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Suppression of non-uniform deformation using die shape in cylindrical deep drawing

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Abstract. This study presents a cylindrical deep drawing method that suppresses non-uniform deformation by die shape. In the cylindrical deep drawing, the material inflow in the circumferential direction varies due to the material anisotropy, resulting in unevenness at the edges of the cup, called the ear, after forming. Since the ears are usually trimmed after forming, there are concerns that the ear reduces yield rate and productivity due to the increased number of processes. The main approach study to the suppression of non-uniform deformation due to anisotropy has been the development of materials with suppressed material anisotropy. However, material development has been difficult to introduce because of the increased costs involved, and there has been a lack of development from the press process side. Therefore, this study clarified the effect of die shoulder radius on forming shapes in “Multiple R die” for cylindrical deep drawing by experiments and finite element analysis. Ear height can be suppressed if forming is performed in such a way that the effects of anisotropy and die shape cancel out each other by experimental and analysis results.

Introduction

Deep drawing, shown in Fig. 1, is used for automotive parts and beverage cans as a basic sheet press forming method. In recent years, electric vehicles and other transportation machinery have become increasingly electrified, requiring higher output and lighter-weight motors and batteries [1]). Therefore, further expansion of demand for high-quality and highly functional housings and cases is expected. In press forming, studies have been reported on the application of high-performance materials and improved formability by utilizing forming temperatures and press motions [2, 3]. On the other hand, these studies often require special press machines, which are often restrictive from an equipment standpoint.

From the viewpoint of formability, one of the issues is that ears occur in the formed cups due to non-uniformity of deformation caused by material anisotropy in deep drawing. Thus, there are concerns about yield reduction due to the occurrence of ear and difficulty in forming as designed. The main approach study to the suppression of non-uniform deformation due to anisotropy has been the development of materials with suppressed material anisotropy [4]. Several studies on press forming analysis considering anisotropy have also been reported and its practicality has been examined [5, 6]. However, material development has been difficult to introduce because of the increased costs involved, and there has been a lack of development from the press process side. For suppression of non-uniform deformation, “Multiple R die” in which the die shoulder R shape is varied in the circumferential direction has also been proposed in contrast to the conventional “Single R die” in which the die shoulder R dimensions are uniform [7]. The effect of “Multiple R die” on forming behavior is shown in Fig. 2. In “Multiple R die”, the blank folder force can be relatively changed in the circumferential direction by changing the die shoulder R in the circumferential direction, and material flowing into the die can be expected to be controlled.

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However, previous study has been limited to "Multiple R die" shapes and have not adequately examined the forming shape relative to the die shape.

In this study, cylindrical deep drawing experiments using a "Multiple R die" were conducted on stainless steel, and the ear height and wall thickness distribution were measured to clarify the basic machining characteristics in the "Multiple R die". Finite element analysis was also conducted to clarify the relationship between material anisotropy and "Multiple R die".

Deep Drawing by "Multiple R die"

Die shape. The determination of the method in the die shoulder shape of "Multiple R die" is shown in Fig. 3. The die R shape of "Multiple R die" can have various possible shapes. In this study, the die R shape is defined as a die shoulder R dimension function and determined by the following procedure.

(1) Set R_{Dmin} and R_{Dmax} to be the minimum and maximum die shoulder R dimensions.

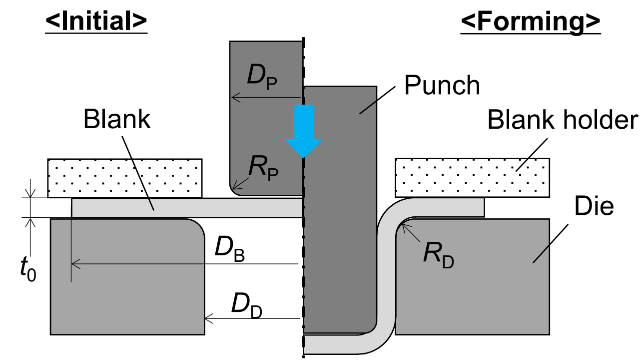

Fig. 1. Cylindrical deep drawing.

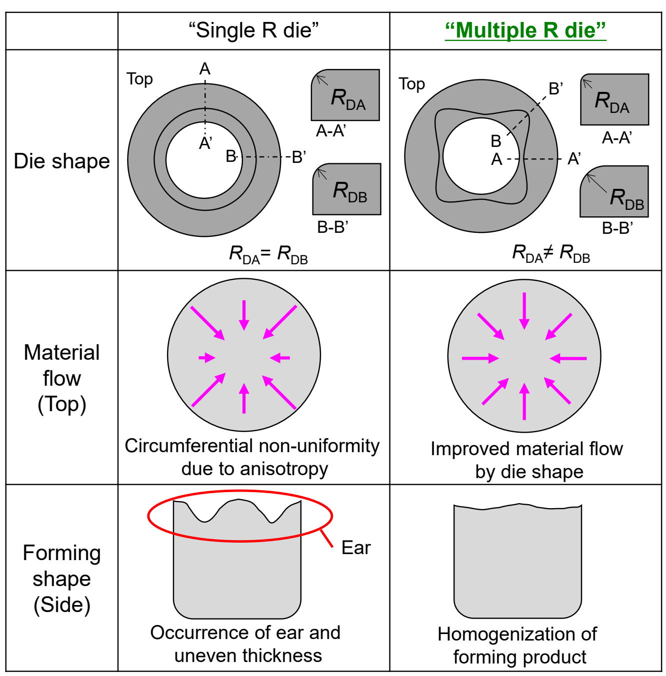

Fig. 2. Effect of "Multiple R die" forming.

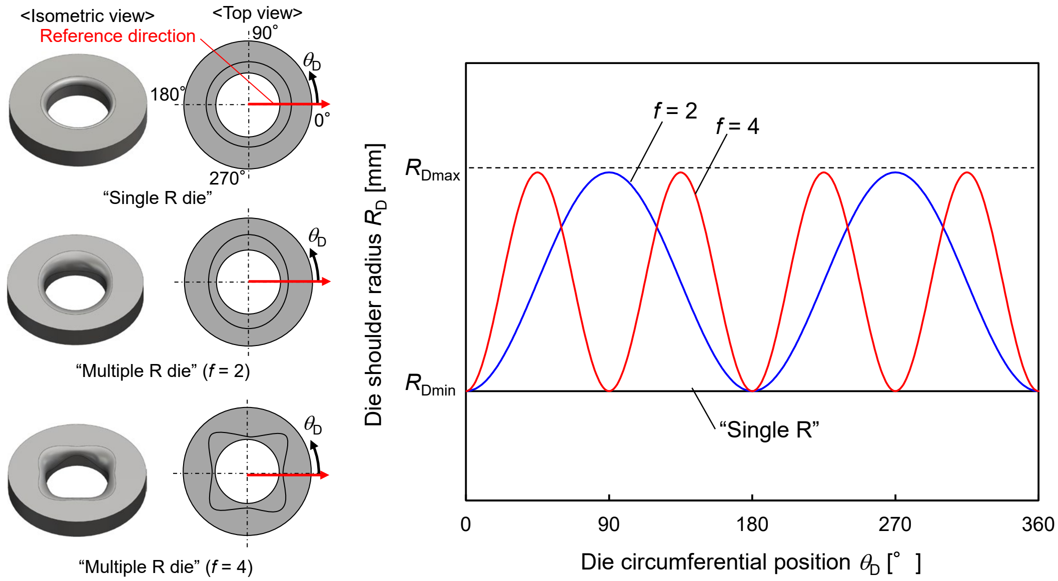

Fig. 3. The determination of the method in die shoulder shape of "Multiple R die".

(2) Set a shape factor f.

(3) Eq. 1 determines the die shoulder R dimension R_D at the circumferential die angle position θ_D.

$$R_D(\theta_D) = \frac{R_{Dmax}+R_{Dmin}}{2} - \frac{R_{Dmax}-R_{Dmin}}{2}\cos(f \cdot \theta_D) \quad (1)$$

In this study, the dies were formed using $f = 2$ and 4 dies shown in Fig. 3. The direction in which $\theta_D = 0$ ° will be referred to as the die reference direction.

Material anisotropy. To investigate the relationship between material anisotropy and die shape, material anisotropy was measured beforehand. The anisotropy of the material was obtained by tensile test to obtain Lankford values. The tensile test conditions and specimen shape are shown in Table 1 and Fig. 4. In this study, SUS304 (Japan Industrial Standard, JIS), an austenitic stainless steel, was used as the work material. JIS 13B specimens with rolling directions $\theta_B = 0$, 45, and 90 ° were cut from the same lot of sheet as the work material. The Lankford value (r-value), an anisotropy parameter, was calculated from the change in the width direction strain and the longitudinal strain of the parallel section of the specimen [7]. The results of the r-value measurement are shown in Table 2. The highest r-value was obtained at $\theta_B = 45$ °.

Forming experiment

Experimental condition. The experimental conditions for the cylindrical deep drawing test are shown in Table 3. Each dimension of the die is shown in Fig. 1. "SERVOPULSER universal testing machine (SHIMADZU CORPORATION)" was used for deep drawing. In this study, the forming results depend on the material anisotropy and the die position. Hence, the angle between the rolling direction and the die reference direction was defined as the material installation angle α, as shown in Fig. 5. The forming experiment was performed with $\alpha = 0$, 45, and 90 ° for $f = 2$ and $\alpha = 0$ and 45 ° for $f = 4$.

Table 1. Tensile test condition.

Material	SUS304 (JIS)
Specimen shape	JIS13B test specimen
Thickness t_0 [mm]	0.5
Tensile direction (Rolling direction) θ_B [°]	0, 45, 90
Test temperature	Room temperature
Test velocity V_t [mm/min]	20
Strain measurement equipment	Extensometer
Pre-strain ε_{pre} [%]	15

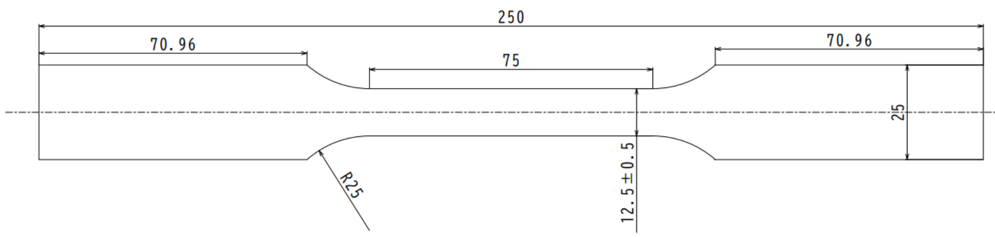

Fig. 4. Specimen shape.

Table 2. Tensile test result.

Rolling direction θ_B [°]	Lankford value $r_{\theta B}$
0	0.852
45	1.388
90	0.781

Formed products were measured for cup height $H_C(\theta_B)$ and external and internal surface shape. A CMM (Coordinate Measuring Machine) was used for the measurements. Ear height ΔH_E was obtained from the difference between the maximum and minimum cup heights $H_C(\theta_B)$. The external and internal surface shapes were measured circumferentially at two heights h = 7, 19 mm from the cup bottom, compared to the approximate height of the formed product of 30 mm. The circumferential wall thickness distribution $t(\theta_B)$ was obtained from the coordinate positions of the outer and inner surfaces. The difference between the maximum and minimum values of the wall thickness distribution was used to determine thickness deviation Δt.

Experimental result. The appearance of the formed product is shown in Fig. 6. Compared to “Single R die”, “Multiple R die” changes the ear height under all conditions. Therefore, material flow can be changed by changing the die shoulder R shape.

The cup height distribution is shown in Fig. 7. The cup rim shapes are changed by using “Multiple R die” and the change in material flow can be confirmed. For f = 2, cup height was generally lower than “Single R die”, but the cup height distribution itself did not change. For f = 4, the cup height distribution changes abruptly at α = 0 °, and the distribution flattens out at α = 45 °. Therefore, the material inflow can be well controlled by setting f = 4 for “Multiple R die”. A comparison of ear heights calculated from cup heights is shown in Fig. 8. For f = 2 of “Multiple R die”, the ears were larger than “Single R die” under all conditions. On the other hand, for f = 4 in

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Table 3. Experimental condition.

Blank	Material	SUS304 (JIS)
	Outer diameter D_B [mm]	60
	Thickness t_0 [mm]	0.5
Punch	Material	SKD11 (JIS)
	Outer diameter D_P [mm]	28.4
	Shoulder radius R_P [mm]	3
Die (Common)	Material	SKD61 (JIS)
	Inner diameter D_D [mm]	30
"Single R die"	Shoulder radius R_D [mm]	3
"Multiple R die"	Shape factor f	2, 4
	Minimum shoulder radius R_{Dmin} [mm]	3
	Maximum shoulder radius R_{Dmax} [mm]	5, 7 (only f = 4)
Punch speed V_P [mm/s]		5
Blank holder pressure P_B [MPa]		2.94
Lubricant		G-3060M (NIHON KOHSAKUYU CO., LTD.)

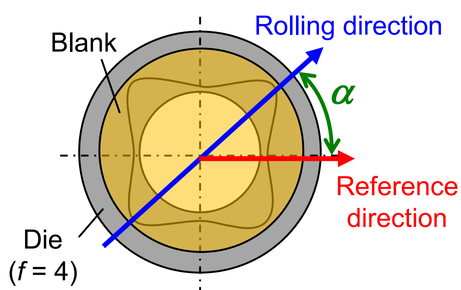

Fig. 5. Material anisotropy and die positioning.

"Multiple R die", the ear heights tended to be smaller at α = 45 °.

The circumferential wall thickness distribution of the formed product is shown in Fig. 9. First, in "Single R die" at h = 7 mm, near the cup bottom, there was a tendency for the wall thickness to decrease at θ_B = 0 ° and increase at θ_B = 45 °, with a reversed relationship at h = 19 mm. Fig. 9(a) and Fig. 9(c) show the forming results at f = 2. At both position angles α, "Multiple R die" produced more wall thinning and thickening than the "Single R die". Fig. 9(b) and Fig. 9(d) are the results at f = 4. At α = 0 °, there is almost no thickness change at h = 7 mm, but at h = 19 mm, the wall thickness increases at θ_B = 0 ° and decreases at θ_B = 45 °.On the other hand, at α = 45 °, the wall thickness distribution was similar to "Single R die" but there was no significant increase or decrease in wall thickness compared to α = 0 °. The thickness deviation of the circumferential direction is shown Fig. 10. At f = 2, the thickness deviation increased more than that of the "Single R die" under all forming conditions. For f = 4, the thickness deviation could be suppressed at

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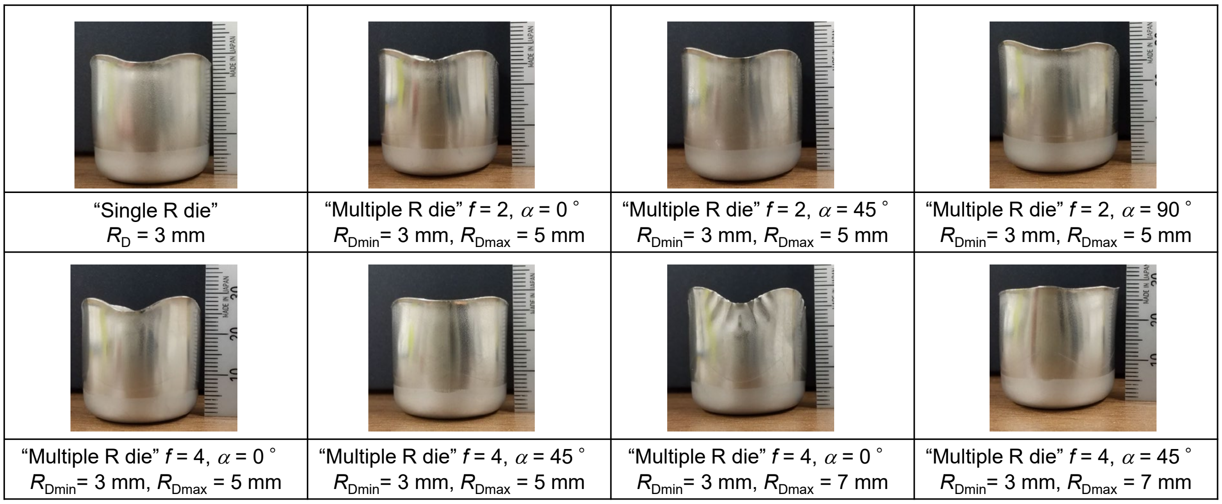


Fig. 6. Formed product.

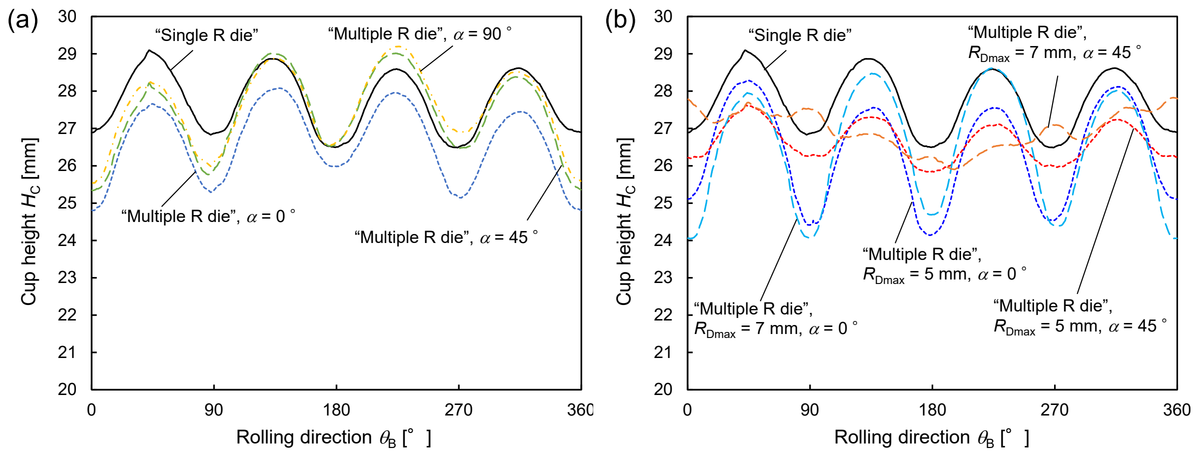
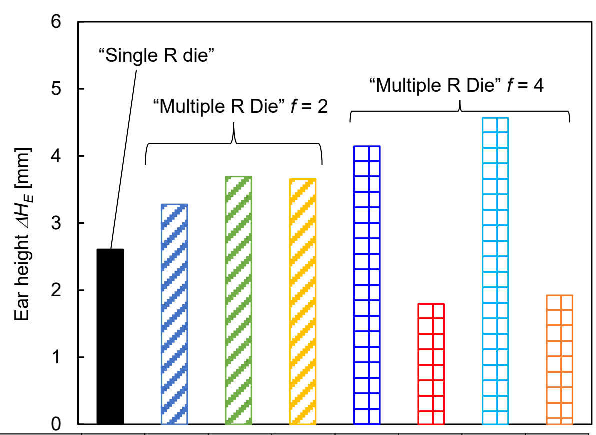


Fig. 7. Effect of die shape on cup height shape (a) “Multiple R die”, f = 2 (b) “Multiple R die”, f = 4.



R_{Dmin} [mm]	3	3	3	3	3	3	3	3
R_{Dmax} [mm]	3	5	5	5	5	5	7	7
α [°]	-	0	45	90	0	45	0	45

Fig. 8. Effect of die shape on ear height.

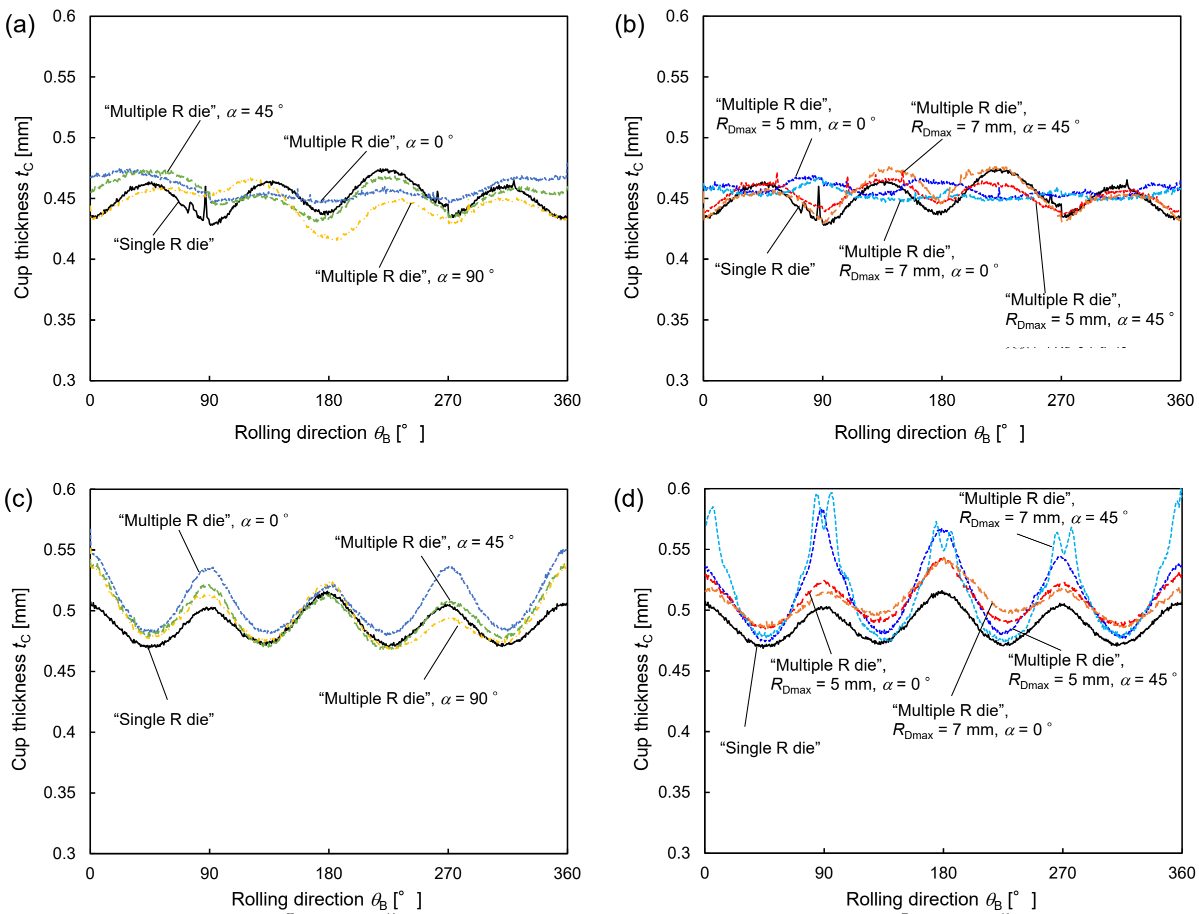
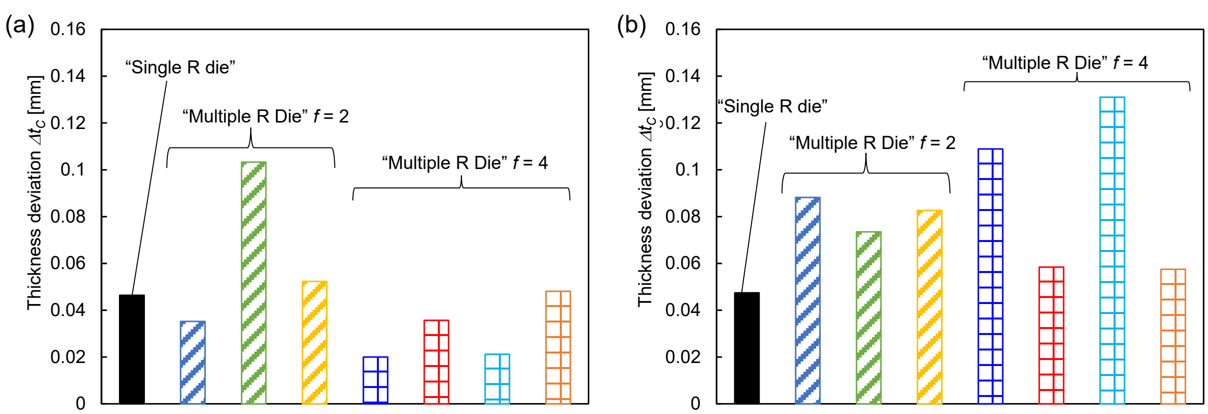


Fig. 9. Effect of die shape on thickness distribution (a) h = 7 mm, "Multiple R die", f = 2 (b) h = 7 mm, "Multiple R die", f = 4 (c) h = 19 mm, "Multiple R die", f = 2 (d) h = 19 mm, "Multiple R die", f = 4.



R_{Dmin} [mm]	3	3	3	3	3	3	3	3
R_{Dmax} [mm]	3	5	5	5	5	5	7	7
α [°]	-	0	45	90	0	45	0	45

R_{Dmin} [mm]	3	3	3	3	3	3	3	3
R_{Dmax} [mm]	3	5	5	5	5	5	7	7
α [°]	-	0	45	90	0	45	0	45

Fig. 10. Effect of die shape on thickness deviation (a) h = 7 mm (b) h = 19 mm.

h= 7 mm and α=0°, but the thickness deviation increased markedly at h = 19 mm. At α = 45 °, the trend of the thickness deviation was slightly larger than that of "Single R die". Therefore, if "Multiple R die" is formed with f = 4 and α = 45 °, it is possible to form less ear height and the same thickness deviation as "Single R die".

Forming analysis

Analysis condition. Numerical analysis using the finite element method was conducted to discuss the forming experiment results. The analysis condition and analysis model are shown in Table 4 and Fig. 11. In this study, the analysis was carried out using the dynamic explicit method of the general-purpose finite element analysis code "LS-Dyna". The work-hardening characteristics of the work material were approximated by Swift's equation by obtaining the stress-strain relationship from tensile tests. The quadratic Hill yield criterion [9] was used for the anisotropic yield function, and Lankford values from Table 2 were used for the anisotropic hardening parameters. In the forming of "Multiple R die", dies at $f = 4$ which had the greatest effect on the ear height suppression in the experiment were used. In this study, isotropic materials were also analyzed to investigate the effects of pure die shapes only.

Table 4. Analysis condition.

Blank	Element type	Solid
	Outer diameter D_B [mm]	60
	Thickness t_0 [mm]	0.5
	Young's modulus E [GPa]	210
	Material hardening (σ_T: True stress, ε_p: Plastic strain)	$\sigma_T = 1535(\varepsilon_p+0.029)^{0.41}$
Punch	Element type	Shell
	Outer diameter D_P [mm]	28.4
	Shoulder radius R_P [mm]	3
Die (Common)	Element type	Shell
	Inner diameter D_D [mm]	30
"Single R die"	Shoulder radius R_D [mm]	3
"Multiple R die"	Shape factor f	4
	Minimum shoulder radius R_{Dmin} [mm]	3
	Maximum shoulder radius R_{Dmax} [mm]	5, 7
Blank holder pressure P_B [MPa]		2.94
Coefficient of friction μ		0.05

Analysis result. The appearance of typical analysis results is shown in Fig. 12. It is similar to the experimental results shown in Fig. 6, confirming the validity of the analysis results.

The analysis results of the cup rim shape at a punch stroke S of about 15 mm are shown in Fig. 13. The vertical axis is the distance r from the cup center to the cup rim, and the horizontal axis is the angle θ_B from the rolling direction. The trend of the cup rim shape during the forming process is very similar to the results for the height of the formed cup in Fig. 7. Increasing R_{Dmax} also results in a significant change in cup rim shape. When the analysis is performed on isotropic material, the cup rim distribution is qualitatively consistent with the cup rim shape in the "Single R die". Thus, it can be seen that the effect of anisotropy in "Single R die" and the effect of die shape in "Multiple R die" $f = 4$ show similar trends. Therefore, if the directionality of the effects of material anisotropy and die shape is matched ($\alpha = 0$ °), the ears will be larger, and if they are placed so that material

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and die cancel out each other (α = 45 °), the effect of ear shape will be smaller. In this study, stainless steel was used as the material, and the highest *r*-value was obtained at θ_B = 45 °. The higher the *r*-value, the greater the circumferential shrinkage deformation of the flange section and the more the sidewall section becomes a mountain shape [10]. The same effect can be obtained by "Multiple R die" if the materials show the same tendency of anisotropy. On the other hand, a slight increase in thickness deviation is observed when "Multiple R die" is used, as shown in Fig. 9 and Fig. 10.

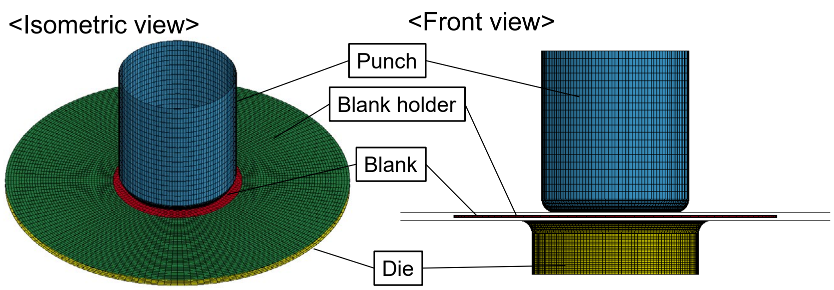

Fig. 11. Analysis model ("Single R die").

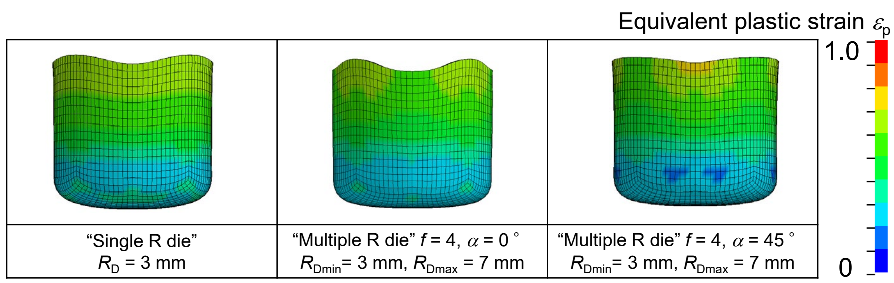

Fig. 12. Analysis result of appearance.

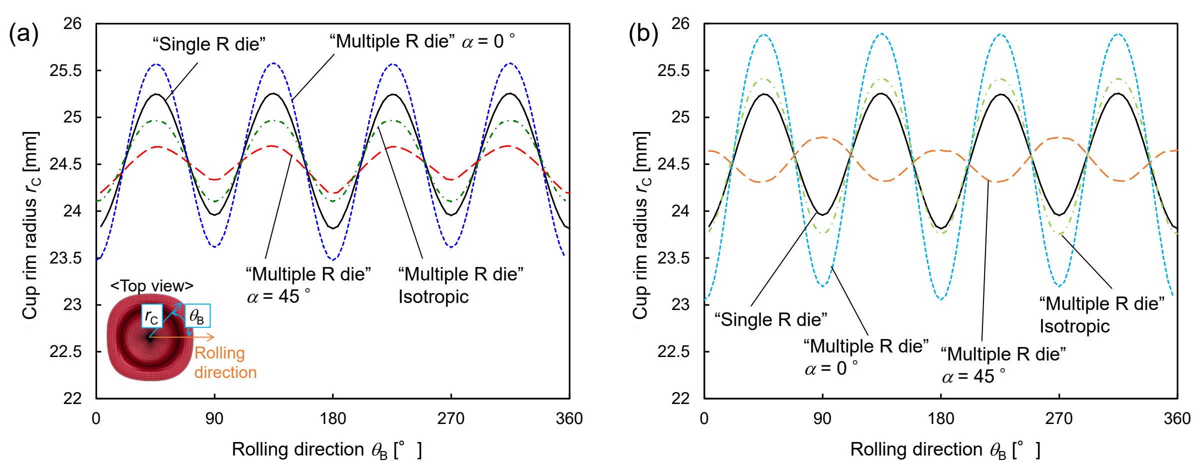

Fig. 13. Analysis results of cup rim shape during forming (Stroke S = approx. 15 mm) (a) f = 4, R_{Dmax} = 5 mm (b) f = 4, R_{Dmax} = 7 mm.

Conclusion

In this study, "Multiple R die" in which the die shoulder R shape was changed in the circumferential direction was proposed for cylindrical deep drawing. Forming experiments and finite element analysis were conducted to investigate the suppression effect of die shape on non-uniform deformation caused by anisotropy. The results are shown below.

- By using a "Multiple R die" the amount of material circumferential flow can be controlled.
- When stainless steel SUS304 (JIS), which has the highest Lankford value in the rolling direction θ_B = 45 °, is formed, the ear height can be suppressed when the shape factor f = 4 and the material installation angle α = 45 °. On the other hand, the thickness deviation in the side wall of the cup tends to be larger than that of "Single R die".
- The results of the finite element analysis showed qualitative agreement between the deformation behavior due to the anisotropic material in the "Single R die" and the deformation behavior due to the isotropic material in the "Multiple R die" at f = 4. Therefore, it was found that ear height can be suppressed if the material and die positions are installed so that the effects of non-uniform deformation due to material anisotropy and the die shape due to "Multiple R die" cancel out each other.

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