevent local thinning.

Fig. 6 (b) shows the influence of the clearance c_{pc} and the pin shoulder corner radius r_{cp} on the local thinning ratio γ when r_{cd} was 0.2 mm. γ decreased with the decrease in c_{pc} for each r_{cp}, and the backflow occurred when c_{pc} was near the limit clearance c_{pcl}. γ increased with the increase in r_{cp} under the same conditions of c_{pc}, but there was c_{pc} for reducing the local thinning for each r_{cp}. Large r_{cp} could suppress the local thinning because the stress concentration is relieved at the pin shoulder. Therefore, the pin could be pushed in deeper without the local thinning when the pin length l_p was large due to large r_{cp}. The above result indicated that the influence of r_{cp} on the local thinning is small, and the bottom thickness of the formed cup could be controlled by adjusting r_{cp}.

Influence of Clearance between c_{pc} Pin and Counter Punch on Formability in Experiment

The influence of the clearance c_{pc} on the formability was investigated in the experiment in order to verify the FEM result. c_{pc} was selected to 1.9, 2.2, and 2.5 mm based on the FEM results. c_{pc} = 1.9 mm was the optimum condition for reducing the local thinning in the FEM analysis. The condition of c_{pc} = 2.2 and 2.5 mm could cause the local thinning or the crack because the γ for c_{pc} = 2.2 and 2.5 mm were 0.19 and 0.40 in the FEM analysis.

Fig. 7 shows the cross-sectional view of the formed cup after the second step. When the clearance c_{pc} was 1.9 mm, the cup was successfully formed without any defects. However, a crack appeared near the bottom corner when c_{pc} was 2.2 and 2.5 mm. Fig. 8 shows a magnified view of the bottom corner. In the case of c_{pc} = 2.2 mm, there was a small dent on the outer side, and a crack appeared on the inner side of the cup. In the case of c_{pc} = 2.5 mm, there was a large dent on the outer side, and a crack propagated from the inner side. Fig. 9 shows the distribution of the cup radius R in the height direction for the experiment and the FEM analysis. The experimental results qualitatively agreed with the FEM results. This result indicates that the optimum conditions could be predicted by the FEM analysis.

(a) c_{pc} = 1.9 mm (b) c_{pc} = 2.2 mm (c) c_{pc} = 2.5 mm

Fig. 7. Cross-sectional view of formed cup for each clearance c_{pc} after second step.

(a) c_{pc} = 1.9 mm (b) c_{pc} = 2.2 mm (c) c_{pc} = 2.5 mm

Fig. 8. Magnified view of bottom corner of formed cup for each clearance c_{pc} after second step.

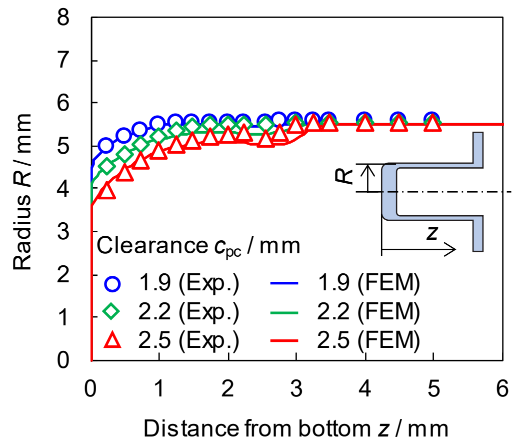

Fig. 9. Distribution of the cup radius R in height direction.

Conclusions

This paper proposed two-step compression forming, which is composed of the boss forming and the flange compression, for producing an extremely deep with high shape accuracy. In the first step of the boss forming, the bottom shape is formed by compressing the sheet between the pin and the counter punch. In the second step of the flange compression, the side wall is formed by compressing the flange portion between the punch and the die. The influences of the tool position and shape, which is the clearance c_{pc} between the pin and the counter punch, and the shoulder corner radius r_{cp} and r_{cd} of the pin and the die, were investigated for forming the bottom shape without any defects by FEM analysis. The bottom shape of the cup was successfully formed by setting c_{pc}, r_{cp} and r_{cd} appropriately. When c_{pc} was too small, the backflow of the material occurred, and then the forming load became too large. When c_{pc} was too large, the local thinning appeared due to the stress concentration at the pin shoulder. A small value of r_{cd} was appropriate because the range of c_{pc} for reducing the local thinning was wider with the decrease in r_{cd}, and there was no appropriate value of c_{pc} in the case that r_{cd} was too large. On the other hand, there were appropriate values of c_{pc} for each r_{cp}, while the appropriate value of c_{pc} decreased with the increase in r_{cp}. To verify the analysis results, the experiment was carried out. The deep cup with good shape accuracy was successfully formed under the appropriate conditions, and the experimental results agreed with the analysis results.

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