Effect of Forming Conditions on Bending Characteristics in Push-Through Bending of Aluminum Extrusion Sections

Hidemitsu Hamano, and Hisaki Watari

***Abstract*—**It has been initially investigated t the clearance between the die and the extrusion section in order to clarify the influence of processing conditions on cross-sectional deformation and slide marks in push-through bending. Next, we determined that the value of the die bending angle relative to the stroke of the movable die affects the cross-sectional deformation. We then investigated the effect of delaying the die-bending angle application on reducing slide marks. Finally, we examined the effect of the distance between the fixed die and the movable die. As a result, we found the following. The curvature decreases as the clearance between the die and the extrusion section increases with an identical movable die stroke. The longitudinal-section dimension change rate, wrinkling, and roughness of the slide mark decrease when the die-bending angle is correct. Delaying the die-bending angle application relative to the transfer start of the movable die reduced the cross-sectional deformation and slide marks when the distance between the dies was large. The maximum load of the bending axis decreases as the distance between the dies increases, but the cross-sectional deformation increases, so there is an optimum value.

***Keywords*—**aluminum extrusions, push-through bending, tube forming, forming condition

I. Introduction

LIGHTWEIGHT and recyclable aluminum extruded sections are used in a wide range of fields (e.g., motor cars, airplanes, and buildings)[1-3]. They are also used in sections with complicated curves to meet diversified needs, so complete three-dimensional bending technologies for long materials are required[4-6]. Push-through bending, which the authors are developing, is a method used to bend an extruded section to the required shape by passing the section through a fixed die and a movable die, and pushing it while moving the movable die vertically and laterally and turning it to a certain angle[7]. Unlike rotary draw bending, press bending, or stretch bending, push-through bending can bend the material into various forms by NC control using a pair of dies. However, the prescribed form may not be obtained or irregular deformation including cross-section deformation may occur, depending on forming conditions. Furthermore, slide traces, which degrade appearance, remain on the surface of the bent material.

This study (1) investigated the effect of the clearance between the die and the extruded section, (2) obtained the optimum value of the die-bending angle for the die movement, which greatly influences cross-section deformation, (3) proposed a delay-control method for the die-bending angle to reduce slide traces, and (4) investigated the effect of the distance between the fixed die and the movable die to clarify the influences of forming conditions on cross-section deformation and slide traces in push-through bending.

II. Experiments

A. Specimens and Test Apparatus

We used two extruded sections with different dimensions and materials for the experiments. Their cross-sectional dimensions and mechanical properties are listed in Table 1. All heating was done by T1.

All movements of five axes of the movable die and the movement in the push-through direction are set for complicated bending shapes through NC control. The test apparatus configuration was described in detail in a previous report[8].

TABLE I
DIMENSION AND MECHANICAL PROPERTIES OF USED MATERIAL

TP No.	Material	Cross section dimension $H_0 \times W_0 \times t_0$ /mm	$\sigma_{0.2}$ /MPa	σ_B /MPa	δ / %
1	A6063	40×40×2	85	171	18
2	A6N01	83×130×4, 8	85	185	30

B. Clearance Between the Die and the Extruded Section

The clearance between the die and the extruded section influences mainly the cross-section deformation of bent materials. For the dies used in the present study, the material was SKD11, the surface roughness was Ry = 0.64μm, and the hardness was Hv = 721. To investigate the influence of clearance on cross-section deformation, material No. 1 in Table

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The research topics are manufacturing technology for light weight metals, such as aluminum and magnesium alloys.

1 was passed through a die while the clearance between the extruded section was changed to 0.2, 0.4, 1.2, and 2.0mm on each side (a total of 0.4, 0.8, 2.4 and 4.0mm for both sides). The die was 40mm thick. When material No. 2 was passed through the die, the clearance between the extruded section was kept constant at 1.0mm with a die thickness of 100mm.

C. Test method

We performed two-dimensional bending with a single curvature to investigate basic bending characteristics. In push-through bending, the material is bent by moving the movable die horizontally by distance Y while simultaneously applying die-bending angle θb. The distance L between the fixed die and the movable die is kept constant during processing. The bending force, slide traces, and wrinkle height increase if die-bending angle θb is not optimized. Furthermore, the optimum θb varies depending on die movement Y and distance L between dies, so we investigated a method for determining θb that can be obtained unequivocally from Y and its influences on irregular deformation of the cross section.

Distance L between dies is set in the initial stage and is an important forming condition. Here, the distance between dies was changed from 20 to 60mm for material No. 1 and from 130 to 200mm for material No. 2. Mandrels were used concurrently to suppress cross-section deformation of the extruded sections. The push-through speed of the extruded sections was 63mm/s, and mineral oil was used for lubrication. referees, and to make it easy for you to distribute preprints.

D. Items evaluated

If Push-through bending can be considered as continuous four-point bending, two points on the fixed die and two points on the movable die (Fig. 1). Therefore, the surfaces of the extruded sections may be scuffed with slide traces if curvature ρ if bending is too large or slide characteristics between the extruded section and the die are inappropriate. We thus measured the roughness of the slide traces and the push-through force during the experiment.

Furthermore, the cross section of the extruded section deforms after bending (Fig. 2), so each measurement item was evaluated in accordance with the previous report.

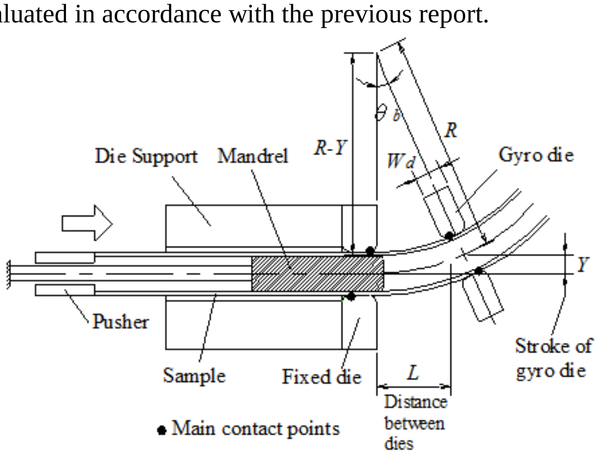

Fig.1 Main contact point on push-through bending and relation of relativity at dies

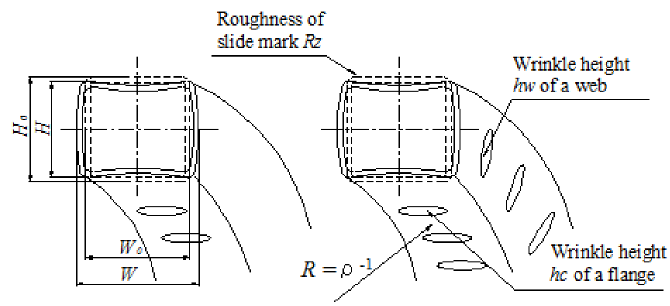

Fig.2 Measurement position

III. Results and Discussion

A. Effect of Clearance on Bending Characteristics

The clearance between the die and the extruded section should be reduced to suppress cross-section deformation and wrinkling. However, it cannot be reduced to zero considering dispersion of external dimensions and handling characteristics of aluminum extruded sections. Therefore, we investigated the relationship between the curvature and the amount of die movement when the clearance between the die and the extruded section on one side was changed to 0.2, 0.4, 1.2, and 2.0mm while using material No. 1 in Table 1 (Fig. 3). There tends to be play when the clearance is increased while the die movement is kept constant and curvature is decreased. However, it is simple to obtain the targeted curvature if the relationship between curvature and the amount of die movement is understood beforehand. The problem is that the rate of change in the cross-section dimensions increases (Fig. 4) when clearance increases. When there is little clearance with the die, the die restricts the extruded section and swelling to the outside is somewhat restricted. However, if the clearance on one side is 1.2mm or more as in the present experiment, the lateral cross section, which swells in proportion to the increase in curvature, cannot be restricted. The rate of change in the lateral cross--section dimensions increases, thus promoting buckling and wrinkling. These results suggest that the clearance between the die and the extruded section in push-through bending should be minimized considering the dispersion of external dimensions of the extruded sections. In subsequent experiments using material No. 1, clearance on one side will be kept constant at 0.2mm.

B. Effect of the Die-Bending Angle on Cross-Section Deformation

Die-bending angle θ_b that is given together with the amount of die movement can be obtained geometrically after determining the distance *L* between dies, bending radius *R*, and die thickness W_d (Fig. 1).

$$\sin\theta_b=(L+(W_d/2))/R \quad (1)$$

However, using the movement *Y* of the movable die, bending radius R also can be expressed by Eq. (2).

$$R^2=(R-Y)^2+(L+W_d/2)^2 \quad (2)$$

Based on Eqs. (1) and (2), θ_b can be obtained from Eq. (3).

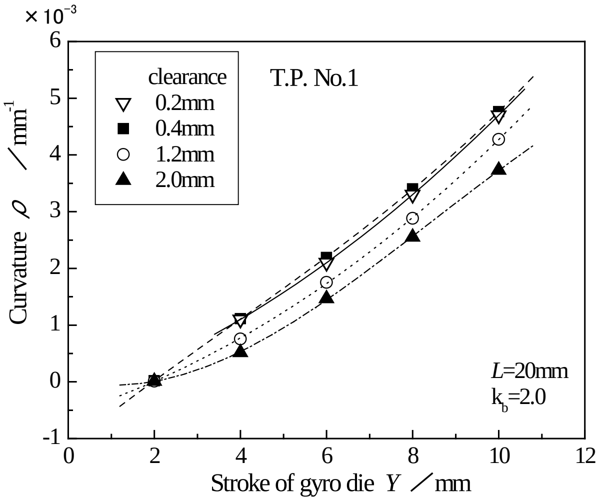

Fig.3 ρ vs Y as a function of clearance

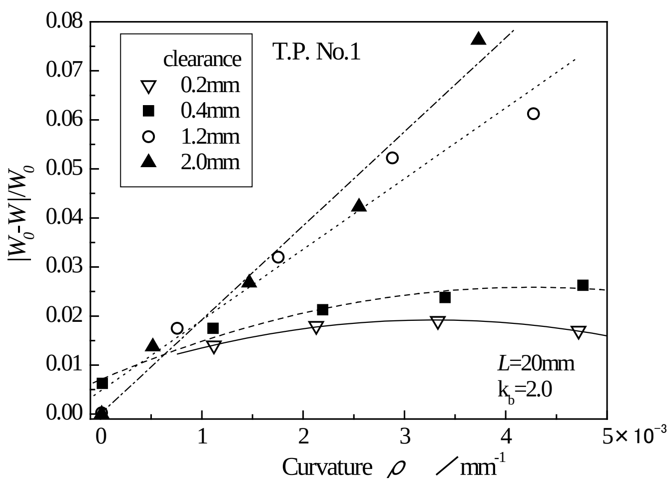

Fig.4 $|W_0\text{-}W| / W_0$ vs ρ as a function of clearance

$$\theta_b = \sin^{-1}(2Y(L+W_d/2)/(Y^2+(L+W_d/2)^2)) \qquad (3)$$

Figure 5 presents θ_b calculated from Eq. (3) while changing Y. At any distance L between dies, Y and θ_b are directly proportional. It is usually necessary to input die movement Y and die-bending angle θ_b when programming push-through bending, so they should be simply related. This can be expressed with Eq. (4) without using the more complicated Eq. (3).

$$\theta_b = k_b \times Y \qquad (4)$$

Here, k_b is the coefficient of die-bending angle and can be obtained unequivocally from Eqs. (3) and (4) after the targeted bending radius has been determined.

In practical bending, however, it is difficult to determine the absolute value of k_b using this equation because of the influence of spring back. Figure 6 depicts the rate of change in the dimensions of the cross sections when the distance between dies is set to L = 20mm and the die-bending angle is changed from

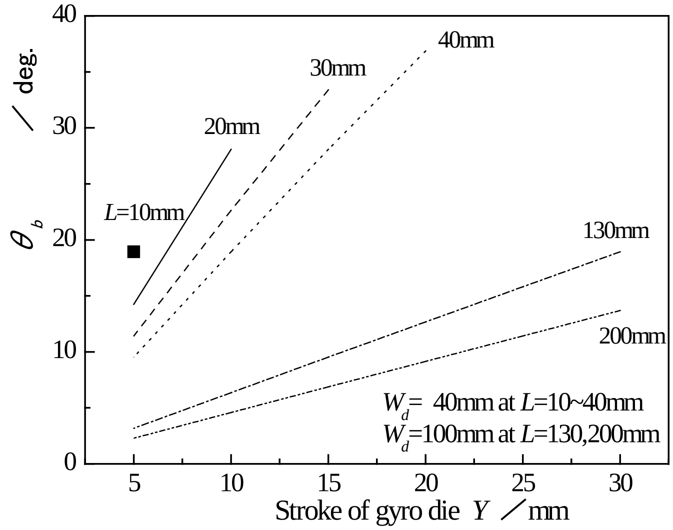

Fig.5 Value of θ_b by geometric calculation

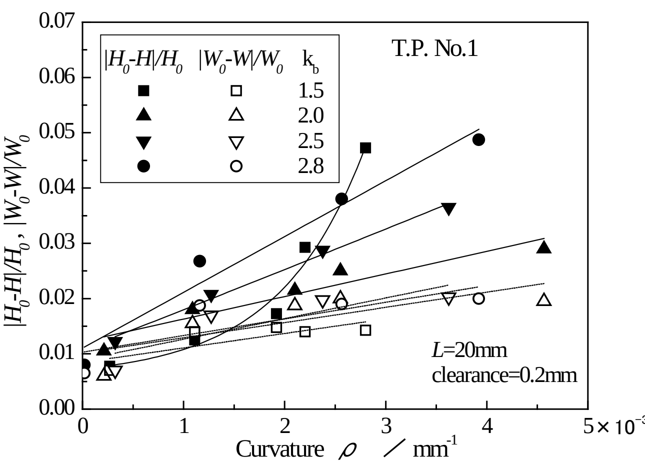

Fig.6 $|H_0\text{-}H|/H_0$ and $W_0\text{–}W|/W_o$ vs ρ as a function of k_b

1.5 to 2.8 in push-through bending of material No. 1. The clearance between the die and the extruded section is only 0.2mm, so if the die-bending angle is inappropriate, the die suppresses any deformation, including swelling to the outside. Thus, the rate of change in the dimensions of the cross sections is almost constant. However, there is no mandrel near the movable die, so some differences do occur in the dimensions of the longitudinal cross section, causing it to go to the inside. The rate of change of the longitudinal cross-section dimensions increases rapidly at k_b = 1.5 because, although the extruded section is bent by the die movement (Fig. 7), the die-bending angle is too small, so the material is subject to rapid unbending near the exit of the movable die and is crushed in the longitudinal direction. Conversely, if k_b is too large, the extruded section is bent too much by the bending angle of the die, in addition to bending by the die movement (Figs. 7 and 8), promoting the growth of wrinkles in the web. The results indicate that kb increases rapidly after exceeding 2.6. When the distance L between dies is set to 20mm for material No. 1, the optimum value of kb is 2.0, which is smaller than the calculated 2.8. Hereafter, kb for material No. 1 is set to 2.0 unless otherwise specified. However, material No. 2 has thicker walls and higher rigidity than material No. 1, so the difference in the coefficient of die-bending angle is greater when the difference in curvature is constant.

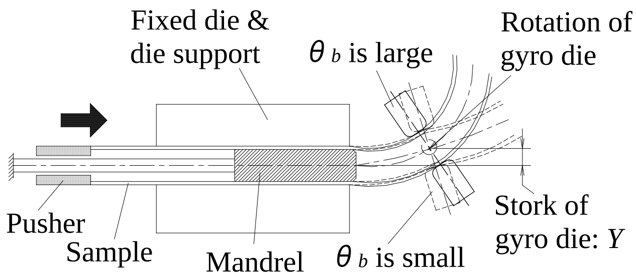

Fig.7 Bending shape by a die bending angle

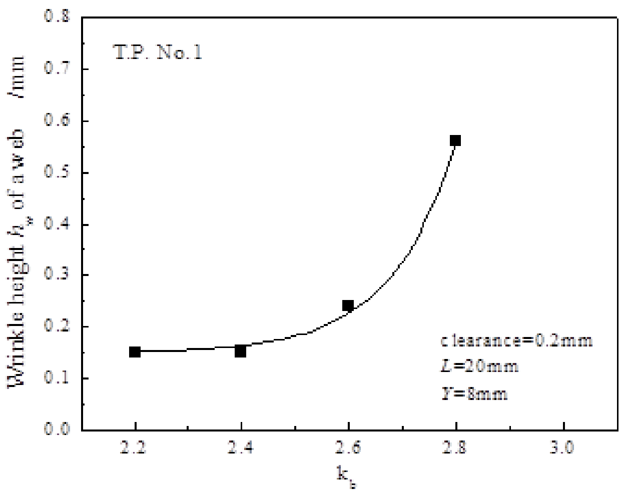

Fig.8 Effect of k_b on wrinkle height h_w of a web

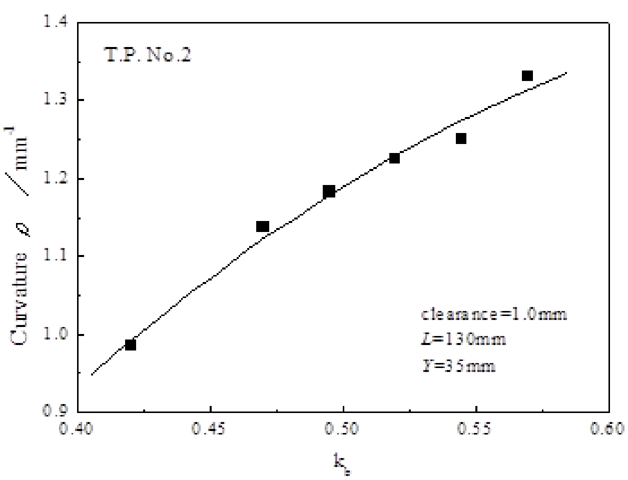

Fig.9 Effect of k_b on ρ at large cross section

Figure 9 depicts the effect of the coefficient of die-bending angle k_b on the curvature when the distance L between dies is set to 130mm and the die movement is set to Y = 35mm. The value of k_b obtained geometrically from Eqs. (3) and (4) is 0.86. Thus, a small difference in k_b leads to a large change in curvature for material No. 2, and setting the optimum value of k_b is important.

It is difficult to evaluate material No. 2 with changes in the dimensions in the lateral cross section or the wrinkle height in the web since it has higher rigidity than material No. 1. Therefore, it should be evaluated from the roughness of slide traces instead. Figure 10 depicts the effect of the efficient of the die-bending angle on *Rz* in the slide section at Y = 35mm. The extruded section passed smoothly at $k_b \fallingdotseq 0.5$, which seems to be the optimum value of the coefficient of the die-bending angle.

C. Effect of Retarding Die-Bending Angle Application on Materials with Large Cross Sections

When subjecting materials with large cross sections to push-through bending, both the fixed die and the movable die are large. It is thus necessary to provide a certain distance between dies to prevent their mutual interference. As was clarified in a separate report, regular plastic deformation in

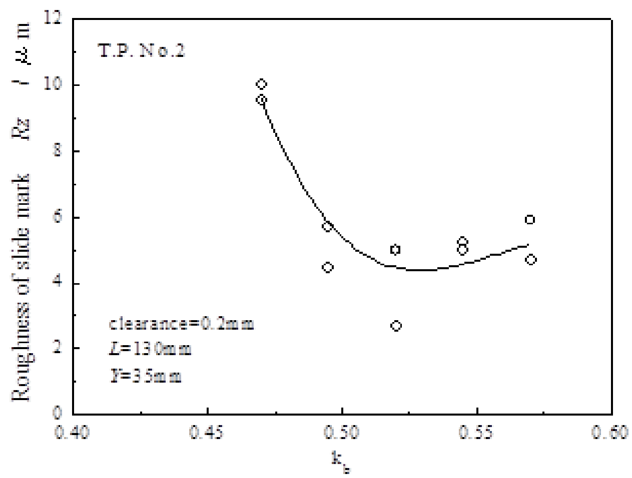

Fig.10 Effect of k_b on roughness of slide mark at large cross section

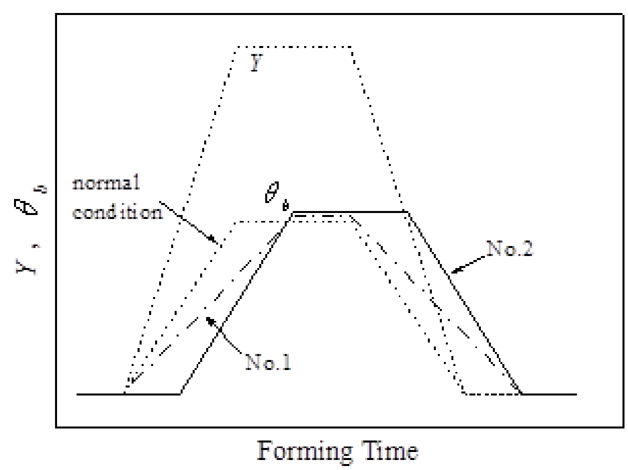

Fig.11 Delay patterns of bending angle at die movement

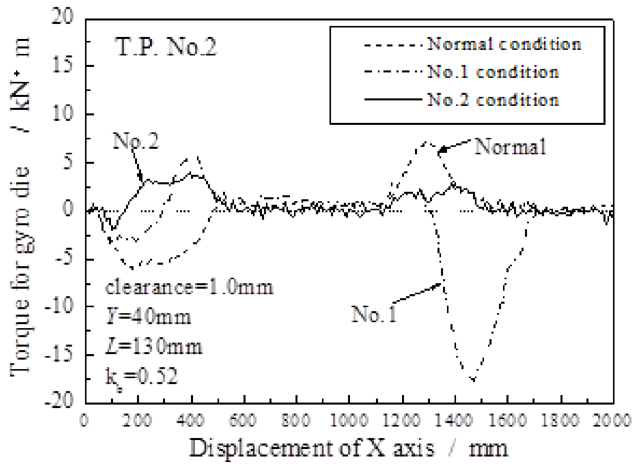

Fig.12 Change of torque for gyro die at die movement

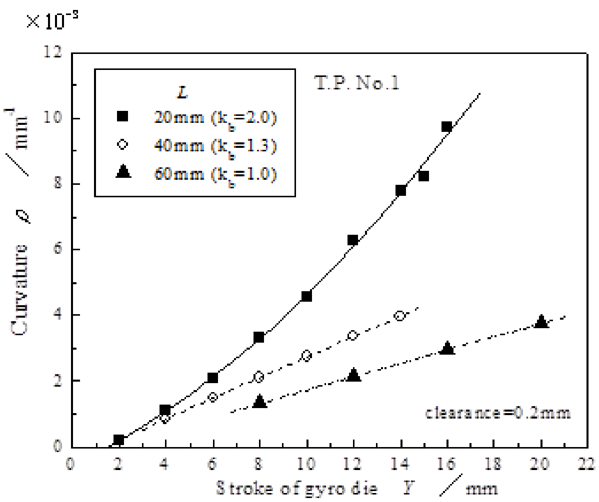

Fig.13 ρ vs Y as a function of distance between dies L

Push-through bending begins inside the fixed die, and deformation is complete when the material passes out of the fixed die. However, the portion of material between the dies immediately after bending starts is still straight, so if the die-bending angle and the die movement are started simultaneously, it is highly probable that the extruded section that has not yet reached the prescribed curvature will be pried by the movable die. The movement of the movable die and applying the die-bending angle are usually simultaneous (Fig. 11), but the load on the extruded section is smaller if the timing to apply the die-bending angle (angle movement start point) is delayed. Therefore, we tried the two types of delay patterns depicted in Fig. 11. In Condition 1, the angle movement started simultaneously with movement of the die, but the speed was reduced to produce the angle. In Condition 2, the start of the angle movement itself was delayed from the movement of the die by one cycle.

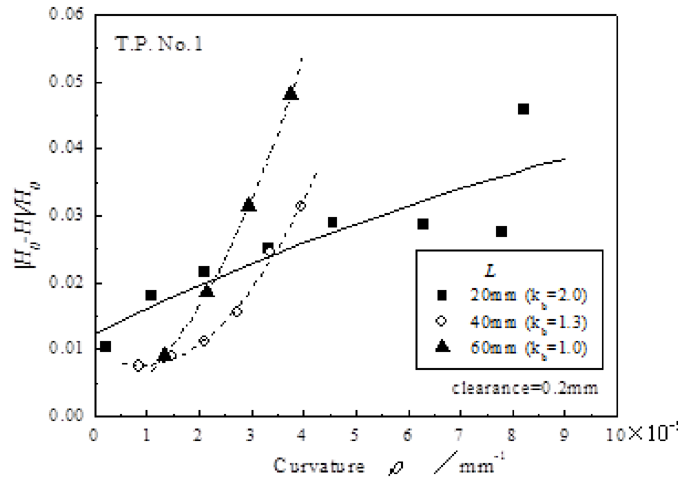

Fig.14 $|H_0\text{-}H|/H_0$ vs ρ as a function of distance between dies L

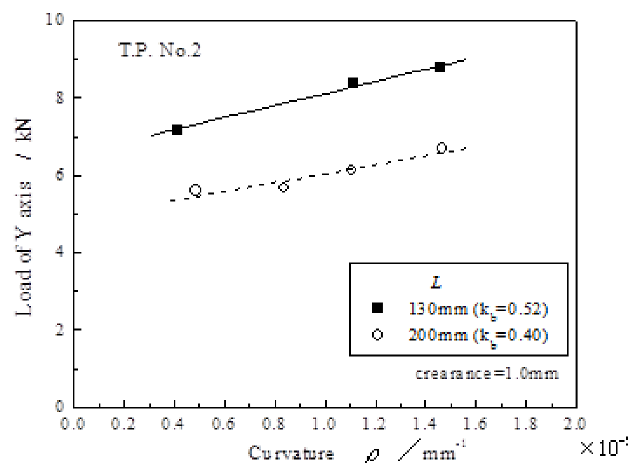

Fig.15 Load of Y axis vs ρ as a function of distance between dies L at large cross section

Figure 12 depicts the fluctuations of torque on the axis that produces the die-bending angle when material No. 2 in Table 1 is bent under the conditions of $Y = 40$mm, $L = 130$mm, and $k_b = 0.5$ by programing the above-mentioned pattern (die-rotating torque). The die-rotating torque depicted in Fig. 7 is minimum if θ_b changes appropriately throughout the entire process of bending. Under ordinary conditions where die movement and die-bending angle change are completely synchronized, the die-rotating torque that is applied to the extruded section during die movement is large and becomes worse under Condition 1 where the speed of angle movement decreases. Under Condition 2, however, the die-rotating torque is small, and therefore damage to the sliding section is small.

D. Effect of the Distance Between Dies on Bending Characteristics

An important forming conditions for push-through bending, comparable with the die-bending angle, is the distance between dies. Since push-through bending can be understood as continuous four-point bending, as discussed previously, it can be assumed that when the distance between dies is large, bending force decreases, and the slide traces on the bending material decrease. In practice, however, the distance cannot become longer than a certain limit, due to restrictions by mechanical interference. Figure 13 depicts the effect of the amount of die movement on curvature on with the distance between dies set to 20 , 40 , and 60mm using material No.1. the coefficient of die-bending angle k_b was set to 2.0 , 1.3 , and 1.0.

Coefficient k_b is not optimized at L = 40mm and 60mm, so the curvature increases as the distance between dies decreases for the same amount of die movement. However, if the distance between dies increases, the distance over which the extruded section moves after exiting the fixed die until being restricted again by the movable die increases, so the rate of changes in the dimensions of the longitudinal cross section in the area of high curvature tends to become greater than that at L = 20mm (Fig. 14). The rate of change in the dimensions of the longitudinal cross section at L = 40mm and 60mm rises steeply as the curvature increases, but the same trend as that at L = 20mm can be obtained if k_b is optimized. The same trend can also be observed in the height of wrinkles in the web section.

For comparison, material No. 2 was subjected to experiments after the coefficient of the die-bending angle at L = 130mm and 200mm was optimized. Material No. 2 has large cross sections and thick walls, so the bending force (the maximum load on the Y axis) changes remarkably, depending on the bending conditions. Figure 15 depicts the effect of curvature on the maximum load on the Y axis when the distance between dies was changed. The maximum load on the Y axis corresponding to the bending force decreases as the distance between dies increases. However, no step is taken to retard the die-bending angle movement.

As described above, the optimum distance between dies is observed with a balance between cross-section deformation of the extruded sections and maximum load on the Y axis.

IV. Conclusion

We investigated the effect of forming conditions on cross-section deformation and slide traces in push-through bending and clarified the following.

As the clearance between the die and the extruded section increases, the curvature becomes smaller and the rate of change in the dimensions of the lateral cross section becomes larger if the amount of die movement is kept constant. The optimum clearance should be minimized after considering the dispersion of external dimensions of the extruded sections.

Die-bending angle θ_b is expressed such that the amount of die movement Y is multiplied by coefficient k_b; if θ_b is inappropriate, the rates of change in the dimensions of the longitudinal cross section, wrinkle, and roughness of slide traces increase. The optimum value differs depending on the distance between dies, but it is less than the value that can be obtained geometrically due to spring back of the extruded section.

If there is a large distance between dies as with push-through bending of materials with large cross sections, there is a time lag from the point where the material is bent by the fixed die until it passes through the movable die. Therefore, it is possible to reduce the load on the extruded section by retarding the die-bending angle application before the start of die movement, which greatly mitigates cross-section deformation and slide traces.

The maximum load on the Y axis required for bending (bending force) decreases as the distance between dies increases, but the section where the extruded section being bent is not restricted becomes longer and cross-section deformation increases, so there is an optimum distance.

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