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EFFECTS OF ROTATIONAL FEED EMULATING FOUR-DIE RADIAL FORGING ON FORGED SHAPE IN MANDREL-LESS INCREMENTAL FORGING OF THICK CIRCULAR TUBE

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Abstract. This paper focuses on the formability of mandrel-less incremental forging to produce tubes with variable wall thickness. Tubes with variable wall thickness corresponded to their load distribution have advantages in weight-saving and resource-saving; therefore, the author proposed a new incremental forging to produce those tubes. One of the proposed incremental forging difficulties is obtaining the forming conditions to produce desired shapes because forging a tube with two flat dies and without mandrel freely deforms except a small area where the two flat dies are contacted. In order to examine the possibility of formability improvement in the proposed mandrel-less incremental forging of thick circular tube, the effects of rotational feed emulating four-die radial forging on forged shape were evaluated by conducting finite element simulation. As a result, emulating four-die radial forging pass reduces the oval deformation of the workpiece.

1 INTRODUCTION

Tubes with variable wall thickness corresponded to their load distribution, as shown in **Figure 1**, have advantages in weight-saving and resource-saving. Because of the advantages, those tubes are applied to bicycles frame [1] and proposed to apply automotive driveshafts [2-4] and railway axles [5, 6]. Those tubes should be tailor-made to reduce their weight effectively; therefore, flexible forming is suitable for their production. Most tubes with variable wall thickness are produced by radial forging [5, 7], rotary swaging [2, 4], cross-wedge rolling [6], and drawing [7]. Those forming processes are relatively flexible; however, their dies and mandrels must be prepared according to the tubes' size to be produced.

The author proposed a new incremental forging to produce tubes with variable wall thickness [8]. One of the proposed incremental forging difficulties is obtaining the forming conditions to produce desired shapes because forging a tube with two flat dies and without mandrel freely deforms except a small area where the two flat dies are contacted. **Figure 2** illustrates the schematics of the arrangement of the die of (a) two-die incremental forging and (b) four-die radial forging. In the proposed two-die incremental forging, deformation in the y-axis is free; the workpiece easily becomes an oval shape. In contrast, in four-die radial forging, the workpiece is compressed in both the z-axis and y-axis; the oval deformation is suppressed. Thus, in the proposed two-die incremental forging, there is a possibility to suppress the oval deformation emulating four-die radial forging. In order to examine the possibility of formability improvement, the author conducted finite element simulation. In this paper, the effects of rotational feed emulating four-die radial forging on forged shape ware clarified as a fundamental research.

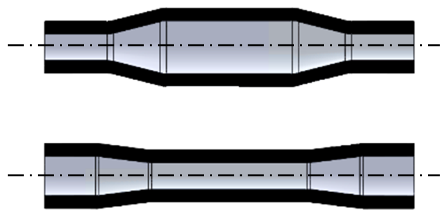


Figure 1: Schematic illustration of tubes with variable wall thickness

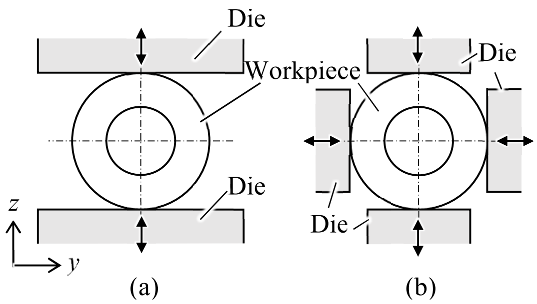


Figure 2: Schematic illustration of die arrangement of (a) two-die incremental forging and (b) four-die radial forging

2 PRINCIPLE OF MANDREL-LESS INCREMENTAL FORGING OF THICK CIRCULAR TUBE

Figure 3 illustrates the schematic of the proposed mandrel-less incremental forging of a thick circular tube. A tube is held by a manipulator, controls the rotational and axial position of the tube, and is forged by flat dies. In mandrel-less incremental forging, rotational feed and axial feed by the manipulator and height reduction (minimum distance between dies) by flat dies are controllable forming factors. In addition, there are influential forming factors determined by the specification of the forged products and the forging equipment, such as material, the ratio of inner to outer diameter, die width, and die shape. Formed shapes are categorized into seven shapes by considering the forming factors and condition of tube end: stepped shape at fixed end side, stepped shape at free end side, straight shape, taper shape at fixed end side, taper shape at free end side, straight shape at tube end, and taper shape at tube end. Combinations of the seven shapes can define various kinds of tubes with variable wall thickness.

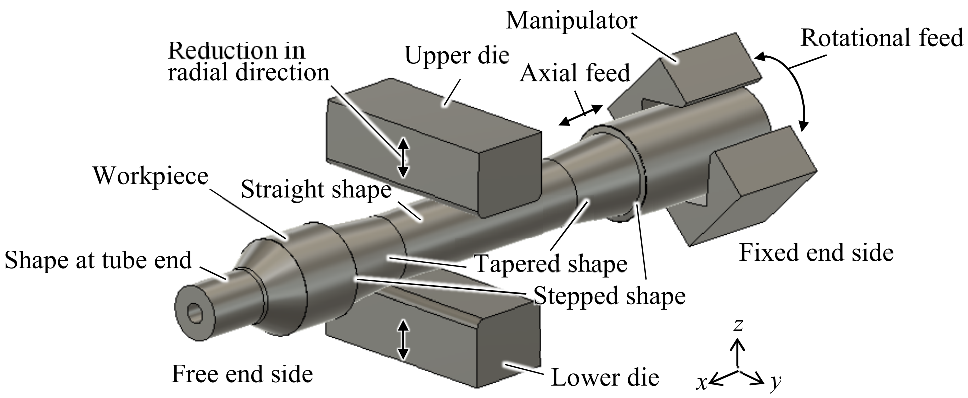


Figure 3: Schematic illustration of mandrel-less incremental forging of thick circular tube

3 SIMULATIONS

Figure 4 shows a model of the finite element simulation. The model was composed of a workpiece and a pair of flat dies. The model for the workpiece was tetrahedral solid elements with adaptive remeshing. The model for the dies was triangular shell elements and moved toward the center of the workpiece in the *z*-axis. A manipulator was modeled as boundary conditions of the workpiece's nodes at the negative end of the *x*-axis: while the dies compressed the workpiece, the translation of the nodes in *x*, *y*, *z* direction was constrained; after unloading dies, the workpiece rotated. The solver for the simulation was FORGE NxT 3.0.

Workpiece material was AA1070-O with 28.0 mm in outer diameter, 14.0 mm in inner diameter, and 80.0 mm in length. Flow stress σ was obtained from compression test as $\sigma = 35 + 29\varepsilon^{0.33}$ MPa where ε is strain. The friction between the workpiece and dies was obtained from ring compression test as 0.07 in Coulomb friction coefficient.

Table 1 shows the forming conditions. As a fundamental research, the maximum distance between dies C_m, equivalent to height reduction of the workpiece, was not varied, and axial feed f_a was 0 mm·blow^{-1}. **Table 2** shows the details of the conditions of rotational feed. In four-die radial forging, the relative position of each pair of dies is π/2 rad rotated position in the axial direction. Therefore, rotational feed f_r for emulating four-die radial forging is defined as π/2 rad after odd numbers of the blows and $(\pi/2 + f_r)$ rad after even numbers of blows. Pass-A and Pass-B is pass type of emulating four-die radial forging. For comparison, a pass type of constant angles in rotational feed was also as examined as Pass-C and Pass-D. The expected shape in regular n-gon is the ideal forged shape determined from the geometrical relationship between the maximum distance between dies C_m and rotational feed f_r.

The shape of the forged workpiece was evaluated in outer diameter D_O, inner diameter D_I, elongation ΔL, and twisted angle β. Outer diameter D_O and inner diameter D_I were cross-sectional distances at the center of the forged area in the axial direction. Elongation ΔL was an amount of change in distance between both ends of the workpiece. Twisted angle β was an amount of change in rotational angle between both ends of the workpiece.

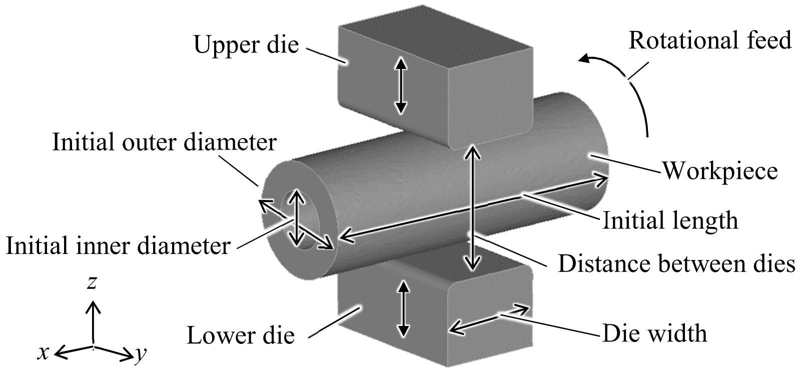


Figure 4: Model of finite element simulation

Table 1: Forming conditions

Initial outer diameter of workpiece D_{Oini}/mm	28.0
Initial inner diameter of workpiece D_{Iini}/mm	14.0
Initial length of workpiece L_{ini}/mm	80.0
Die width B/mm	25.0 (R = 2.5)
Minimum distance between dies C_m/mm	24.0
Axial feed f_a/mm·blow^{-1}	0
Rotational feed f_r/rad·blow^{-1}	π/18 - π/5

Table 2: Details of conditions of rotational feed

Pass type	Expected shape in regular n-gon n/side	Rotational feed f_r/rad·blow^{-1}
Pass-A	20, 24, 28, 32, 36	π/10, π/12, π/14, π/16, π/18 (emulating four-die radial forging)
Pass-B	20, 28, 36	π/5, π/7, π/9 (emulating four-die radial forging)
Pass-C	20, 24, 28, 32, 36	π/10, π/12, π/14, π/16, π/18
Pass-D	22, 26, 30, 34	2π/11, 2π/13, 2π/15, 2π/17

4 RESULTS AND DISCUSSION

Figure 5 shows the appearance of the forged workpiece, and **Figure 6** shows the cross-sectional shape of the forged workpiece at the center in the axial direction. As shown in the figures, the shape of the forged workpiece depends on the forging pass. The following are detailed evaluations of the effects of rotational feed emulating four-die radial forging on forged shapes.

Figure 7 shows the relationship between expected shape in regular n-gon and (a) maximum and (b) minimum outer diameter with the variation of pass type. The maximum outer diameters D_{Omax} at both Pass-B and Pass-D were smaller than the initial outer diameter D_{Oini}; the outer diameter of the forged area was reduced. On the other hand, the maximum outer diameters D_{Omax} at both Pass-A and Pass-C were larger than the initial outer diameter D_{Oini}; the outer diameter of the forged area was not reduced. The minimum outer diameters D_{Omin} at Pass-A, Pass-B, and Pass-D were almost the same as the minimum distance between dies C_m, and Pass-C was smaller than the minimum distance between dies C_m.

Figure 8 shows the relationship between expected shape in regular n-gon and (a) maximum and (b) minimum inner diameter with the variation of pass type. The maximum inner diameters D_{Imax} at Pass-A, Pass-B, Pass-D were smaller than the initial inner diameter D_{Iini}. In contrast, the maximum inner diameter D_{Imax} at Pass-C was larger than the initial inner diameter D_{Iini}. The minimum inner diameters D_{Imin} at Pass-B and Pass-D were almost the same and slightly smaller than that of Pass-A and Pass-C.

Figure 9 shows the relationship between expected shape in regular n-gon and elongation with the variation of pass type. Elongations ΔL of 20-gon were almost the same regardless of pass type. At Pass-D, the elongation ΔL increased with increasing the side of the expected shape in regular n-gon. The amount of the increment was Pass-D, Pass-B, Pass-A, and Pass-C in descending order; Pass-C was almost flat.

Figure 10 shows the relationship between rotational feed and twisted angle with the variation of pass type. The twisted angle β increased with decreasing rotational feed at all of the passes. The increment of the twisted angle β at Pass-A and Pass-B, and Pass-C and Pass-D were almost the same, respectively. The increment of the twisted angle β at Pass-A and Pass-B was smaller than that of Pass-C and Pass-D: the twisted angle β of emulating four-die radial forging pass decreased compared with that of constant angle in rotational feed pass.

Emulating four-die radial forging pass reduces oval deformation as intended. **Figure 11** shows the schematic illustration of the forging sequence with the variation of pass type. The number in the figure is a blow number corresponding to each expected shape in regular n-gon. Emulating four-die radial forging pass, the pair of dies moves in the direction of suppressing oval deformation at even numbers of blows. For this reason, the formability of Pass-A and Pass-B is better than that of Pass-C. Additionally, the result of the decrease of the twisted angle β at Pass-A and Pass-B is in good agreement with the finding that ovalization of the workpiece increase in twisted angle [8].

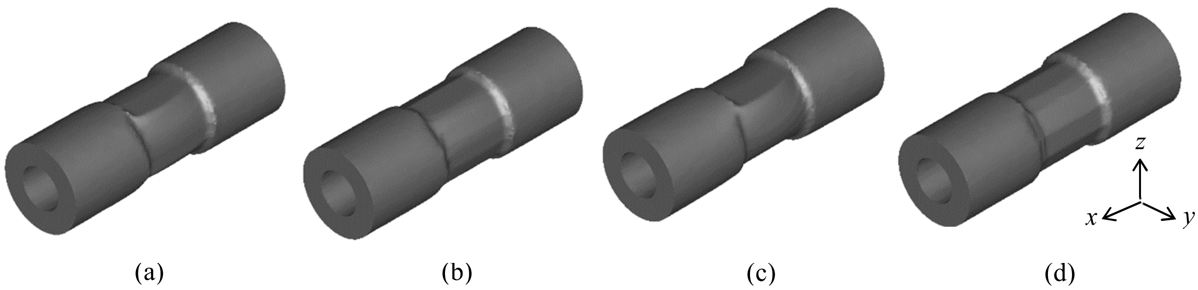


Figure 5: Appearance of forged workpiece: (a) Pass-A, n = 20; (b) Pass-B, n = 20; (c) Pass-C, n = 20; (d) Pass-D, n = 22

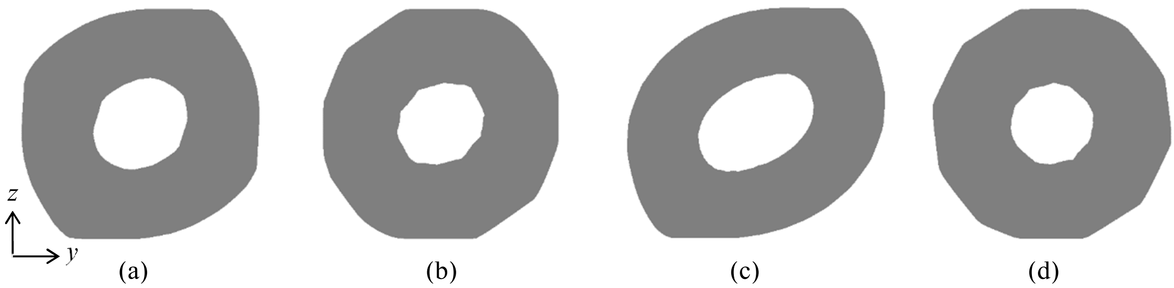
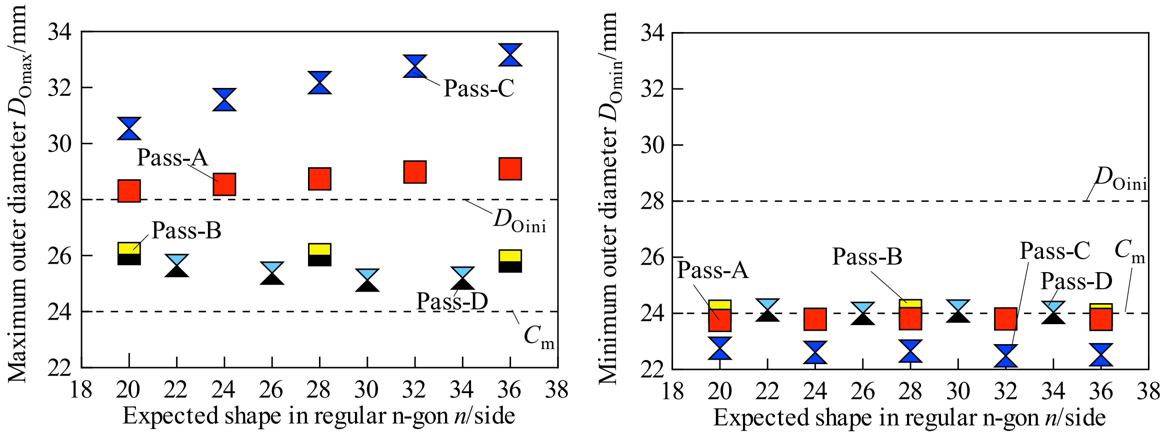
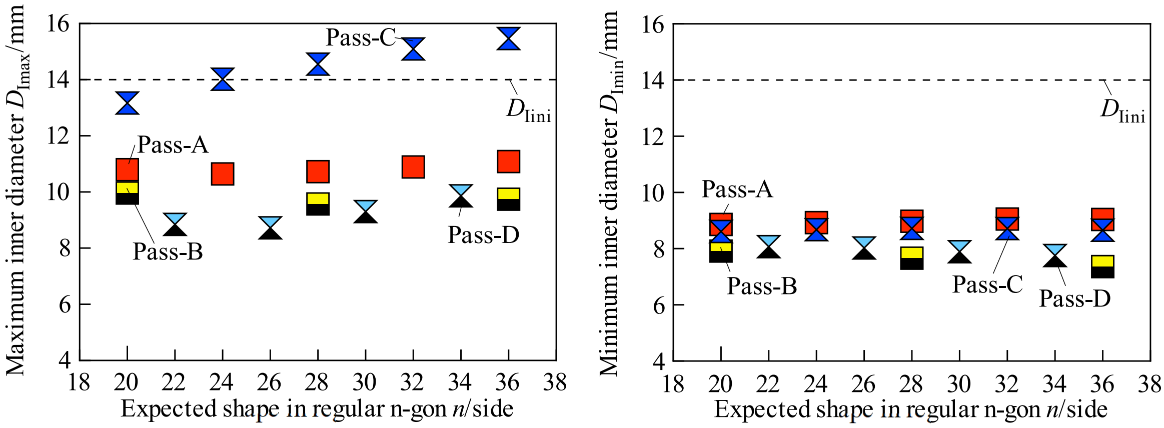


Figure 6: Cross-sectional shape of forged workpiece at the center in axial direction: (a) Pass-A, n = 20; (b) Pass-B, n = 20; (c) Pass-C, n = 20; (d) Pass-D, n = 22



(a) (b)

Figure 7: Relationship between expected shape in regular n-gon and (a) maximum and (b) minimum outer diameter with variation of pass type



(a) (b)

Figure 8: Relationship between expected shape in regular n-gon and (a) maximum and (b) minimum inner diameter with variation of pass type

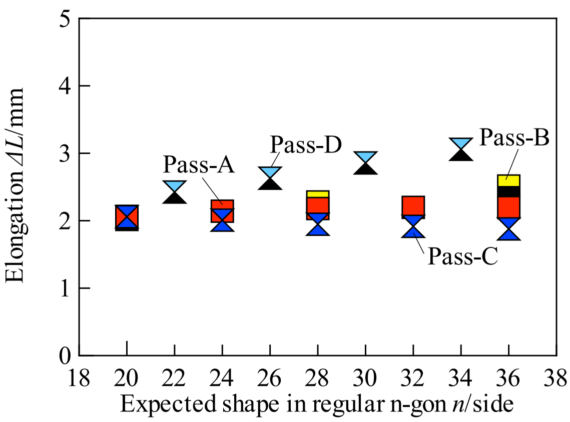


Figure 9: Relationship between expected shape in regular n-gon and elongation with variation of pass type

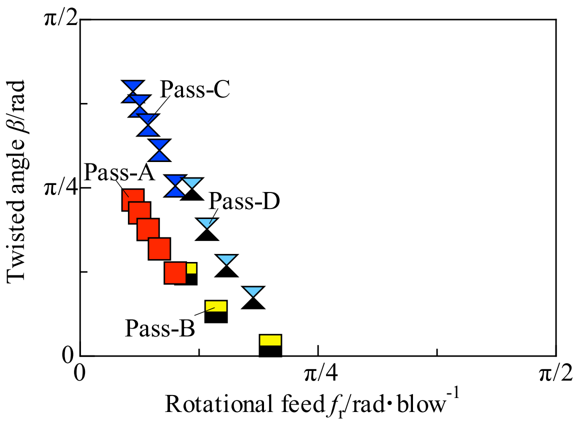


Figure 10: Relationship between rotational feed and twisted angle with variation of pass type

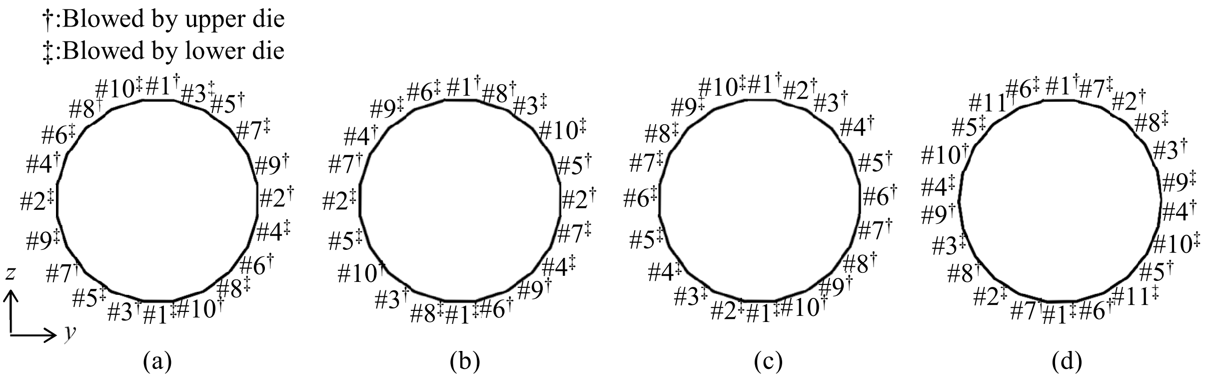


Figure 11: Schematic illustration of forging sequence with variation of pass type: (a) Pass-A, n = 20; (b) Pass-B, n = 20; (c) Pass-C, n = 20; (d) Pass-D, n = 22

5 CONCLUSIONS

- In order to examine the possibility of formability improvement in the proposed mandrel-less incremental forging of thick circular tube, the effects of rotational feed emulating four-die radial forging on forged shape was evaluated by conducting finite element simulation.
- Emulating four-die radial forging pass reduces the oval deformation of the workpiece because the pair of dies moves in the direction of suppressing oval deformation of the workpiece at even numbers of blows.
- Emulating four-die radial forging pass reduces the twisted angle of the workpiece caused by suppression of oval deformation.

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