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A METHOD FOR SUPPRESSION OF DEFECTS IN ZIGZAG BENDING OF SHEET METAL

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Abstract. This study presents methods for suppression of defects observed in zigzag bending of sheet-metal or plate. This type of bending is widely used in industry for manufacturing structural parts in automobiles. Although it is easily conducted by press forming using upper and lower dies which have zigzag shape, it often has defects, such as spring-back and dents. A series of finite element analyses and experiments were conducted for suppression of the defects in two-place bending, which has three segments. As a result, it is revealed that that the distance between two bending positions is dominant for occurrence of the dents and that the dent area was able to be reduced by selecting the optimum moving direction of the upper die. It is also revealed that the cause of spring-back is elastic recovery of the straight segments instead of the bent parts against engineers' and technicians" intuition, and that there is an optimum moving direction of the upper die for the least spring-back. Furthermore, another realistic method for suppression of spring-back was suggested for four-place bending.

1 INTRODUCTION

Sheet-metal/plate bending is a commonly used manufacturing process in industry. The bent metals are used as structural components in vehicles, chassis in train cars and medical instruments and so on. Although the mechanism of bending is simple and concise, bending process can bend the metal into various shapes by selecting proper bending angles or die shapes.

One-place bending, which includes V-bending and L-bending, is the most popular bending method. Imai et al. proposed a precise V-bending process, which is composed of 2 steps of bending [1]. During the 1st step bending with less bending angle, the spring-back behaviour is observed and mechanical properties are estimated. The sheet metal is bent again up to a certain amount, which is determined based on the estimated mechanical properties. Jin et al. analysed camber deformation which is caused by V-bending [2]. Matsumoto et al. tried to predict spring-back in V-bending using homogenization method [3]. There are some studies on multi-place bending in press forming. Geka proposed a method for reducing spring-back in hat channel forming. However, there are few research works on zigzag bending, which is one of multi-place bending processes.

This study presents methods for suppression of defects observed in zigzag sheet-metal or plate bending which are spring-back and dents. A series of finite element analyses and experiments were conducted for suppression of the defects in two-place bending, which has three segments. Furthermore, another realistic method for suppression of spring-back was suggested for four-place bending.

2 DEFECTS IN ZIGZAG BENDING

Figure 1 shows an example of plates, which was press-formed by zigzag bending, and its defects. Figure 1(a) shows an approximate shape of a supporting member in an autotruck which was press-formed by four-place bending using a pair of upper and lower dies. There are two types of defects in zigzag bending, and they are spring-back and dent. In order to examine the defect behavior, two-place bending was conducted numerically and experimentally, assuming that two place bending inside the rectangle broken line in Figure 1(a) must be dominant in four-place bending. Figure 1(b) shows a schematic illustration of two-place bending. The dominant working parameter is the length ratio l_2: l_0: l_1.

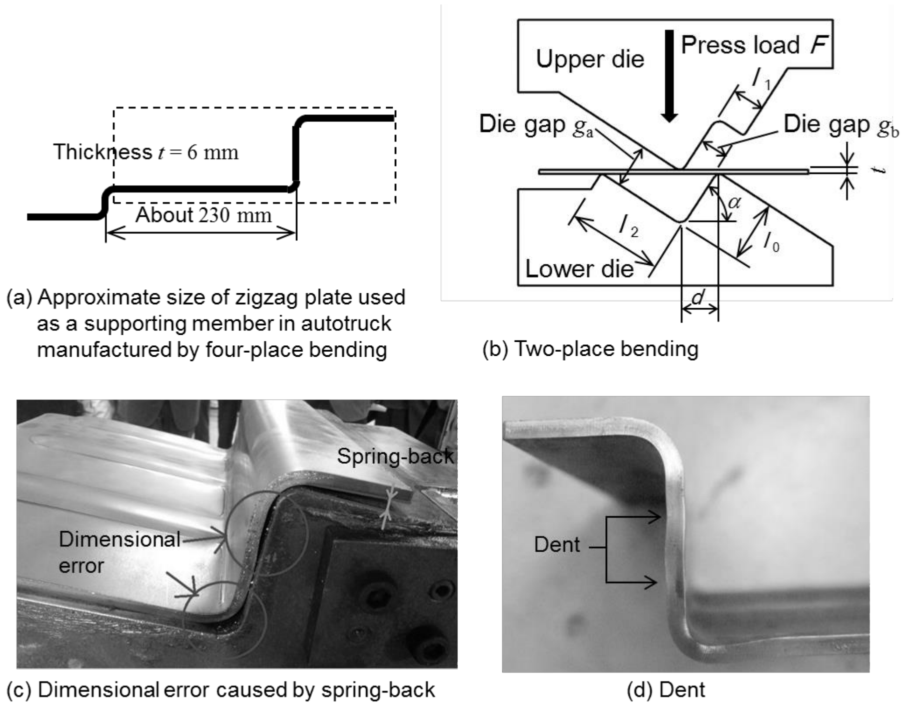


Figure 1: Zigzag bending and its defects

3 EXAMINATOIN PROCEDURE

A series of Finite Element analyses was conducted using the commercial code ELFEN, which was developed by Rockfield Software Limited, Swansea. Plane-strain elastic-plastic analysis was carried out using an implicit scheme. A von Mises' yield criterion was adopted, and the normality principle was applied to the flow rule. Constraints were dealt with by the penalty function method. A quadrilateral element was used because of the simplicity of the material deformation. The F-bar method was applied to the element for overcoming volumetric locking with simple 4-node quadrilateral elements [4].

Figure 2 shows a model when $l_2 < l_1$. The plate is elasto-plastic, and the upper and lower dies were rigid. There were four rubber-like supports [S1]-[S4] with low Young's Modulus of 100 MPa. The supports prevented the plate from flipping away from between the two dies. The two places were bent with time lag when $l_2 < l_1$. The plate was bent by three apexes [D], [A] and [C], followed by the 2nd bending by [A], [C] and [B]. The two places were bent at the same time when $l_2 = l_1$. After bending, the upper and lower dies were placed back from the plate, which was constrained in the space as shown in Figure 2(e), for stable and short-time calculation. The constraints were released in as step by step method from left to right side as shown in Figure 2(e)-(h). The amount of spring-back at each section could be evaluated by observing the tilting-angle change of the left side of the plate during the releasing procedure. The detailed conditions are shown in Tables 1 to 3. The gaps between the two dies g_a and g_b in Figure 1(b) were set to be equal to the metal thickness t at the end of bending.

Figure 3 shows the experimental set-up. A thinner sheet metal of thickness t = 1.6 mm was used for the laboratory experiment. The dies are set inside a die guide, and then the upper die was pushed down using a universal test machine. A cylindrical load cell with strain gauge was inserted for the measurement of horizontal load if necessary.

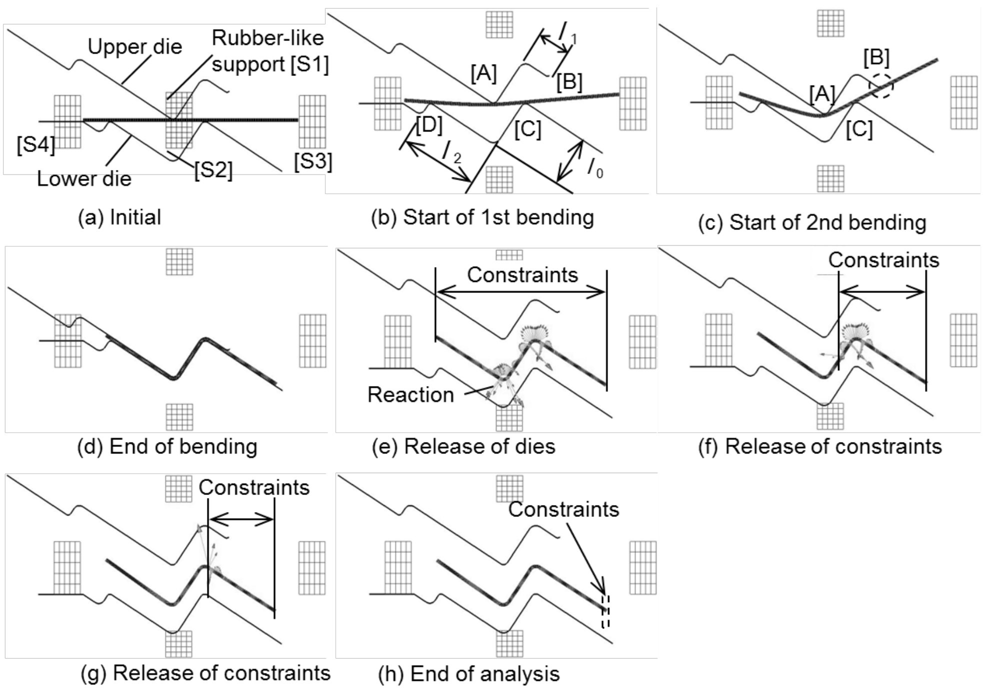


Figure 2: FE model for two-place bending (l_2<l_1)

Table 1: Bending condition

Die	Material	Rigid
	Reference length l_0/mm	100
Plate	Thickness t/mm	6
	Die length of upper die l_1	0.5 – 1.5 l_0
	Die length of lower die l_2	0.5 – 1.5 l_0
	Material	SS400
Other	Gaps between dies g_a *and* g_b at end of bending	$g_a = t$ and $g_b = t$.

Table 2: Element size

Thickness direction	4 division for thickness
Longitudinal direction	1.11-1.38 mm/div

Table 3: length ratio (e: examined)

		l_2/l_0		
		0.5	1.0	1.5
l_2/l_0	0.5	e		
	1.0	e	e	
	1.5	e	e	e

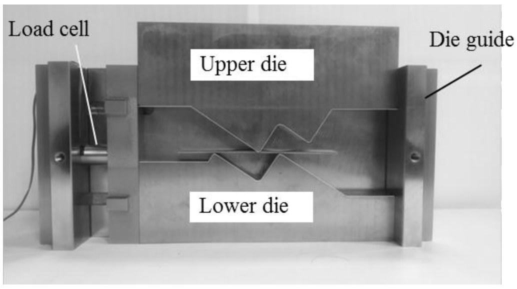


Figure 3: Experimental set-up for sheet metal of thickness t = 1.6 mm (l_2: l_0: l_1 = 1.5: 1: 1)

4 EXAMINATION RESULTS

4.1 Mechanism of dent occurrence

The mechanism for occurrence dent was examined by the FEM taking length ratio of l_2: l_0: l_1 = 1.5: 1: 1 as an example. The deformation during bending is shown in Figure 4. The formation of initial dent shape and its movement seemed to be the cause of dent. When the 1st bending starts, the initial dent shape was formed at contact point P_1 as shown in Figure 4(a)-(b). The similar phenomenon occurred at P_2 as shown in Figure 4(b)-(c). The dent at positions P_1 and P_2 are drawn into inside the middle straight portion. As a result, the dent would occur. This assumption was confirmed by the fact that the dent part had burnished surface in the actual four-point bending and the laboratory experiments. The surface must have been scratched by the die apexes during the movement of the initial contact point P_1 and P_2. The moving distance of P_1 and P_2 are denoted by S_1 and S_2 in the figure.

Figure 5 shows the effect of length ratio l_2: l_0: l_1 on the dent area, which is evaluated as the moving distance S_1 and S_2 in the analysis and burnished area in the experiment. It is noteworthy that moving distances S_1 and S_2, and the burnished area decreased with decrease of l_2. This phenomenon can be explained by focusing upon difference between the distance between two bending positions d and length l_0, which are shown in Figures 1(b) and 4(a). The bending-distance d is almost equal to the distance between P_1 and P_2. When the difference between l_0 and d is large, the moving distance S_1 and S_2 becomes large. With decrease of l_2, the tilting angle α of middle straight portion decreases leading to increase of d, and then the moving distances S_1 and S_2 decreases. If d is equal to l_0, the moving distances S_1 and S_2 should almost be zero.

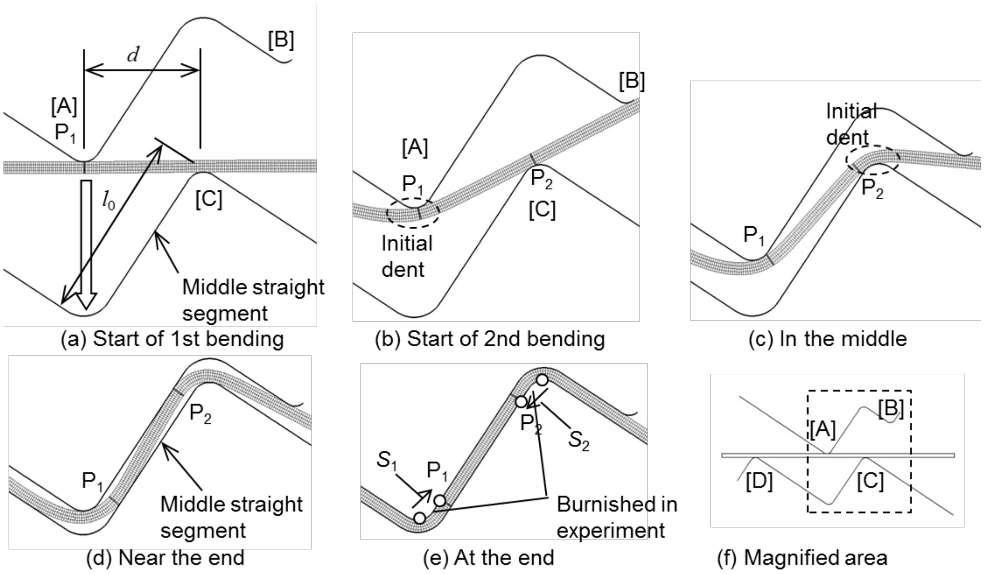
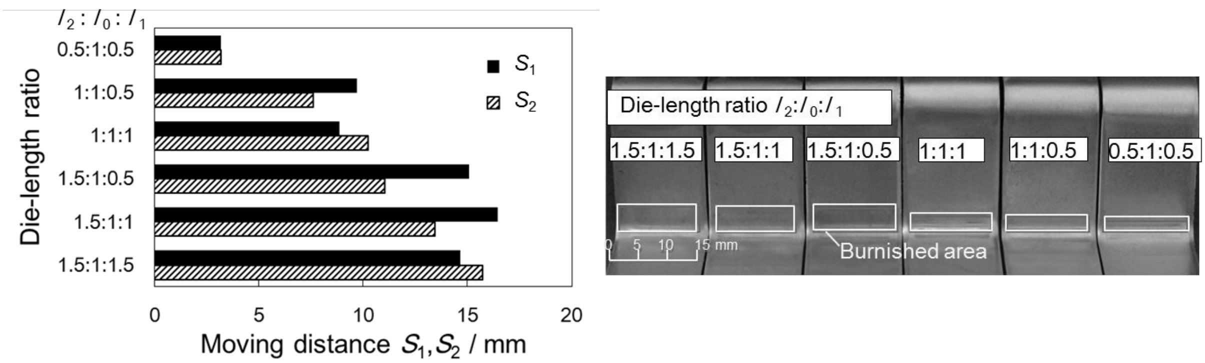


Figure 4: Mechanism for dent occurrence

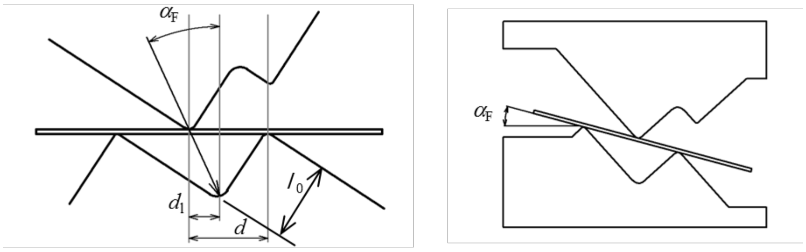


(a) Moving distance of contact points in FEM (b) Burnished surface in experiment at P_1

Figure 5: Effect of length ratio on moving distance of contact points and burnished area

4.2 Method for reduction of dent area

A method for reduction of dent area, or burnished area, is derived by the previous examination on dent occurrence. The essential point is to make d equal to l_0 by change the die-moving direction α_F as shown in Figure 6. While it is easy to change the moving direction in the analysis, the plate should be tilted in actual operations as shown in Figure 6(b). The effect of the proposed method is shown as a result of FEM in Figure 7. The proposed method is able to significantly reduce the moving distances S_1 and S_2.



(a) In FEM (b) Actual operation

Figure 6: Method for reduction of dent area

Arrangement of die-moving direction

l_2: l_0: l_1	Moving angle α_F	Apex position d_1/mm	Apex distance d/mm
0.5:1:0.5	11.3	12.1	98.9
1 :1:0.5	28.7	33.6	104.3
1 :1: 1	20.9	23.4	94.1
1.5:1:0.5	38.2	58.6	115.7
1.5:1: 1	28.1	41.1	98.2
1.5:1:1.5	26.5	37.0	94.2

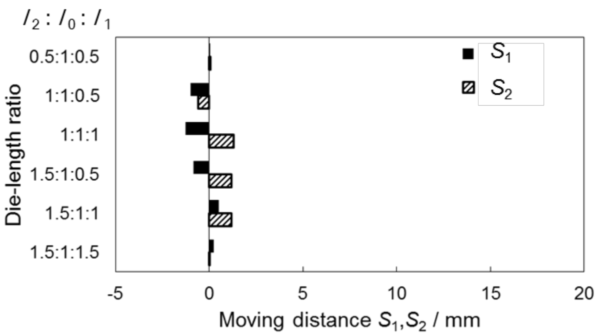
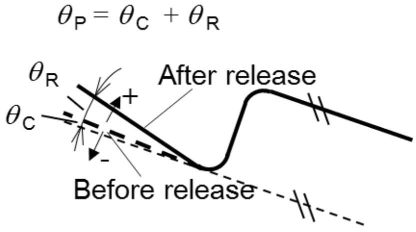


Figure 7: Effect of die-moving direction arrangement on moving distance of contact points

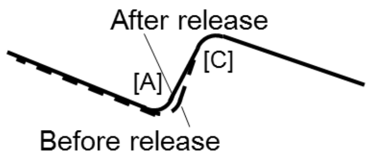
4.3 Mechanism of spring-back occurrence

Figure 8 shows effect of length ratio on spring-back. Total spring-back θ_P was defined as parallelism tolerance after release of constraints, and θ_P is composed of angular tolerance before release θ_C and spring-back during release θ_R. As the gaps between the upper and lower dies g_a and g_b were equal to the metal thickness t at the end of bending, angular tolerance before release θ_C is small, and total spring-back θ_P is almost the same as spring-back during release θ_R. It is predictable but noteworthy that the spring-back θ_P and θ_R were small when l_1 and l_2 were equal as the deformation became point-symmetric as shown in Figure 8(c). Even if local spring-back at [A] and [C] is large, these effects will be canceled out in terms of parallelism tolerance.

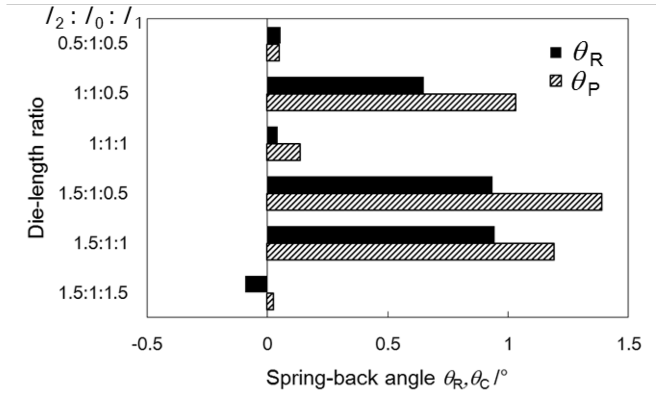
Finite element analysis was conducted in order to clarify the most influential part on spring-back as shown in Figure 2 by releasing the constraints on the bent metal from the left to the right. The results are shown in Figure 9. Even though local spring-backs are large at bent segments #2 and #5, they canceled each other. On the other hand, spring-back at segment #3 is larger than that at segment #4 when the length ratio l_2: l_0: l_1 is 1.5:1:0.5 and 1.0:1:0.5, resulting in increase of spring-back during release θ_R. Therefore, the unbalance of local spring-back at middle straight portions #3 and #4 is the main cause of total spring-back θ_P.



(a) Definition of spring-back

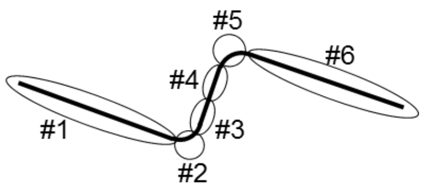


(c) Spring-back in symmetrically bent metal

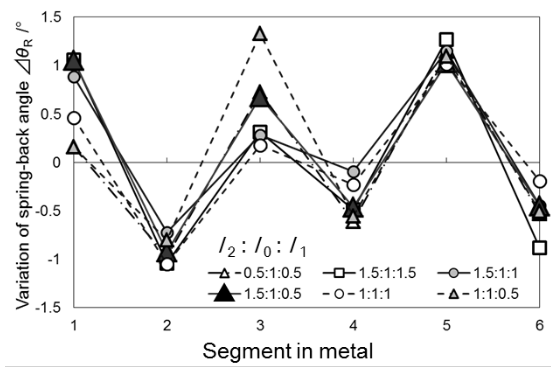


(b) Effect of length ratio

Figure 8: Effect of length ratio on spring-back



(a) Definition of segments

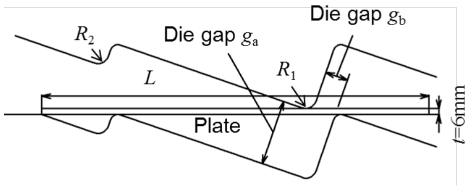


(b) Spring-back caused by each segment

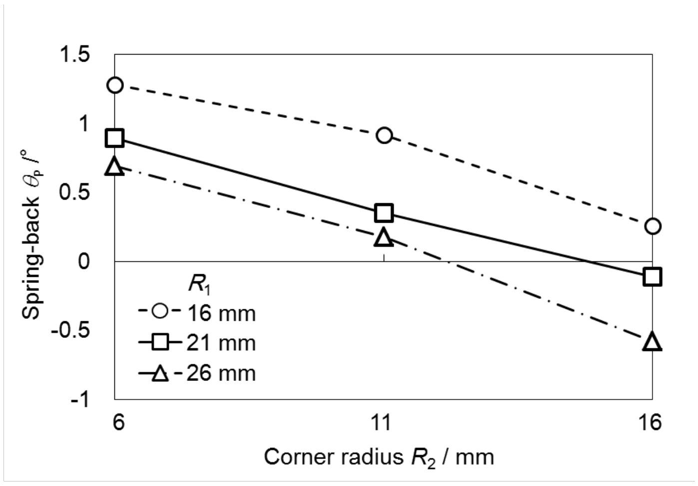
Figure 9: Spring-back caused by segments of bent metal

4.4 Method for reduction of spring-back

As the die-moving direction has a significant effect on dent area, it may have some effect on spring-back. Figure 10 shows effect of the die-moving direction on spring-back. It is noteworthy that spring-back is able to be reduced by applying small distance between two bending positions d, i.e. negative value of die-moving angle α_F. Therefore, reduction of distance between two bending positions is an effective method for reduction of spring-back.



(a) Corner radius to be increased



(b) Effect of corner radii

Figure 11: Effect of die-corner radii on spring-back

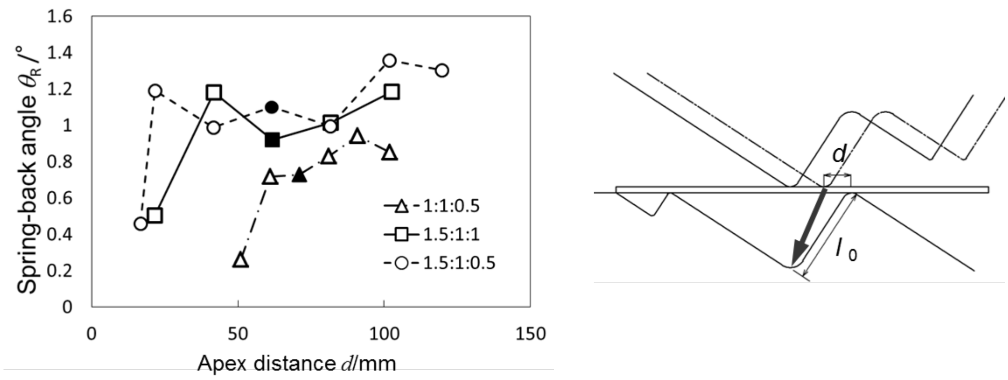


Figure 10: Effect of die-moving angle on spring-back

4.5 Method for reduction of spring-back for four-place bending

The methods for reduction of dent area and reduction of spring-back unfortunately contradict each other. While distance between two bending positions d should be increased up to die length l_0 for reduction of dent area, d should be decreased for reduction of spring-back. Therefore, another method for reduction of spring-back is proposed here. It is to enlarge the die corner radii R_1 and R_2 for four-place bending in Figure 11(a). Bent portions at the corners of R_1 and R_2 will spring-back locally to negative direction in Figure 8 (a) so as to reduce the total spring-back θ_P. Enlargement of R_1 and R_2 should increase this reduction effect. It is because spring-back angle is an integrated value of curvature change by length. As the enlargement of corner radii would increase the integration range [6], the local spring-back in the negative direction would increase, leading to decrease of total spring-back θ_P. Although this method would be applicable for two-place bending, it would be more effective for four-bending as it has many bending points. In the case of two-place bending, corner radius R_1 should be increased excessively. On the other hand, the enlargement of corner radii R_1 and R_2 would be limited in the case of four-place bending. The effect of enlargement of corner radii is shown in Figure 11(b). Increase of die-corner radii certainly has effect of reducing spring-back. Spring-back decreased with increase of corner radii R_1 and R_2.

5 CONCLUSIONS

- This paper presents methods for reducing dent area or spring-back in zigzag bending.
- A series of FEA was carried out for investigation of the deformation. In the FE model, the metal was constrained during release of dies, and the constraints were released from the right to the left so that the effect of each portion can be observed.
- The dent area was evaluated by the moving distance of the contact points in the analyses.
- A proposed method for reduction of dent area was to make the distance between two bending positions be equal to the middle straight portion.
- A proposed method for reduction of spring-back was to decrease the distance between two bending positions, though this may contradict the method for dent-area reduction.
- Another method for reduction of spring-back was to increase certain die-corner radii and this method would be compatible to the method for dent-area reduction. This method would be realistic for four-place bending rather than two-place bending.

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