

# Ear height control by die radius shape in cylindrical deep drawing

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**Abstract.** This study presents the relationship between die radius shape and anisotropy that suppresses ear height in cylindrical deep drawing. In deep drawing, the cup is formed with irregularities on the edge, called “earring”, due to the anisotropy of sheet material. In previous studies, suppression of ear height has mainly been conducted by suppression of anisotropy through material development. The authors have previously confirmed that ear height can be suppressed in cylindrical deep drawing using “Multiple R die” in which the die shoulder R shape varies in the circumferential direction. However, the detailed relationship between the die radius shape in Multiple R die and material anisotropy has not been clarified. Therefore, in this study, the effect of the die radius shape in Multiple R die on the formed shape was investigated by experiment and finite element analysis. The larger the difference in the R dimension of the die shoulder, the larger the change in the earring shape. In addition, it was confirmed that the ear height can be suppressed by changing the die shoulder R shape according to the anisotropy distribution.

**Keywords:** Deep drawing; Anisotropy; Die radius shape; Earing.

## 1 Introduction

Deep drawing is a forming method for forming sheet materials into cups. Formed cups are used in various fields, such as automotive parts and beverage cans. The cup edges are formed with irregularities called “earring” due to the anisotropic sheet metal material [1]. In normal products, a trimming step is required to remove the earring, which increases manufacturing time and scraps. Previously, earring suppression has focused on suppressing material anisotropy [2, 3]. Simulation

studies have also been conducted to predict earring [4]. However, material development requires a large cost depending on the material.

The authors have proposed “Multiple R die” in which the die shoulder R is varied in the circumferential direction in cylindrical deep drawing as shown in Fig. 1 for conventional “Single R die” with constant die shoulder R dimension in the circumferential direction [5]. Multiple R die shows that the earring shape can be suppressed by properly matching the rolling direction of the material and the die radius shape. However, the effect of each parameter constituted Multiple R die, which is the die radius shape, and its relationship to the anisotropy has not been reported. Therefore, this paper mainly uses finite element analysis to clarify the effects of die radius shape and material anisotropy parameters on the forming results in Multiple R die.

## 2 Multiple R die

Fig. 2 shows the determination method for the die shoulder shape of Multiple R die. In this study, the die R shape is defined as a die shoulder R dimension function and determined by the following procedure.

- i. Set  $R_{Dmin}$  and  $R_{Dmax}$  as the minimum and maximum die shoulder R dimensions.
- ii. Set a shape factor  $f$ .
- iii. Equation (1) determines the die shoulder R dimension  $R_D$  at the circumferential die angle position  $\theta_D$ .

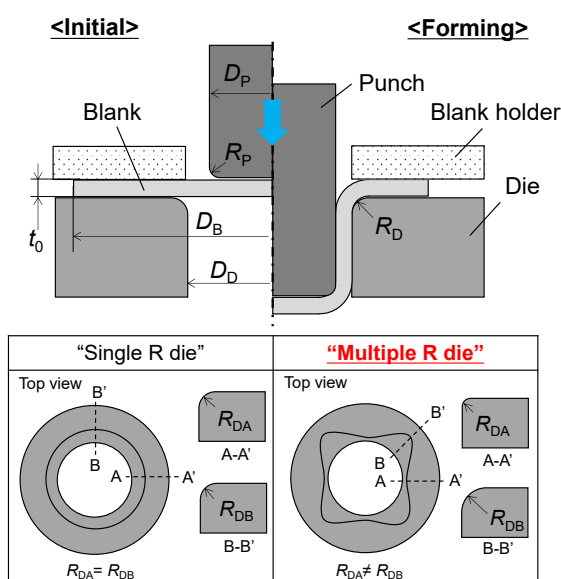


Fig. 1. Cylindrical deep drawing and Multiple R die.

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

The direction in which  $\theta_D = 0^\circ$  will be referred to as the die reference direction.

### 3 Effect of Multiple R die parameters on formed shape

#### 3.1 Analysis condition

The analysis condition, material data, and analysis model are shown in Table 1, Table 2, and Fig. 3. In this study, the analysis was carried out using the dynamic explicit method of the general-purpose finite element analysis code “LS-Dyna”. Analysis conditions such as friction coefficient and element size were determined by

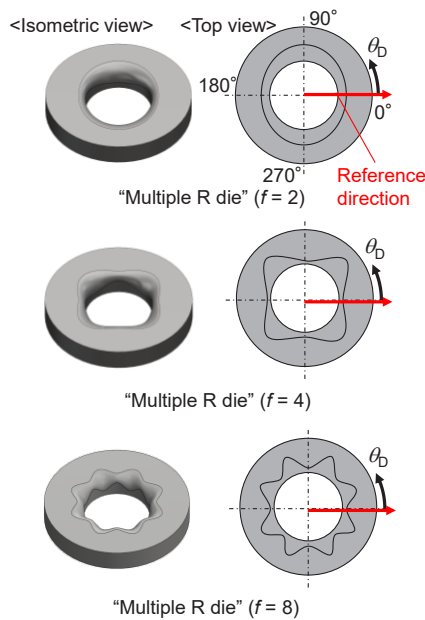


Fig. 2. Die radius shape of Multiple R die.

Table 1. Analysis condition.

Blank	Material type	Elasto-plastic
	Outer diameter $D_B$ / mm	60
	Thickness $t_0$ / mm	0.5
Punch	Material type	Rigid
	Outer diameter $D_P$ / mm	28.4
	Shoulder radius $R_P$ / mm	3
Die	Material type	Rigid
	Inner diameter $D_D$ / mm	30
	Shoulder radius $R_D$ / mm	3, 5, 7, 9
Blank holder pressure $P_B$ / MPa		2.94
Coefficient of friction $\mu$		0.05

Table 2. Material data.

Material	SUS304 (JIS)
Young's modulus $E$ / GPa	210
Material hardening ( $\sigma_T$ : True stress, $\epsilon_p$ : Plastic strain)	$\sigma_T = 1535(\epsilon_p + 0.029)^{0.41}$
Lankford value $r_0$	0.852
Lankford value $r_{45}$	1.388
Lankford value $r_{90}$	0.781
In-plane anisotropy $\Delta r$	-0.572

comparison with experimental results for cup edge shape.

An austenitic stainless steel of SUS304 (Japan Industrial Standard, JIS) was used as the work material. Swift's equation approximated the work-hardening characteristics of the work material by obtaining the stress-strain relationship from tensile tests. In this study, isotropic materials were also analyzed to investigate the effects of pure die radius shapes only. When the analysis was conducted considering anisotropy, the Lankford value ( $r$ -value), an anisotropy parameter, was used. The Lankford values with an angle from rolling directions  $\theta_B = 0, 45, \text{ and } 90^\circ$  were calculated from the change in the width direction strain and the longitudinal strain of the parallel section of the specimen [6].  $\Delta r$  is the in-plane anisotropy, expressed by Equation (2), and affects the earing shape [7].

$$\Delta r = \frac{r_0 + r_{90}}{2} - r_{45} \quad (2)$$

The quadratic Hill yield criterion [8] was used for the anisotropic yield function, and Lankford values from Table 2 were used for the anisotropic hardening parameters.

#### 3.2 Die radius shape factor

The effect of shape factor  $f$  was analyzed using isotropic material to investigate the effect of earing shape on die outline in Multiple R die. The analysis result of the formed cup shape is shown in Fig 4. The higher the shape factor  $f$ , the greater the number of mountains on the cup edge. It was confirmed that the shape factor can change the earing shape formation pattern. The cup edges form a valley at an angular position where the die shoulder  $R$  is small and form a mountain at an angular position where the die shoulder  $R$  is large. At  $f=2$ , there is a slight decrease in the peaks at the angular positions

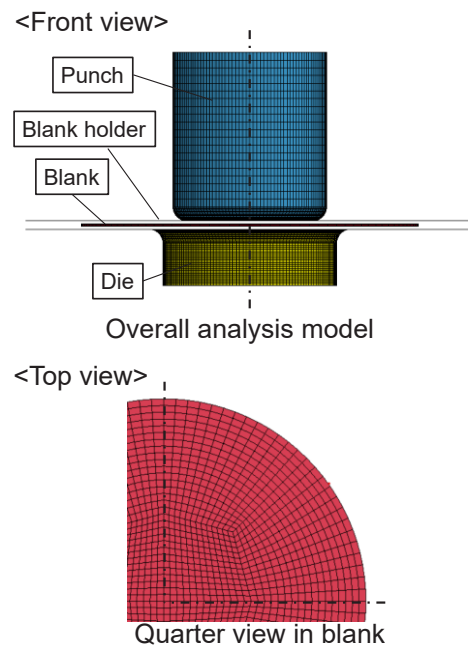


Fig. 3. Analysis model.

of  $\theta_D = 90, 270^\circ$ . This is because the cutway of blank mesh changes from octagonal to circular, as shown in Fig. 3. Originally, mountains are formed at  $\theta_D = 90, 270^\circ$  because this is the point where the die shoulder R is large. However, the material tends to flow in at  $\theta_D = 90, 270^\circ$  because the elements in  $\theta_D = 90, 270^\circ$  directions deform in the direction of the element's edges, whereas in the other directions, the elements deform diagonally during squeezing deformation. Therefore, at  $f=2$ , the peaks formed a little decrease in  $\theta_D = 90, 270^\circ$ .

### 3.3 Die shoulder R dimension

In Multiple R die, the die shoulder R dimension is considered to affect the forming results. Therefore, the effects of minimum and maximum die shoulder dimensions on earing shape were investigated.

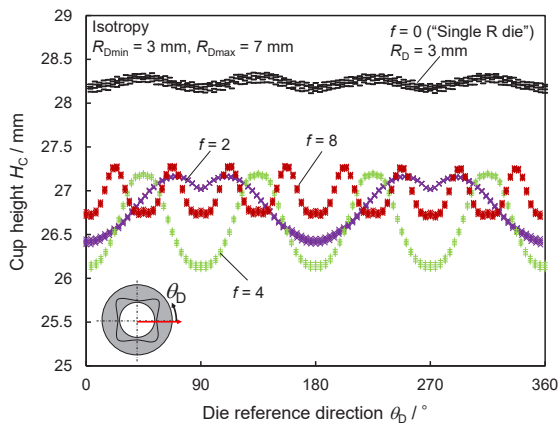


Fig. 4. Effect of shape factor  $f$  on earing shape.

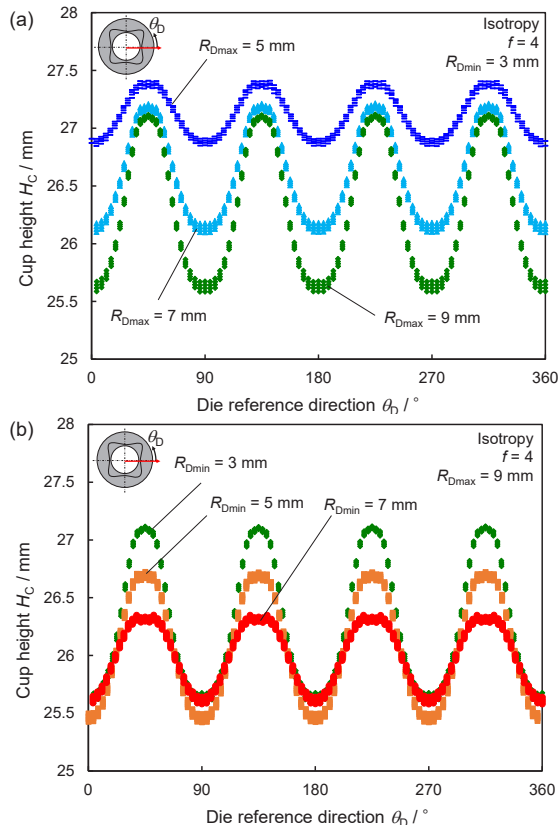


Fig. 5. Effect of die shoulder R dimension on earing shape (a) Effect of  $R_{Dmax}$ , (b) Effect of  $R_{Dmin}$ .

Preliminary experiments showed that die shoulder R of less than  $R_D = 3$  mm causes fracture. Hence,  $R_D = 3$  mm or more was used for the analysis.

The analysis results of varied die shoulder R are shown in Fig. 5. Fig. 5 (a) shows the analysis result in which the minimum die shoulder R dimension  $R_{Dmin}$  is fixed and the maximum die shoulder R dimension  $R_{Dmax}$  is changed. As  $R_{Dmax}$  increases, the cup height  $H_C$  decreases overall, especially the valley height. The larger the  $R_{Dmax}$ , the more material flows in at  $\theta_D = 0, 90^\circ$ , where the die shoulder R is relatively small, and the deeper the valley. Fig. 5 (b) shows the analysis result in which  $R_{Dmax}$  is fixed and  $R_{Dmin}$  is changed. As  $R_{Dmin}$  increases, the valley height does not change significantly, but the mountain height decreases. As the difference in die shoulder R gradually decreases, the tendency is similar to Single R die, and the ear height decreases for isotropic material. In addition, since the die shoulder R is larger overall, the blank holder force decreases relatively late in the forming, resulting in a small cup height overall. By increasing the difference between  $R_{Dmin}$  and  $R_{Dmax}$ , the ear height becomes large; thus, this can increase the amount of earing control by the die radius. On the other hand, if the die shoulder  $R_D$  is too small, there is a risk of fracture, and if  $R_D$  is large, there is concern about a decrease in forming height, roundness worsening, or wrinkling. Therefore, in forming with Multiple R die, it is considered advisable to determine  $R_{Dmin}$  that does not fracture and  $R_{Dmax}$  that can adequately control the ear height.

### 3.4 Positional relationship between material rolling direction and die

Since the forming in Multiple R die is a non-

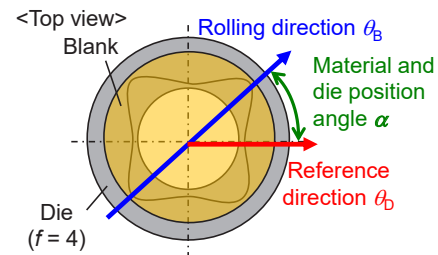


Fig. 6. Material and die position angle  $\alpha$ .

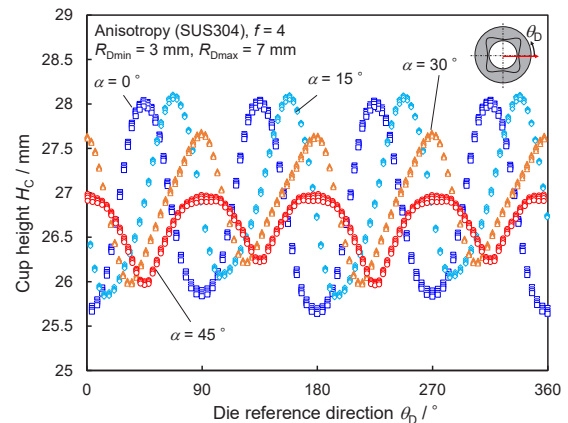


Fig. 7. Effect of angular positioning of material and die on earing shape.

Therefore, the angle between the rolling direction and the die reference direction  $\theta_D = 0^\circ$  was defined as  $\alpha$ , shown in Fig. 6, and the effect of  $\alpha$  on the ear height was investigated. Analysis was conducted at  $f = 4$ ,  $R_{Dmin} = 3$  mm,  $R_{Dmax} = 7$  mm. The anisotropy parameters in Table 2 were used. For symmetry considerations, the analysis was conducted at  $\alpha = 0 - 45^\circ$ . The analysis results of the relationship between rolling direction and die position are shown in Fig. 7. Although the ear height is large at  $\alpha = 0^\circ$ , the ear height decreases as  $\alpha$  increases, with the smallest ear height at  $\alpha = 45^\circ$ . The analyzed material SUS304 has a negative value of  $\Delta r$  so that a peak is formed in the direction of  $\theta_B = 45^\circ$  in Single R die forming [9]. The results of previous studies, which can suppress ear height formation by placing the anisotropy and die radius shape effects cancel each other out, were reconfirmed. It was found that the ear height could be best controlled if the maximum die shoulder R  $R_{Dmax}$  was placed at the angular position where the mountain is formed in Single R die forming.

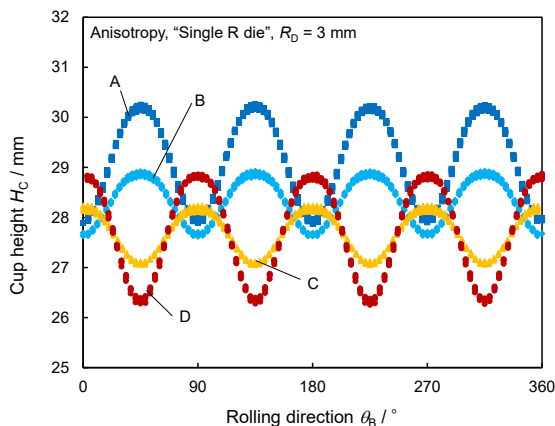
### 3.5 Relationship between anisotropy and die radius shape

The relationship between material anisotropy and die radius shape was investigated by using virtual materials. The virtual materials analyzed are shown in Table 3. In this study, four types that are common in steel and copper materials [10] were analyzed: high Lankford values at  $\theta_B = 45^\circ$  and negative  $\Delta r$  (materials A and B), and high Lankford values at  $\theta_B = 0$  and  $90^\circ$  and positive  $\Delta r$  (materials C and D).

Firstly, the earing shape in Single R die was analyzed to investigate the effect of anisotropy. The analysis results are shown in Fig. 8. For drawing by Single R die, the horizontal axis illustrates the angle from the rolling direction  $\theta_B$ . For materials A and B with negative  $\Delta r$ , peaks were formed at  $\theta_B = 45^\circ$ , and for materials C and D with positive  $\Delta r$ , peaks were formed

**Table 3.** Anisotropy parameters of virtual materials.

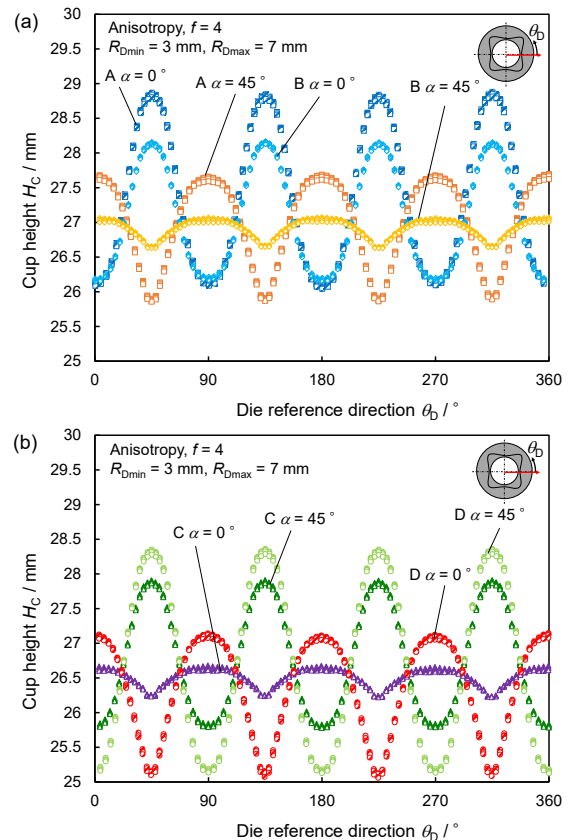
Material	$r_0$	$r_{45}$	$r_{90}$	$\Delta r$
A	0.6	1.4	0.6	-0.8
B	0.8	1.2	0.8	-0.4
C	1.2	0.8	1.2	0.4
D	1.4	0.6	1.4	0.8



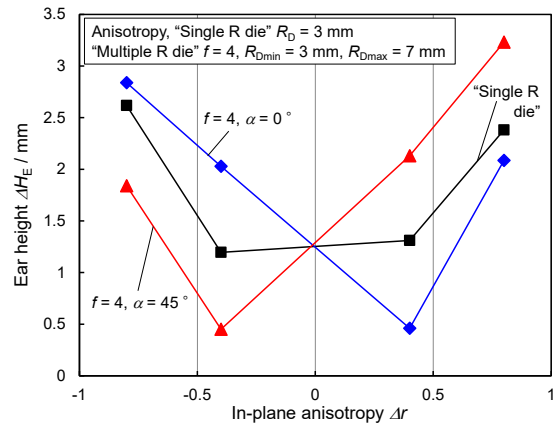
**Fig. 8.** Effect of anisotropy parameters on earing shape in Single R die.

at  $\theta_B = 0^\circ$ .

The analysis results using Multiple R die are shown in Fig. 9. For materials A and B in Fig. 9 (a), there was an increase in ear height at  $\alpha = 0^\circ$  and a decrease in ear height at  $\alpha = 45^\circ$ . The opposite trend was observed for the material C and D analysis results in Fig. 9 (b). Besides, the smaller the absolute value of  $\Delta r$ , the more the ear height tended to be suppressed. The analysis results summarizing the ear height  $\Delta H_E$  are shown in Fig. 10. Ear height  $\Delta H_E$  was calculated from the difference between the maximum and minimum values of cup height  $H_C$ . Ear height can be suppressed by setting  $\alpha = 0$  and  $45^\circ$  for positive and negative  $\Delta r$ , respectively.



**Fig. 9.** Effect of anisotropy parameters on earing shape in Multiple R die (a) Materials A, B (b) Materials C, D.



**Fig. 10.** Effect of anisotropy parameters on ear height.

### 3.6 Verification experiment and discussion

The analysis and experimental results were compared to evaluate the validity of the analysis results. The materials used in the analysis and experiments were SUS304, as shown in Table 2. The earing shape and the appearance of the formed shape are shown in Figs. 11 and 12. The horizontal axis  $\theta_D$  of Single R die in Fig. 11 is synonymous with  $\theta_B$ . The analysis results roughly matched the experimental results quantitatively. For  $\theta_D = 0$  and  $90^\circ$  with  $\alpha = 0^\circ$ , the analysis and experimental results diverged. This is because the material is deformed in the radial direction due to wrinkling in the experiment as shown in Fig. 12. On the other hand, the analysis assumed the tool as a rigid body so that the material could not deform in the cup radial direction and

reproduce wrinkles. Hence, the valley height increased, and the material may have been stretched.

### 4 Conclusions

In this study, the effect of forming parameters about Multiple R die, such as shape factor, die shoulder dimension, die angular position, and anisotropic parameter on the earing shape, was investigated using finite element analysis. The results are shown below.

The shape factor  $f$  roughly corresponds to the number of earing, and by changing  $f$ , the earing shape mode can be changed.

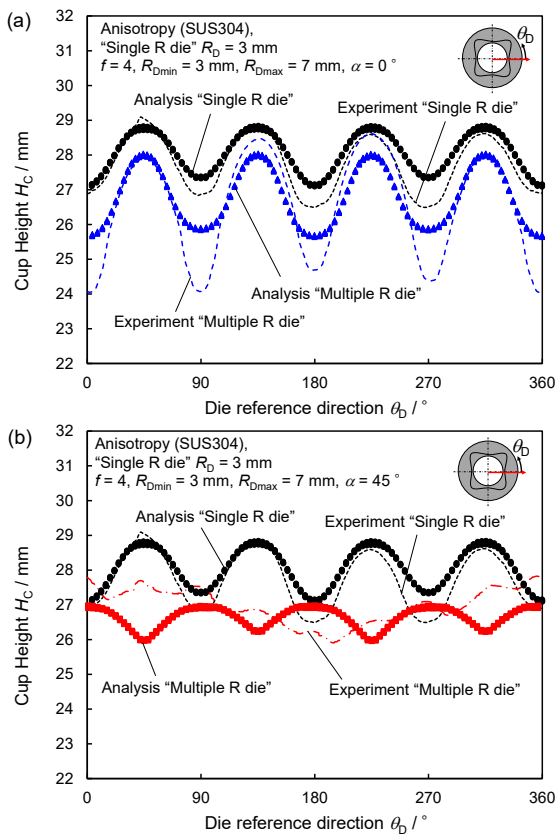
The larger the difference in the R dimension of the die shoulder, the larger the change in the earing shape. In drawing with Multiple R die, it is recommended to determine  $R_{Dmin}$ , which does not fracture, and then determine  $R_{Dmax}$ , which allows sufficient control of the ear height.

The ear height is best suppressed by placing the maximum die shoulder  $R_{Dmax}$  at the angular position where the peaks are formed in the Single R die.

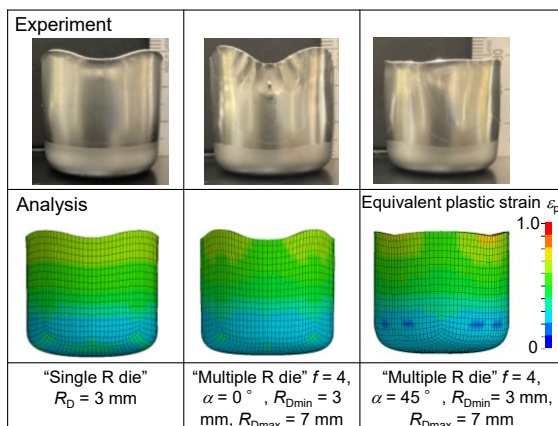
If the material is anisotropic, such as steel or copper material, the in-plane anisotropy  $\Delta r$  will change the die positioning relationship of Multiple R die that suppresses the ear height.

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**Fig. 11.** Comparison of earing shape between analysis and experiment (a)  $\alpha = 0^\circ$ , (b)  $\alpha = 45^\circ$ .



**Fig. 12.** Comparison of formed shape between analysis and experiment.